

Variability in water masers and possible accretion burst in NGC 2071-IR

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Dissertation accepted in partial fulfilment of the requirements for the degree *Master of Science in Astrophysical Sciences* at the North-West University

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Graduation July 2023

36566454

Declaration

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Acknowledgements

First and foremost, I would like to express my warmest gratitude to my supervisor Prof. James Chibueze for making this study possible. His guidance, advice and insight enabled me to overcome the obstacles faced at all stages of this work. My sincere appreciation also goes to my second supervisor, Dr Stefanus van den Heever for providing the data, advice, and continuous support for my work, as well as the HartRAO staff who worked endlessly to provide me with observational data and the PSS values. My gratitude also goes to Prof. Johan van der Walt for his advice and book recommendations. I would also like to thank the driving forces of the Centre for Space Research at the North-West University, Prof. Christo Venter for being such a welcoming person who is always ready to listen to our challenges and find solutions, Mrs Petro Sieberhagen who was more of a mother to me than an administrator, and Mr Lendl Fransman for assisting me with all my administrative issues. I am thankful to my lab members, Jean-Marie Morgan, Mavis Seidu, Job Vorster, Andrea Nel, Dakalo Phuravhatu, Robin Wessels, Brenda Homera, Riku Urago, Thabiso Mgwambane, Jude Ugwu, Lebogang Mfulwane, and Janie du Preez for their assistance at one point or another.

Special thanks to Prof. Melvin Hoare at the University of Leeds UK, the brain behind the DARA project, who provided the opportunity for me and many other Africans like me to study, and later assist in building the future of astronomy in Africa. I would like to thank Dr Sharmilla Goedhart, Dr Bernard Asabere, and Mr Evans Owusu for their encouragement.

Finally, I would like to thank my family, my son, Dario Ollendorf and my partner Dr Franziska Ollendorf for tolerating my absence at the critical stages of our family life. I am extremely grateful to my father, the late Dr Hayford Dzodzomenyo and my mother Bernice Sekyi-Dzodzomenyo for their love, prayers and the sacrifices they made to ensure that I got a good education. To my siblings, Christine, Francis, Renate and John, thank you for being there for me.

Research reported in this dissertation was supported by a Newton Fund project, DARA (Development in Africa with Radio Astronomy), and awarded by the UKs Science and Technology Facilities Council (STFC) - grant reference ST/R001103/1.

Abstract

Although stars are ubiquitous in the Universe, the processes leading to their formation are still poorly understood. Developing a unified theory of star formation is hindered by the fact that stars in the different mass regimes, namely, low ($M_* < 2 M_\odot$), intermediate ($2 M_\odot < M_* < 8 M_\odot$), and high-mass ($M_* > 8 M_\odot$) regimes have similar but differing formation processes. Further compounding the challenge is that intermediate-mass protostars are more obscured than their low-mass counterparts and also do not affect their surrounding environments like high-mass stars, making it difficult to establish a clear criterion for identifying intermediate-mass protostars observationally. One process common to star formation across all mass regimes is accretion, and episodic accretion events known as accretion bursts are reported to drive strong flares in water masers accompanied with an increase in luminosity.

Interstellar masers serve as indirect indicators of ongoing star formation as well as probes of the physical conditions such as temperature and density in star-forming regions. In 2019, flaring of the 22 GHz water maser (hereafter H₂O maser) in the NGC 2071-IR star forming region was reported by the Maser Monitoring Organisation (M2O). Single-dish spectra of the H₂O maser from the Hartebeesthoek 26-m telescope covering a period from 2019 to 2022 were analysed, revealing high variability and a strong flare in November 2019 which reached a peak of 4722 ± 4 Jy. Observations conducted to detect the mainline 6.7 GHz methanol maser towards NGC 2071-IR yielded no detections. This study aims to investigate the variability observed in the H₂O maser spectra and verify if the 2019 flare was a result of an accretion burst event. Signatures of accretion bursts such as flaring of multiple maser species and increase in infrared luminosity were probed. Interferometric imaging of (sub)millimetre dust continuum and spectral line (specifically carbon monoxide (CO)) observations with the Atacama Large Millimetre/submillimetre Array and the Very Large Array, revealed the NGC 2071-IR region is populated with multiple protostars with small spatial separations, driving multiple outflows. Water maser positions from the literature superimposed over the continuum images showed the H₂O masers trace disks and outflows. Ks-band observations made during the 2019 flare with Kanata/HONIR telescope revealed a 0.2 mag increase compared to the 2MASS magnitude.

Keywords: stars: formation, intermediate-mass stars, water masers, methanol masers, ISM: jets and outflows, techniques: interferometric, accretion bursts, NGC 2071 IR

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Table of abbreviations

ALMA	Atacama Large Millimetre/Sub-Millimetre Array
COMs	Complex Organic Molecules
CWB	Colliding Wind Binary
HII	Ionised Hydrogen
GMCs	Giant Molecular Clouds
HartRAO	Hartebeesthoek Radio Astronomy Observatory
HPBW	Half Power Beamwidth
IM	Intermediate Mass
IMYSO	Intermediate-Mass Young Stellar Objects
IMF	Initial Mass Function
ISM	Interstellar Medium
KVN	Korean VLBI Network
KaVA	KVN and VERA Array
MASER	Microwave Amplification by Stimulated Emission of Radiation
MSFRs	Massive Star Forming Regions
MHD	Magneto-Hydrodynamic
PSS	Point Source Sensitivity
PSF	Point Spread Function
RMS	root mean square
SEFD	System Equivalent Flux Density
SMA	Sub- Millimetre Array
UCHII	Ultra Compact Ionised Hydrogen
TTS	T Tauri Star
VANDAM	VLA/ALMA Nascent Disk and Multiplicity
VERA	VLBI Exploration of Radio Astrometry
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
YSO	Young Stellar Object

Chapter 1

Introduction

1.1 General overview

Although stars are ubiquitous and serve as the elementary building blocks of the Universe, providing chemical enrichment of galaxies and forming planets in their circumstellar disks, the physical processes behind their formation are still not completely understood (Lada, 2005). Star formation is an ongoing process that continues to the present day, and the end-to-end understanding of the star formation process is of fundamental importance to the understanding of not only the origin of stars, but also galaxies, planets, and the origins of life (Lada, 1998, 1987). Star formation is inherently a complicated and stochastic process, with the processes guiding the formation of stars and their clusters in the individual molecular clouds still debatable, even in the best-studied cases (Kravtsov, 2003). Stars also form with a broad distribution of masses which are usually grouped into three mass regimes, namely the low ($M_* < 2 M_\odot$), intermediate ($2 M_\odot < M_* < 8 M_\odot$), and high-mass ($M_* > 8 M_\odot$) regimes (Goodwin, 2013), and a further complication to unravelling the mystery of star formation arises from the fact that star formation processes of the three different mass regimes are different, although they share some similarities such as accretion (Beltrán, 2015). Intermediate-mass stars, for example, form in tightly packed clusters as opposed to their low-mass counterparts. Another example of this non-uniformity is the relatively short timescales over which high-mass stars form compared to low and intermediate-mass stars (Russeil et al., 2010). The non-uniformity in the formation processes poses a challenge to the development of a unified theory of star formation. There is currently no testable unified theory of star formation capable of tying together the formation processes across the three mass regimes. Furthermore, another challenge arises from the fact that young stars remain deeply embedded in their natal clouds of gas and dust prior to the commencement of nuclear fusion, making them difficult to observe directly (Lada et al., 1993). In the past decades, the advent of more sensitive instruments, such as Jansky Very Large Array, Atacama Large Millimetre/Sub-Millimetre Array (ALMA),

and Sub-Millimetre Array (SMA), seek to shed more light on the star formation processes through high-resolution observations.

Another disparity is that low-mass stars have been relatively well-studied (Beltrán, 2015), compared to intermediate-mass (IM) stars, which have been grossly understudied (Kun et al., 2004). The lack of research on intermediate-mass stars is also a major obstacle in the development of the unified theory of star formation. Intermediate-mass stars do not drastically modify their environments like their high-mass counterparts, leaving large parts of their parent clouds intact, providing a unique opportunity to study the initial conditions of star formation (Ladd et al., 1991). In essence, therefore, intermediate-mass stars have a principal role in the growth of our understanding of star formation.

Currently, indirect methods of detection and the observation of the star formation processes are utilised. These methods involve, but are not limited to, the observation of spectral line emission from complex organic molecules associated with protostars, such as methanol; the detection of jets from molecules associated with outflows, such as carbon monoxide (CO); and the observation of molecular maser emission from dense condensations of gas molecules in the clouds, such as the water vapor maser line. Maser emission from molecules is widespread in the interstellar medium (Shchurov et al., 2021). This study focuses on masers, specifically water masers as a probe to study the star formation process of intermediate-mass protostars.

Astrophysical masers are compact sources with high brightness temperature, and narrow spectral line widths and are highly variable in nature (Cohen, 1989; Salem and Middleton, 1978). Since their discovery in 1960 by Weaver et al. (1965), masers have been used as tools to probe the physical conditions, kinematics, and magnetic fields of young stellar objects at high angular resolution (Cragg et al., 2005; Seth et al., 2002). Astrophysical masers arise from a wide range of interstellar molecules such as formaldehyde (H_2CO) (Downes and Wilson, 1974), ammonia (NH_3) (Yan et al., 2022), water (H_2O) (Valdettaro et al., 2001), hydroxyl (OH) (Elitzur, 1992), methanol (CH_3OH) (Menten, 1991b), silicon monoxide (SiO) (Cho et al., 2016), and recombination lines of hydrogen (Moran et al., 2018). Among the listed masers, the 22 GHz ($\lambda=1.3\text{ cm}$) water vapour lines originating from the $6_{16} \rightarrow 5_{23}$ transition are the most-studied water masers (Humphreys, 2015). Although their pumping mechanism is fairly understood theoretically, the complete characterisation of water masers remains enigmatic due to the different phenomena they trace, as well as their high variability.

Star formation across all mass regimes has been known to be via accretion (Audard et al., 2014). During accretion, material from the collapsing cloud falls onto the centrifugally balanced circumstellar disk around the protostar and migrates through the disk onto the forming protostar (Meyer et al., 2017). Recently, it has been discovered that this accretion process is non-uniform and is characterised by intermittent periods of a rapid increase in

accretion rate, known as accretion bursts (Strafella et al., 2022). Accretion bursts are accompanied by an increase in near-infrared luminosity of the burst protostar and flux density of maser emission(s) associated with it (Caratti o Garatti et al., 2017). In low-mass stars, these accretion bursts are known as FU Orionis or EXors bursts (Audard et al., 2014). The luminosity increases significantly, and lasts decades to hundreds of years (Strafella et al., 2022). During and after an accretion burst, aside from the increase in amplitude, interstellar masers associated with the protostar also exhibit a significant increase in activity and variability, with new maser features appearing (Szabo et al., 2022). Similar behaviour in methanol masers has been observed in high-mass protostars during and after accretion bursts (MacLeod et al., 2018; Bayandina et al., 2022; Szymczak et al., 2018).

Accretion bursts are suggested to originate from fragments of material in the circumstellar envelopes, quickly driven into the circumstellar disks due to gravitational instabilities in the envelope (Stamatellos et al., 2011; Vorobyov and Basu, 2005). The burst mode is suggested to be triggered when clumps of material move through the disk and fall onto the protostar due to loss of angular momentum (Stamatellos et al., 2011; Meyer et al., 2017). These bursts have relatively short durations (Vorobyov and Basu, 2015), and are accompanied by an increase in accretion rate: $\sim 10^{-5}$ to $10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$ for bursts in low-mass protostars (Stamatellos et al., 2011) and up to $10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ increase in accretion rate for high-mass protostars (Meyer et al., 2017). The fragments are tidally destroyed when they get close to the protostar (Stamatellos et al., 2011). The gravitational energy is transformed into accretion luminosity during the burst leading to an increase in luminosity (Vorobyov, 2009). This study aims to explore the variability in the water masers in the NGC 2071-IR star-forming region and investigate a possible accretion burst in the region.

1.2 Motivation of the study

Stars form via the accretion of material, specifically gas and dust from circumstellar envelopes (Audard et al., 2014; Frank et al., 2014). These envelopes contain various molecular species, with water being particularly abundant compared to their interstellar medium abundances (Rudnitskij, 2002). Since their discovery in the interstellar medium in 1969, the $6_{16} \rightarrow 5_{23}$ ($f = 22.235 \text{ GHz}$) water vapour transition maser has been associated with star formation (Cheung et al., 1969). Abundant around protostars, water masers trace kinematic activity such as ejections, accretion, and shocks around the dense envelopes (Vol’vach et al., 2019). Water masers can be tracers of molecular outflows, circumstellar disks and ionized jets during star formation (Kurtz and Hofner, 2005). Through long-term monitoring programmes, water masers in star-forming regions are known to exhibit variability on the scale of weeks (10^5 s) (Brand et al., 2003, 2005; Felli et al., 2007) and large flaring in amplitude over relatively short timescales, ranging from days to months

(Trinidad et al., 2003). Water masers may also show periodic long-term variations suggested to originate from periodic variations in flow patterns of jets and stellar winds from associated protostar(s) (Ashimbaeva et al., 2020). Periods of 2000 days and 11.5 years have been reported (Brand et al., 2003; Lekht and Krasnov, 2000). Water masers show drifts in velocity and tend to undergo periods of flaring where their flux density increases drastically (40% $\sim$ 1840%) with the appearance of new features (Szabo et al., 2022).

1.2.1 Region of study

NGC 2071-IR is an active star-forming region located in the Orion B molecular cloud L1630, about 4' north of the NGC 2071 nebula. The distance to NGC 2071-IR is estimated to be ~ 400 pc (Kounkel et al., 2017) and is associated with intermediate-mass protostars (Torrelles et al., 1998). The region is dominated by a wide-angle high-velocity bi-polar outflow extended in the NE-SW direction (Seth et al., 2002). The outflow extends $\sim 15'$ and has a velocity of 120 km s^{-1} (Eisloffel, 2000; Stojimirović et al., 2008). There are eight near-infrared (NIR) sources identified in the region (Cheng et al., 2022). The bolometric luminosity of the region is $520 L_{\odot}$, (Butner et al., 1990) and is dominated by one of the NIR sources known as NGC 2071 IRS 1 (Cheng et al., 2022). Most of the NIR sources are identified as protostars and the others as starless ejected condensates (Trinidad et al., 2009). Figure 1.1 shows the NGC 2071-IR region together with the NGC 2071 and NGC 2068 reflection nebulae.

Water masers (22 GHz) were first detected towards the region and reported by Schwartz and Buhl in 1975 (Schwartz and Buhl, 1975). Since then the water maser in the region has been monitored extensively (Lekht et al., 1982; Felli et al., 2007; Lekht et al., 2011; Ashimbaeva et al., 2020). The monitoring began from November 1972 to December 2010 by Lekht et al. (1982) with the Puschino Radio telescope in Russia, which overlapped Felli et al. (2007)'s observations from March 1987 to December 2007 with the Medicina radio telescope in Italy. Lekht et al. (2011) further monitored the water masers from 1994 to 2010. They were subsequently monitored from December 2010 to January 2020 by Ashimbaeva et al. (2020). The spectra from these monitoring observations have been published (Lekht et al., 1982; Felli et al., 2007; Lekht et al., 2011; Ashimbaeva et al., 2020). The water masers have flared in the past, increasing in amplitude by a factor of 16 to 10^4 Jy from its quiescent levels (Felli et al., 2007).

Currently, the water masers in the NGC 2071-IR region are regularly monitored by the Maser Monitoring Organisation (M2O) (Burns, 2021). The M2O is an international collaborative community of observers, theoreticians and astrophysicists who study masers. The water masers were reported by the M2O to have undergone a period of significant activity which commenced in May 2018 (M2O internal communication). The Hartbeesthoek Radio Astronomy Observatory (HartRAO)'s 26-m single-dish radio telescope, which is part

of M2O monitoring stations, commenced high cadence monitoring of the NGC 2071-IR region in January 2019. The M2O organisation continues to monitor water masers towards the region (Burns, 2021). Acquiring long-term observational data enables the revealing of patterns which cannot be determined in short-term data (Goedhart et al., 2007; Olech et al., 2022). NGC 2071-IR water maser data was obtained from HartRAO from January 2019 to April 2022, representing almost four years worth of monitoring data.

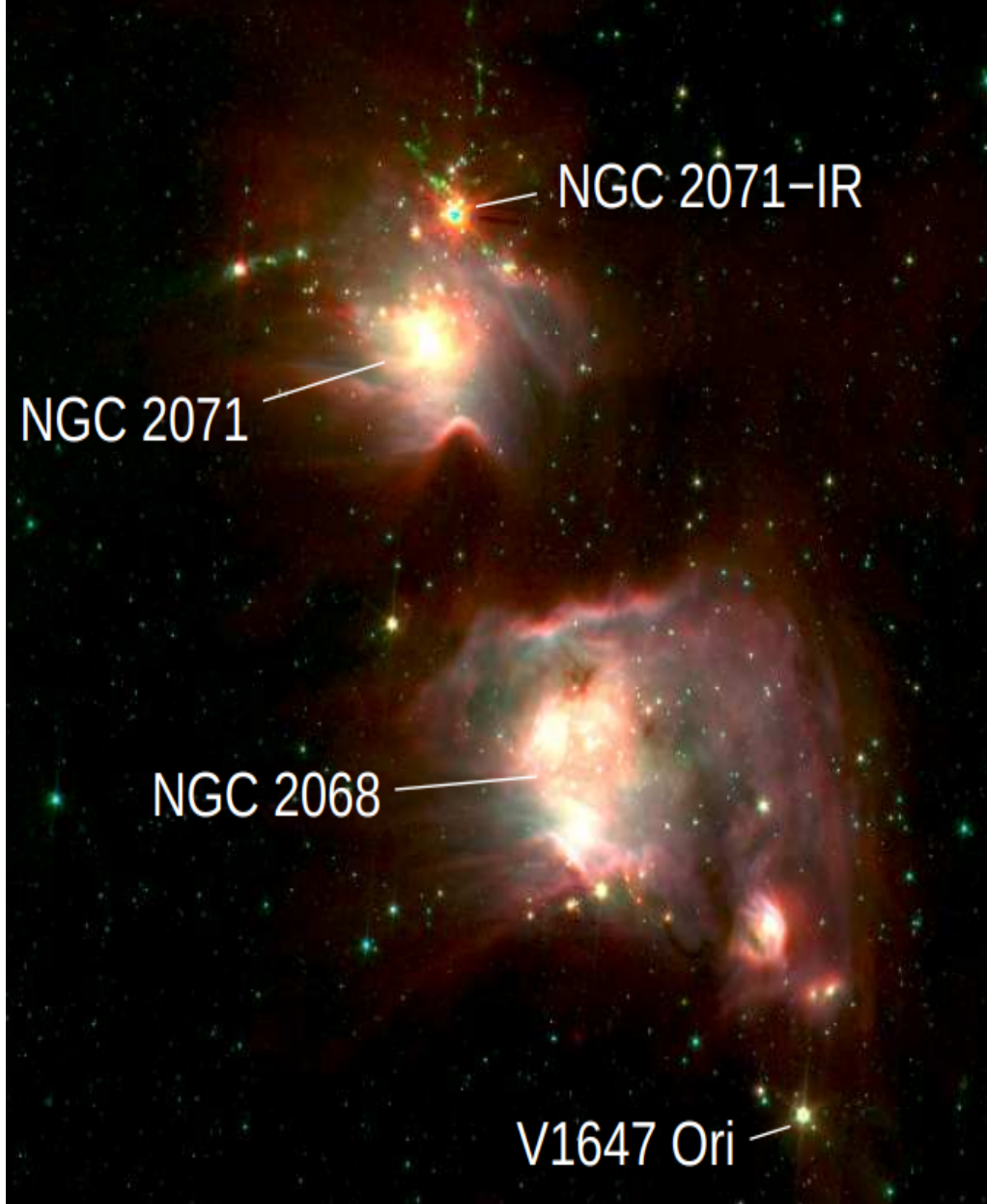


Figure 1.1: Spitzer IRAC image of northern L1630 showing NGC 2071-IR. Blue is 3.6 μm , green is 4.5 μm and red is 24 μm . Taken from Gibb (2008).

Water masers may also trace the infall-outflow boundaries of disks, and the collision of out-flowing gas with the ambient cloud may be the source of shocks pumping the water masers

Ashimbaeva et al. (2020). The NGC 2071-IR region is populated with multiple outflows (Eisloffel, 2000; Carrasco-González et al., 2012; Stojimirović et al., 2008). The outflows may affect the variability of the water masers. Changes in the kinematic properties of the protostar, such as episodic ejections of matter or accretion bursts which translate to changes in the outflows, may lead to an increase in shocks, which are the main pumping mechanisms for water masers (Neufeld and Melnick, 1990, 1991). The position of the two main outflows in the region, specifically the EW-oriented outflow from IRS 1 and the NE-SW-oriented outflow associated with IRS 3, have both been reported to vary over time (Cheng et al., 2022), which was attributed to jet precession. A precessing jet may impact different sections of the outflow cavities where the water masers trace, thus pumping different maser spots. While this scenario seems plausible, it may not be accurate due to the relatively short timescales of the observed variability in the time series of the water masers, which ranges from weeks to months (Lekht and Krasnov, 2000; Ashimbaeva et al., 2020). These short timescale variabilities are suggested to be due to turbulence in the cloud (Lekht and Krasnov, 2000). In essence, other pumping mechanisms may be at play, such as radiation flows from the disk, stellar winds, and cloud-to-cloud collisions. These mechanisms may be working complementarily rather than individually.

This study aims to characterise the variability and evolution of the water masers in NGC 2071-IR in the HartRAO data, as well as establish a relationship between the masers and their possible exciting sources. To obtain insight into the variability of the water masers in the NGC 2071-IR region, there is also the need to have an overview of the distribution of the masers in the region. High angular resolution interferometric millimetre and sub-millimetre continuum maps, and spectral line data of the NGC 2071-IR region from ALMA and VLA will be analysed. This is to provide a better insight into the structure and morphology of the region. Maser positions from literature superimposed on the high-resolution continuum images enable visualisation of the spatial distribution of the masers in the region. Water maser positions from previous studies by Torrelles et al. (1998), Seth et al. (2002), Trinidad et al. (2009), and Shchurov et al. (2021), were obtained and utilised for this purpose. The water masers in NGC 2071-IR have been reported by Lekht et al. (1982) as particularly interesting due to their unusual behaviour. Their behaviour is between what is expected of water masers associated with recently formed protostars and the behaviour of water masers associated with low-mass late B stars (Lekht et al., 1982).

The other objective of this study is to investigate whether the flaring of water masers in NGC 2071-IR reported by the M2O organisation (M2O internal communication) was a result of a disk-mediated accretion burst. Near-infrared (NIR) observations, made with the Hiroshima Optical and Near InfraRed camera (HONIR) during the flare, will be analysed for changes in magnitude. A significant increase in magnitude would point towards a possible recent occurrence of an accretion burst in the NGC 2071-IR star-forming region.

1.3 Overview of chapters to follow

Chapter 2: Theoretical background

Chapter 2 introduces in relative detail the current paradigm of star formation. The concepts of electromagnetic radiation and radiative transfer are also discussed. In addition, kinematic phenomena associated with protostars, such as disk-mediated accretion, outflows and jets, and masers are reviewed in this chapter.

Chapter 3: Radio telescopes and observational techniques

Chapter 3 introduces the radio telescopes used for this study. Their properties and operational methods are presented. The principles of multi-element radio interferometry and aperture synthesis are presented therein.

Chapter 4: Observations and data reduction

The details of the observations made with the instruments introduced in Chapter 3 and the data processing steps are presented in this chapter. Additional background information on the region of study is provided in this chapter.

Chapter 5: Results

Chapter 5 presents the results obtained from the data processing. Analysis of the results is also presented along with plots and figures produced from the data reduction procedures.

Chapter 6: Discussion

Chapter 6 presents a discussion of the results. It covers discussions of the single-dish and interferometric results.

Chapter 7: Summary and Conclusions

An overall summary of the study is presented in this chapter. The conclusions drawn from the discussions as well as suggestions for future work are also presented.

Chapter 2

Theoretical Background

2.1 Introduction

This chapter presents a background on astrophysical concepts on star formation, radiation theory, and astrophysical masers required for the comprehension of the analysis and discussions presented in the latter chapters. The chapter begins with a review of the current paradigm of star formation, with a focus on intermediate-mass star formation. This is followed by a discussion of protostellar accretion, as well as outflows and jets that are typically associated with the process of star formation. An introduction to radiation theory, which aims to present the reader with the nature of the electromagnetic radiation received by radio telescopes from astronomical sources, is presented thereafter. Some physical quantities in radio astronomy, referred to throughout this work are introduced. The chapter ends with a review of astrophysical masers which are the focus of this study.

2.2 General theory of star formation

2.2.1 Molecular clouds

Molecular clouds are pressure-balanced clouds made up of molecular hydrogen. The pressure balance is a result of the internal thermal motions of the gas restricted by the confinement of a more rarefied, warmer medium surrounding the gas (Stahler and Palla, 2004). They are cold (~ 100 K), and the detectable emission from them are from dust or rotational transitions of molecules at far-infrared and millimetre wavelengths (Bally, 1986). In addition to emissions, light from background stars can pass through molecular clouds, making absorption lines probes of the molecular abundances and optical depths of molecular clouds. Abundant in the spiral arms of the Galaxy, molecular clouds provide the

initial conditions for star formation (van Dishoeck et al., 1993). Molecular clouds come in various sizes, with the Boks globules being the smallest in size and the giant molecular clouds being the biggest type of molecular clouds. Although stars have been found to form in other sites such as isolated dark clouds (Bourke et al., 1995), stars are usually formed in giant molecular clouds (GMCs), hence the understanding of star formation is strongly linked to the understanding of giant molecular clouds (Myers, 1999). Table 2.1 presents the types of molecular clouds and their physical properties.

Table 2.1: Types of molecular clouds and their physical properties from Stahler and Palla (2004).

Cloud Type	A_V (mag)	n_{tot} (cm^{-3})	L (pc)	T (K)	M ($M_\odot$)	Example
Diffuse Molecular Clouds	1	500	3	50	50	ζ Ophiuchi
Giant Molecular Clouds	2	100	50	15	10^5	Orion
Dark Cloud Complexes	5	500	10	10	10^4	Taurus-Auriga
Individual Dark Clouds	10	10^3	2	10	30	B1
Dense Cores/Bok globules	10	10^4	0.1	10	10	TMC-1/b335

2.2.2 Giant molecular clouds

Giant molecular clouds (GMCs) are distinct from other molecular clouds due to their different dynamical conditions (van Dishoeck et al., 1993)- they are gravitationally bound and not bound by internal thermal pressure. Giant molecular clouds are the largest structures in the Universe held together by gravity (Bally, 1986). Their masses are greater than $10^5 M_\odot$ and densities go above 10^6 cm^{-3} (Lada, 2005). The Orion complex is the nearest GMC. (Myers, 1999). GMCs are suggested to be formed through the accumulation of numerous individual clumps of gas. This leads to GMCs having highly non-uniform density structures (Myers, 1999). They have expected lifetimes of $\sim 3 \times 10^7$ yr before they are dissipated by stellar winds from massive stars. All galactic O and B stars are closely associated with a GMC (Blitz, 1993). The star formation rate in GMCs is estimated to be $\sim 2 M_\odot$ per year. The star formation efficiency of giant molecular clouds is placed around 3 %, which is the percentage of the GMC's mass that is converted into stars (Blitz and Williams, 1999). GMCs contain clumps which are parcels of high-density material that can maintain their integrity. The GMCs themselves can cluster to form large ($10^7 M_\odot$) structures known as Giant Molecular Cloud Complexes (GMCCs) (Blitz, 1993).

2.2.3 The Virial theorem and cloud collapse

There are physical conditions which need to be present for molecular clouds to collapse into protostars and later form stars. These conditions will be reviewed here quantitatively. The bulk of the review is taken from Stahler and Palla (2004). First, let us consider a molecular cloud in hydrostatic equilibrium, taking into account acceleration and magnetic field effects, the cloud can be described by:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P - \rho \nabla \Phi_g + \frac{1}{c_{gas}} \mathbf{j} \times \mathbf{B}, \quad (2.1)$$

where c_{gas} is the velocity of the cloud particles, $\frac{D\mathbf{u}}{Dt}$ represents the rate of change of the fluid velocity with time $\mathbf{u}$ and ρ is the gas density. The quantity $\mathbf{B}$ is the volumetric magnetic field, $\mathbf{j}$ is the current density and P is the pressure, they are related by:

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j}. \quad (2.2)$$

Substituting equation 2.2 into equation 2.1 and rewriting, we obtain:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P - \rho \nabla \Phi_g + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B} - \frac{1}{8\pi} \nabla |\mathbf{B}^2|. \quad (2.3)$$

The third right-hand term represents the tension generated by a curved magnetic field line, and the fourth term is the gradient of magnetic pressure with magnitude $|\mathbf{B}^2|/8\pi$. The pressure arises from the crowding of both curved and straight field lines. Equation 2.3 governs the fluid behaviour. However, on the large-scale, the behaviour is different. For a spherical molecular cloud with volume V , the global properties can be obtained by integrating over the volume after finding the dot product of the position vector, using the equation of mass continuity and Poisson's equation which introduces gas density ρ . Interchanging the order of differentiation and repeated integration by parts lead to the Virial theorem:

$$\frac{1}{2} \frac{\delta^2 I}{\delta t^2} = 2T + 2U + W + M, \quad (2.4)$$

where partial derivative subscripts have been dropped. The detailed derivation is presented in Appendix A.1. In equation 2.4, I is the quantity representing the moment of inertia:

$$I \equiv \int \rho(x) |\mathbf{r}|^2 d^3 \mathbf{x}, \quad (2.5)$$

T is the summation of kinetic energies of particles in bulk motion:

$$T \equiv \int \rho(x) |\mathbf{u}|^2 d^3 \mathbf{x}, \quad (2.6)$$

U is the thermal motion energy:

$$U \equiv \frac{3}{2} \int n k_B T d^3 \mathbf{x} = \frac{3}{2} \int P d^3 \mathbf{x}, \quad (2.7)$$

W is the gravitational potential energy:

$$W \equiv \frac{1}{2} \int \rho(x) \Phi_g d^3 \mathbf{x}, \quad (2.8)$$

and M is the energy associated with the magnetic field:

$$M \equiv \frac{1}{8\pi} \int |\mathbf{B}|^2 d^3 \mathbf{x}. \quad (2.9)$$

Equating the left-hand side to zero:

$$2T + 2U + W + M = 0, \quad (2.10)$$

the cloud will attain Virial equilibrium. This requires the terms T , U and M to balance W , which is the gravitational binding energy. In this state the giant molecular cloud will be undergoing gravitational collapse.

The simplest form of the Virial theorem is given by Tayler (1994) who neglected the terms T and M , and only considered the random thermal motions U and the gravitational potential W , to redefine the Virial theorem as:

$$2U + |W| = 0. \quad (2.11)$$

This implies the cloud would collapse if $2U + W < 0$. On the other hand, if $2U + W > 0$, the internal pressure force arising from the random kinetic motion of particles within the cloud will overcome the gravitational potential, leading to the expansion of the cloud, and thus no collapse will occur resulting in no stars forming. Since U is dependent on temperature T (equation 2.6), changes in the temperature (pressure) play a significant role in star formation.

2.2.4 Jeans mass limit

The Virial theorem describes the condition of equilibrium for a stable, gravitationally bound system (Carroll and Ostlie, 2017). Given the two conditions of Virial equilibrium

($2U > W$ and $2U < W$), which govern the collapse of giant molecular clouds, a spherical GMC will develop instabilities and commence collapse when its mass exceeds a specific limit. This limit is the Jeans mass (Carroll and Ostlie, 2017), and is derived as follows:

Assuming a GMC of constant density, the gravitational potential energy of the molecular cloud is:

$$W \sim -\frac{3GM_r^2}{5R}, \quad (2.12)$$

where M_r is the mass of the cloud and R the radius of the cloud. The full derivation of the equation for gravitation potential is provided in Appendix A.2.

From the ideal gas law, the cloud's total thermal energy must be related to the temperature by:

$$U = \frac{3}{2}Nk_B T_{kin}, \quad (2.13)$$

where T_{kin} is the kinetic temperature of the gas particles and N is the total particle number. N can also be written in terms of molecular weight, μ and mass M_r as:

$$N = \frac{M_r}{\mu m_H}, \quad (2.14)$$

where m_H is the mass of the hydrogen atom ($1.673532499 \times 10^{-27}$ kg). Substituting N in equation 2.14, the total thermal energy gives:

$$U = \frac{3M_r K_B T}{2\mu m_H}. \quad (2.15)$$

For the case of $U < W$, which causes gravitational collapse, substituting equation 2.12 into 2.15 will give:

$$\frac{3M_r K_B T}{2\mu m_H} < \frac{3GM_r^2}{5R}. \quad (2.16)$$

The radius of the cloud prior to collapse can be expressed in terms of M_r and ρ as:

$$R = \left[\frac{3M_r^2}{4\pi\rho} \right]^{-\frac{1}{3}}. \quad (2.17)$$

Using equation 2.17, equation 2.16 can be rewritten as:

$$\frac{3M_r K_B T}{\mu m_H} < \frac{3}{5}GM_r^2 \left[\frac{3M_r}{4\pi\rho} \right]^{-\frac{1}{3}}. \quad (2.18)$$

Further making M_r the subject in equation 2.18, leads to:

$$M_r > \left[\frac{5k_B T}{G\mu m_H} \right]^{\frac{3}{2}} \left[\frac{3}{4\pi\rho} \right]^{\frac{1}{2}}. \quad (2.19)$$

The right-hand side of equation 2.18 is the Jeans mass M_J . The Jeans mass depends on temperature. The increase in temperature due to the kinetic motion of particles from external shocks caused by feedback mechanisms from high-mass stars, such as expanding ionisation fronts and outflows, may hinder the initiation of cloud collapse by increasing the Jeans mass.

Equation 2.18 can be simplified as:

$$M_r > M_J \quad (2.20)$$

This condition is known as the Jeans criterion.

2.2.5 Free-fall timescales

Gravitational collapse, particularly the spherical collapse of clouds, is the triggering process of star formation (Bally et al., 1989). For a homogeneous spherical cloud that satisfies the Jeans criterion, it will undergo free-fall collapse over a specific time, known as the free-fall time t_{ff} (Stahler and Palla, 2004). Assuming the absence of rotation, turbulence, and magnetic fields, as well as ignoring the effects of pressure gradients on the motion, the free-fall time, t_{ff} , can be estimated.

If R is denoted as $\equiv \frac{l}{2}$, W can be approximated as $-GM^2/R$. This reduces the Virial equation (Equation 2.4) to:

$$\frac{1}{2} \frac{\delta^2 I}{\delta t^2} = -\frac{GM^2}{R}, \quad (2.21)$$

Where I represents the moment of inertia, G is the gravitational constant, and R is the radius of the molecular cloud. I can be rewritten as MR^2 . Solving for t gives:

$$t_{ff} = \left(\frac{R^3}{GM} \right)^{\frac{1}{2}}. \quad (2.22)$$

Since M/R^3 can be approximated to ρ , the timescale can be rewritten as $(G\rho)^{-\frac{1}{2}}$.

The equation of the free-fall time, also called the free-fall timescale, can then be written as:

$$t_{ff} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{\frac{1}{2}}, \quad (2.23)$$

where t_{ff} is the free-fall timescale, ρ_0 is the initial density, and G is the gravitational constant. The full steps of deriving the free-fall timescale is outlined in appendix A.3. The free-fall timescale does not depend on the initial radius of the cloud. In essence, a spherical molecular cloud with uniform original density ρ_0 would collapse isotropically within the same amount of time. This is referred to as homologous collapse.

2.2.6 Initial mass function

A critical parameter in determining several properties of a star, such as surface brightness, evolutionary phases, chemical enrichment, lifetime yields, and remnant properties, is its mass (Ferreras, 2019). The distribution of stellar masses in an assemble of stars immediately after their formation is defined as the initial mass function (IMF), and is fundamental to the understanding of stellar evolution. Salpeter (1955) was the first to characterize the IMF by observing stellar populations of local stars in the Milky Way Galaxy. He defined the IMF as:

$$dN = \xi(M) d(\log_{10} M) \frac{dt}{T_0}, \quad (2.24)$$

where dN is the number of stars in an infinitesimal mass range dM , created in the time interval dt per cubic parsec. T_0 is the time spent on the main sequence by a star (time to burn 12% of mass). Salpeter (1955) further approximated the IMF as:

$$\xi(M) = 0.03 \left[\frac{M}{M_\odot} \right]^{-2.35}. \quad (2.25)$$

The IMF is considered universal based on observations within the Milky Way Galaxy. However, variations have been reported from extra-galactic observations where an excess of massive stars with respect to the IMF of active star-forming systems and an excess of low-mass stars in quiescent galaxies were observed (Stahler and Palla, 2004). Recent large-scale studies by Stahler and Palla (2004) defined a more universal IMF, a piecewise power law function which covers the low-intermediate, and high-mass ranges, given by:

$$\xi(M) = \begin{cases} C_1 \left[\frac{M_*}{M_\odot} \right]^{-1.2} & 0.1 < \frac{M_*}{M_\odot} < 1.0 \\ C_2 \left[\frac{M_*}{M_\odot} \right]^{-2.7} & 1.0 < \frac{M_*}{M_\odot} < 10 \\ 0.4 C_3 \left[\frac{M_*}{M_\odot} \right]^{-2.3} & 10 < \frac{M_*}{M_\odot}, \end{cases} \quad (2.26)$$

where C is the constant of normalisation.

Due to the non-coeval nature of stellar populations, it is often difficult to determine the IMF via direct observations. This is overcome by using the mass-luminosity relation and the observed surface brightness to obtain an estimate for the IMF. There are various definitions of the IMF with their variations, such as additional power law sets or power laws, or simply tapering off the low-mass end. Examples include the Scalo IMF (Scalo, 1986) and Kroupa IMF (Kroupa, 2002), which both feature a power law distribution, and the Chabrier IMF (Chabrier, 2003), which replaces the power law at low masses with a log-normal distribution.

2.3 Intermediate-mass young stellar objects (IMYSOs)

Protostars are categorised as intermediate-mass (IM) protostars if their mass is in the range of $2 M_{\odot} < M_{*} < 8 M_{\odot}$ or bolometric luminosities between $\sim 50 - 2000 L_{\odot}$. They are precursors of Herbig Ae and Be stars and Vega-type systems and contribute to the galaxy's UV radiation field (Kun et al., 2004). Intermediate-mass protostars are grossly understudied compared to their low-mass and high-mass counterparts, although they exhibit less extinction than high-mass protostars (Beltrán, 2015). They are often associated with their low-mass counterparts although they share many properties with their high-mass counterparts (Beltrán, 2015). The upcoming overview of intermediate-mass protostars is taken from Beltrán (2015); Palla (1991); van Kempen et al. (2012).

2.3.1 Formation of intermediate-mass young stellar objects (IMYSOs)

Intermediate-mass protostars are theorised to be formed via turbulent fragmentation of molecular clouds (Kun et al., 2004). This fragmentation is said to occur in two main ways. 1.) Direct Fragmentation: clouds break up into a stable final structure via a single event ($ABC \rightarrow A+B+C$), and 2.) Hierarchical fragmentation: clouds fragment in time steps into smaller fragments which further fragment ($ABC \rightarrow A+BC$ or $AB+C \rightarrow A+B+C$). The level of fragmentation is governed by the shape and non-uniformities in the cloud. Low-mass stars are stable radiatively until nuclear fusion of hydrogen is ignited, this happens at an early stage of accretion. On the other hand, intermediate-mass stars go through phases of radiative stability whilst still undergoing contraction due to gravity. Quantitatively this phase can be defined by:

$$t_{KH} \equiv \frac{GM_{*}^2}{R_{*}L_{rad}} \approx \frac{GM_{*}^2}{R_{*}L_d} \approx \frac{M_{*}}{\dot{M}} \equiv t_{acc}, \quad (2.27)$$

where L_d and $\dot{M}$ are the steady-state luminosity and the mass accretion rate, t_{KH} and t_{acc} are the gravitational contraction time and the accretion time, respectively. L_{rad} is the

luminosity that a star of given mass and radius can carry radiatively.

Equation 2.27 implies that the star is losing heat via radiation at the same rate it accretes new matter, which leads to a phase of rapid gravitational contraction. This leads to the star reaching the Main-Sequence while still undergoing disk accretion. Intermediate protostars have been observed to possess circumstellar disks, irrespective of their luminosity. Young IM protostars rotate below the breakup speed. The accreting core is enveloped by a standing shock resulting from the infalling matter. The surface boundary conditions for pressure and temperature of IM protostars are given by:

$$P = \frac{\dot{M}}{4\pi R_*^2} \left(\frac{2GM_*}{R} \right)^{\frac{1}{2}}, \quad T = \left[\frac{1}{\sigma} \left(\frac{3F_{pre}}{4} - \frac{F_{post}}{4} \right) \right]^{\frac{1}{4}}, \quad (2.28)$$

where F_{pre} and F_{post} are the star's radiative pre and post-shock flux, respectively.

Rotation and magnetic field effects in the molecular cloud, affects the accretion rate of IM protostars. Accreting material from the cloud does not accumulate at the stellar surface directly due to conservation of angular momentum, but rather first falls into the circumstellar disk and then spirals into the star via the filaments (Frank et al., 2014).

Circumstellar disks around IM protostars are critical to their mass growth and stability. The size of their disks ranges from 100-200 AU, and have less mass than the central star (Beltrán, 2015). The rotation of the disks is expected to be Keplerian, albeit inconclusive due to the very few cases that have been studied in detail. In the few detailed studies of IM protostar disks, molecular tracers of regions of high density revealed velocity gradients oriented perpendicularly to the direction of outflowing gas from the disk. Keplerian rotation has been observed towards evolved IM stars, suggesting it is also present in IMYSOs (Cheng et al., 2022). IM protostars have been known to drive molecular outflows (Seth et al., 2002; Cheng et al., 2022). These outflows are more energetic, less collimated and more complex than outflows from low-mass YSOs, suggesting a different driving mechanism. Beltrán (2015) suggested that the complexity of outflows from IM star-forming regions is not an intrinsic property but rather arises from the inability to resolve the individual sources in the often clustered cores, and this may be solved by high-angular resolution observations. Outflows associated with IM protostars are also a source of mechanical feedback onto the parent cloud, thus triggering further star formation. IMYSOs have a higher accretion velocity than low-mass stars and thus accrete material faster (Beltrán, 2015).

2.4 Disk-mediated accretion and accretion bursts in low-mass and intermediate-mass stars

The consensus that stars form via accretion has been well-established (Audard et al., 2014; Kadam, 2020). Stars gain their mass from the accretion of material from circumstellar disks made of gas and dust (Stamatellos et al., 2011). Phases of steady accretion are punctuated by short (< 100 yr) bursts of increased accretion known as accretion bursts (Vorobyov and Basu, 2005). These bursts are found to be episodic (Vorobyov and Basu, 2005; Stamatellos et al., 2011; Audard et al., 2014). Up to 40% of the mass of stars is accreted during episodic accretion bursts (Megeath and Zakri, 2019). This accretion process is orchestrated by magnetohydrodynamic (MHD) processes (Stamatellos et al., 2011). In the inner regions of the circumstellar disk, a gravitational sink forms, and infalling matter into the sink is assumed to flow instantaneously onto the protostar (Stamatellos et al., 2011). Infalling material transits through the inner accretion disks (IAD) inside the sink before falling into the protostar. The material, however does not fall onto the protostar from the disk isotropically, but rather via long collimated structures known as filaments (Frank et al., 2014).

If the disk-sink-filament-protostar transfer of material is not efficient, accretion onto the star is slow and more material piles up in the disk leading to ‘swelling’ of the disk. This may lead to gravitational instability (GI) developing in the disk, which may lead to fragmentation (Bally and Zinnecker, 2005). Localised regions of gravitational instabilities in the disk may form clumps which grow into secondary protostars or planetary-mass objects (Whitworth and Stamatellos, 2006). Angular momentum is transported outward due to the development of magneto-rotational instability (MRI) in the IAD. This allows the accumulated matter to fall onto the protostar. During this process, gravitational energy changes to thermal energy in the disk, building an accretion shock front around the protostar (Stamatellos et al., 2011). The energy produced by the accretion generates heat and stabilises the disk (Krumholz et al., 2010). The gravitational instabilities and magneto-rotational instability cause a sudden increase in accretion rate known as accretion burst. Accretion bursts are thus theorised to originate from circumstellar disk fragmentation, however, the entire episodic accretion process is still not completely understood (Zhu et al., 2007). Stamatellos et al. (2011) outline the burst process as follows, based on work from Zhu et al. (2009):

- The cool outer parts of the circumstellar disk are influenced by gravitational instabilities.
- The gravitational instabilities lead to the transport of angular momentum outwards via gravitational torques, thus allowing the material to fall inward onto the protostar.
- On the other hand, the temperatures in the inner disk region are too high for gravi-

tational instabilities to develop. Further increase in temperature leads to ionisation of gas which generates magneto-rotational instability (MRI).

- The MRI then transports angular momentum outwards, allowing matter to spiral in further and onto the central protostar.
- The accumulated matter in the inner disk steadily heats up and ionises to activate MRI, where the accumulated matter falls onto the protostar, leading to an outburst.
- The steady accumulation of matter resumes when the accumulated matter in the inner disk is depleted and the temperature of the remaining matter falls, dissipating the MRI.

Young eruptive low-mass stars (FUors (Hartmann and Kenyon, 1985) and EXors (Moody and Stahler, 2017)) have been known to undergo episodic accretion, albeit in different fashions. FUors-type accretion bursts are known to increase their accretion rates significantly by up to factors of $10^{-5} M_{\odot} \text{ yr}^{-1}$ and maintain such rates for decades and may display absorption lines. EXors-type bursts, on the other hand, are known to be shorter and repetitive with lower accretion rates of order 10^{-7} to $10^{-6} M_{\odot} \text{ yr}^{-1}$ (Strafella et al., 2022). FU Ori-type stars are characterised by rapid increases (~ 5 mag) in brightness which fade away over tens to hundreds of years (Greene et al., 2008).

Assuming the sink-mass is the sum of the mass of the YSO and the inner part of the accretion disk, that is $M_{SINK} = M_{*} + M_{IAD}$, the flow rate of matter from the disk to the protostar is given as (Stamatellos et al., 2011):

$$\dot{M}_{*} = 10^{-7} M_{\odot} \text{ yr}^{-1} + \dot{M}_{MRI}, \quad (2.29)$$

where $\dot{M}_{*}$ is the material flow rate, and $\dot{M}_{MRI}$ is the rate of accretion based on when MRI is activated in the IAD. The accretion rate, when MRI is activated is significantly higher than the normal accretion rate (first right-hand term).

The accretion rate during the bursts can increase to $\sim 5 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ (Stamatellos et al., 2011).

The contribution to the accretion rate by MRI during a burst event was estimated by Zhu et al. (2010) as:

$$\dot{M} \sim 5 \times 10^{-4} M_{\odot} \text{ yr}^{-1} \left(\frac{\alpha_{MRI}}{0.1} \right), \quad (2.30)$$

where $\dot{M}$ is the accretion rate, α_{MRI} is the effective parameter for magneto-rotational instability viscosity.

The duration of an outburst can also be determined from the equation by Zhu et al. (2010):

$$\Delta t_{MRI} \sim 0.25 \text{ kyr} \left(\frac{\alpha_{MRI}}{0.1} \right)^{-1} \left(\frac{M_*}{0.2 M_\odot} \right)^{2/3} \times \left(\frac{\dot{M}_{IAD}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^{1/9} \quad (2.31)$$

Thus, based on observations and models, the rate of rapid accretion onto an FU Ori-type protostar is given as Stamatellos et al. (2011):

$$\dot{M}_{MRI} = \frac{M_{MRI}}{\Delta t_{MRI}} \exp \left\{ - \frac{(t - t_0)}{\Delta t_{MRI}} \right\}, \quad t_O < t < t_O + \Delta t_{MRI}, \quad (2.32)$$

where t_O is the time of occurrence of the burst. The burst ends at $t_O + \Delta t_{MRI}$.

The time for rebuilding the instabilities in the disk derived from $\Delta t_{ACC} \sim M_{MRI} / \dot{M}_{IAD}$ is:

$$\Delta t_{ACC} \simeq 13 \text{ kyr} \left(\frac{M_*}{0.2 M_\odot} \right)^{2/3} \left(\frac{\dot{M}_{IAD}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^{-8/9} \quad (2.33)$$

Equation 2.31 shows that it takes a longer time to generate or regenerate the MRI than the duration of the burst. The free parameter α_{MRI} determines the strength and duration of bursts but does not significantly affect the total mass deposited onto the protostar during a burst. Increasing α_{MRI} will result in powerful but shorter bursts (Stamatellos et al., 2011). α_{MRI} is estimated to be between 0.01 to 0.4 based on observations and simulations (King et al., 2007).

Figure 2.1 shows the results of time-dependent simulations by Stamatellos et al. (2011) of the evolution of an accretion disk around a main protostar forming in a turbulent molecular cloud undergoing collapse. The simulations were based on the equations presented earlier. The simulations that do not take into account radiative feedback from the protostar, their results show in the first panels (top row) that the main protostar gains mass and becomes unstable, leading to fragmentation. In the second row of panels, continuous radiative feedback and continuous accretion are taken into account, and the results show the disk increases in mass but do not fragment due to the heating of the disk from radiative feedback. In the bottom rows, the accretion disc around the primary protostar undergoes an accretion burst event. The disk becomes gravitationally unstable, leading to a burst, which occurs in the third panel. The accretion burst heats the disk, preventing fragmentation due to turbulence. Post-burst, the disk proceeds to cool and undergoes gravitational fragmentation, forming two low-mass stars.

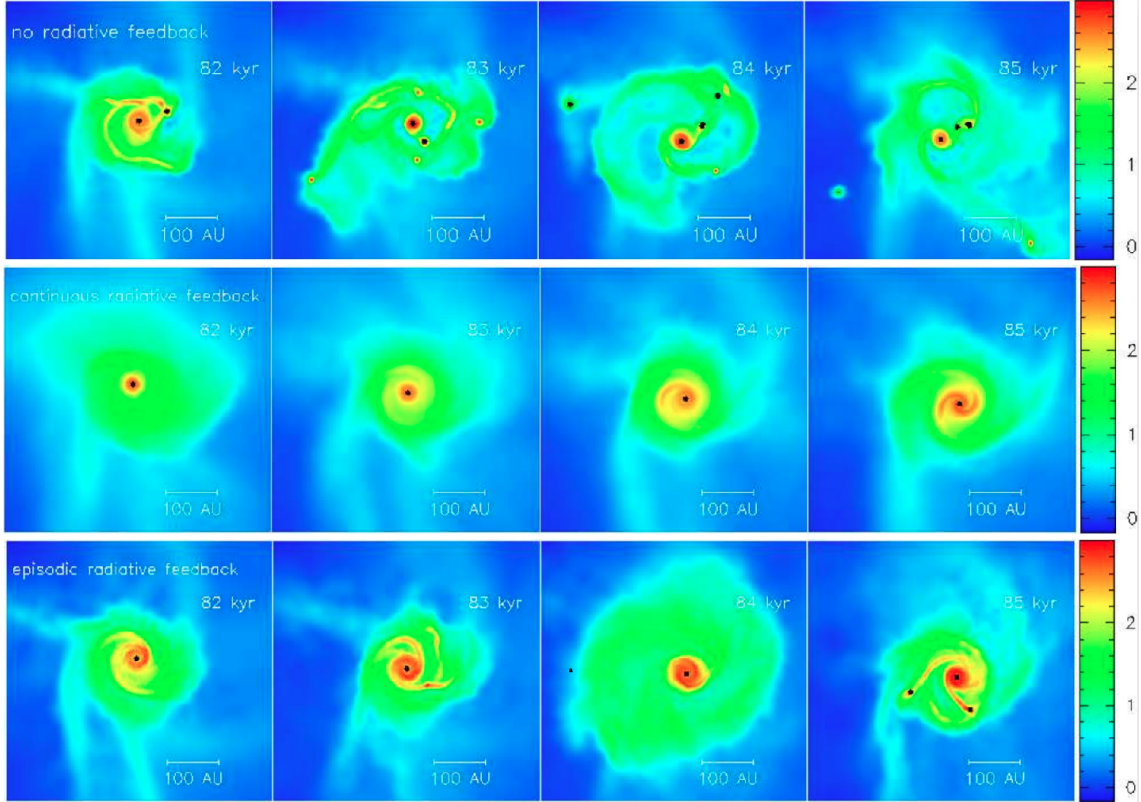


Figure 2.1: Results from simulations of the evolution of an accretion disk. The colour scale is the log of column density in units of g cm^{-2} . In the bottom panels, an accretion burst occurs in the third panel (see text for details). Figure from Stamatellos et al. (2011).

The protostellar accretion process is non-uniform but episodic. Major outflow events are thus traceable to major accretion events. Discrete knots observed in jets may suggest multiple accretion bursts within a period. Fischer et al. (2016) estimated 740 years as the interval between accretion bursts.

2.5 Jets and molecular outflows

A review of jets and outflows related to star formation is presented in this section. Their properties and the effect on interstellar masers, specifically water masers and star formation, are reviewed.

Star formation is known to be accompanied by periods of energetic mass outflows (Hartigan et al., 1994). All stars, regardless of their mass, go through an outflow phase in the early stages of evolution. In the three mass regimes, outflows appear to be a ubiquitous aspect to star formation (Shu et al., 1987). Outflows enable young stars to dissipate some of the excess angular momentum accrued from accretion if the mass outflow rate is $\gtrsim 10\%$ of

the accreted mass, thereby avoiding reaching break-up speeds. Outflows are composed of atomic and/or molecular, or ionised gas (Hirota et al., 2017) and usually manifest in two forms: 1) as loosely collimated bipolar molecular outflows transporting massive amounts of energy and mass at low velocities ($1 \sim 30 \text{ km s}^{-1}$), or 2) as narrow, highly collimated high velocity ($100 \sim 1000 \text{ km s}^{-1}$) ‘jets’ which become visible when material behind the shock waves in the flow cools (Hartigan et al., 1994). These outflows are large-scale ($\gtrsim 10^{12} \text{ km}$) and can extend up to parsecs (Stojimirović et al., 2008).

Outflow material is often distributed in two lobes, blue-shifted and red-shifted lobes (Snell et al., 1980). These types of outflows are known as bipolar outflows, and they are common around YSOs of different masses (Bally and Lada, 1983). Bipolar molecular outflows are made up of swept-out shells of ambient molecular cloud material (Shu et al., 1991). They are composed of large masses of gas travelling at high velocities (a few km s^{-1} to about 100 km s^{-1}) (Bachiller and Tafalla, 1999) and are confident indicators of new stars (Raga et al., 2012). Bipolar outflows are best traced by their CO emission. Their properties can be derived by converting CO line observations into physical gas parameters (Bachiller and Tafalla, 1999). Their flow sizes range from 0.1 pc to several parsecs. Their total kinematic timescales range from about 10^3 yr to 10^5 yr . The total mass of material in outflows is in the orders of $10^{-2} M_{\odot}$ to several hundred $M_{\odot}$ (Bachiller and Tafalla, 1999). Stars disperse the remains of their prenatal clouds via bipolar outflows (Bachiller and Tafalla, 1999). Bipolar outflows usually form V-shaped cavities (Bachiller and Tafalla, 1999). Cavities with material travelling at low velocities are suggested to be a result of mass ejected by jets at the very early stages of protostellar evolution. Cavities around Class 0 YSOs often have an opening angle of 20° to 50° . Outflows associated with Class I and Class II YSOs have 80° to 120° and 100° to 160° opening angles, respectively (Frank et al., 2014).

2.5.1 Properties of outflows and jets associated with star formation

Observations of outflows and theoretical modelling suggest that jets and outflows arise from magneto-hydrodynamic (MHD) processes in disk-star systems (Natta et al., 2006; Shu et al., 1991). Large-scale outflows are known to be driven by accretion disks around protostars. Outflows can be in the form of wide-angle conical outflows or narrowly collimated jets. While the dense and fast jets propagate into the environment, the wide-angle outflow is swept-up, developing a cavity which enlarges over time into the ambient cloud. Jets often possess more mass and momentum than molecular flows (at least 2 orders of magnitude). Jets from T Tauri Stars (TTs) begin with wide angles (10 to 30°) close to their sources before quickly collimating to a few degrees in the innermost regions (50 to 100 AU) (Ray et al., 2007). The degree of collimation is determined by the ratio of the width to the length (Bachiller, 1996). These regions of collimation are difficult to observe with the current instruments due to very high levels of dust extinction but are often traced

with molecular tracers such as SiO, [Fe II], and H₂ lines (Frank et al., 2014). Studies of these tracers suggest that the in-falling envelope does not play a major role in focusing the jets and that there must be a universal collimation mechanism at play at all stages of formation which produces the observed beams of radius 15 AU on 50 AU scales. Jet collimation is hypothesised to be controlled by the magnetic field present in the circumstellar disk (Frank et al., 2014). Jets and outflows are challenging to detect since the large molecular clouds are optically thick, and there is significant extinction due to dust (Frank et al., 2014).

Improvement in the sensitivity of modern telescopes and spectroscopy have made the observation of jets and outflows easier (Stahler and Palla, 2004). Through multi-epoch observations and spectroscopy, physical properties such as the radial velocity of an outflow and its proper motion velocity, can be estimated. Stellar jets show bright emission lines, hence their radial velocities can be easily estimated. Measuring the proper motions of spatially resolved jets enable the estimation of their cross-sectional area (Seth et al., 2002). Also by measuring the jet radius, ionisation fraction, and electron density, the mass loss rate of a jet can be calculated with:

$$\dot{M}_{jet} \approx \pi r_{jet}^2 \rho_{jet} V_{jet} \quad (2.34)$$

where $\dot{M}_{jet}$ is the mass loss rate, r_{jet} is the radius of the jet and ρ_{jet} and V_{jet} are the total density and velocity of the jet, respectively.

The mass loss rate estimated with equation 2.34 is the bulk average over the shocked gas. The actual jets contain shocks and knots, which have different spatial properties (e.g density). For low-intermediate mass stars, typical outflow rates are 10^{-7} to $10^{-9} M_{\odot} \text{ yr}^{-1}$. Higher rates are found in more embedded protostars (Caratti o Garatti, 2012).

Jets emit radiation at various wavelengths. For low-intermediate mass protostars, the inner disk radius is known as the co-rotating radius and UV emission is generated in this region (Gullbring et al., 2000). This UV excess which is hard to observe directly due to high extinction, is related to the luminosity of lines produced in the accretion funnel flow, such as H α , CaII, Br γ , and Pa β , lines (Natta et al., 2006). Extended X-ray emission has been detected along jets at distances up to 2.5 pc from the associated protostar. The x-rays are suggested to be tracing hot plasma at 10^6 Kelvin. The source of the heated plasma is suggested to be heated material downstream from a shock front (Schneider et al., 2009) or jet-jet collisions (Cunningham et al., 2009). Jets can bend by significant angles ($\approx 30^\circ$) without destruction. Simulations by Lebedev et al. (2004) show the source of these curvatures to arise from interactions between jets and ram pressure from side winds (Lebedev et al., 2004).

2.5.2 Effects of jets and outflows on star formation

Figure 2.2, Frank et al. (2014) summarises the effects of jets and outflows on different scales of star formation as per below:

- On the scales of stars and disks ($1 \text{ AU} - 10^2 \text{ AU}$), jets can alter disk properties and affect planet formation via disk irradiation and magnetohydrodynamic (MHD) effects associated with the launching of outflows. Magnetic fields anchored in the disk which are oriented in a helical structure about the jet axis, enable jets to achieve high terminal velocities and converge to achieve narrow collimation angles.
- On the scales of envelopes and parent clumps ($10^2 \text{ AU} - 0.5 \text{ pc}$), jets and outflows explain the low (30%) core-to-star efficiency observed through feedback processes such as MHD ejections during early collapse phase and the dissipation of envelopes by wide-angle winds during latter stages.
- On the scales of clusters and molecular clouds ($0.5 \text{ pc} - 10^2 \text{ pc}$), multiple jets and outflows drive turbulence in clouds, altering star formation efficiencies and mean stellar masses as well as unbound cluster gas. Jets impact the parent clump and clouds at parsec-scale distances with collimated outflows efficient in generating feedback on cluster level rather than the full GMC scale. Jets may contribute to the turbulent energy in clouds and outflows and could change properties of star formation by depleting reservoirs of material from still forming high-mass stars, thus reducing their stellar mass to lower levels.

2.5.3 Effects of jets and outflows on water masers

Shocked high-density gas may produce velocity-coherent sheets and filamentary structures, which may produce collimated beams of radiation. These beams of radiation, when amplified, may produce water masers (Felli et al., 1992). Jets and outflows which produce shocks when interacting with ambient material may thus serve as pumping sources for water masers (Felli et al., 1992).

Based on the model by Elitzur et al. (1989) (hereafter ‘EM model’), water masers can form behind dissociative shocks ($v_s \geq 30 \sim 200 \text{ km}^{-1}$) moving in dense ($n \geq 10^7 \text{ cm}^{-3}$) shocked molecular clumps with column densities of $N(H) \sim 10^{22} \text{ cm}^{-2}$. The gas, which is heated to temperatures $\sim 400 \text{ K}$ post-shock, provides energy which serves as a pump source for the masers via collisions (Elitzur et al., 1989). This pump energy is derived from kinetic energy dissipating from the shocked and unshocked gas. Dissociative shocks produce masing mediums with velocity coherence length to thickness ratio a of ~ 10 , and velocity dispersion Δv of $\sim 1 \text{ km}^{-1}$. Based on the EM model, the luminosity of the maser is given by:

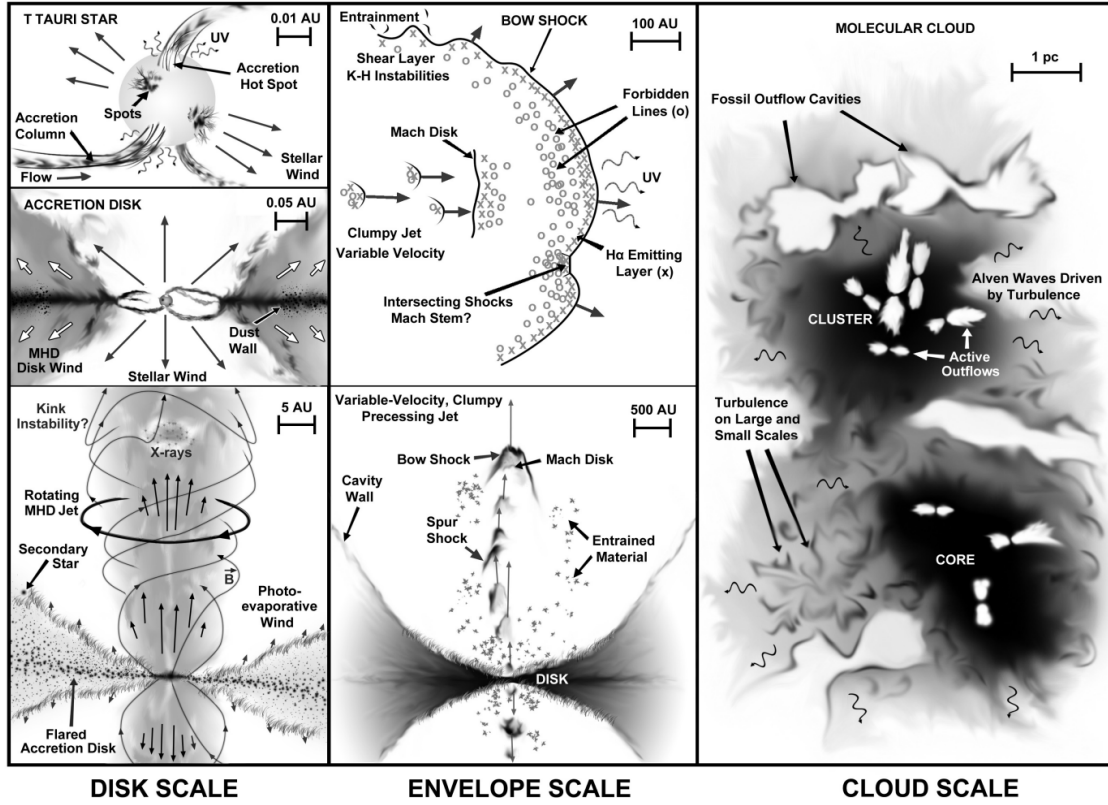


Figure 2.2: A schematic of jets and outflows on six different scales. Scales are provided by scale bars in each panel (Frank et al., 2014).

$$L_{H_2O}/L_{\odot} = 4.2 \times 10^{-6} a_i^3 d_{13}^2 \Delta v_5 N_c, \quad (2.35)$$

where $a_1 = a/10$, $d_{13} = d/10^{13}$ cm, Δv_5 is the half power width of the line in 10^5 cm s $^{-1}$ and N_c is the number of masers beamed in the observer's direction.

From the EM model, based on the assumption that all the kinetic energy from the outflow shock is dissipated through collisions and only a fraction of the wind pumps the water masers, the mechanical luminosity of the shocks is given by:

$$L_{mH_2O}/L_{\odot} = 14.3 n_7 \nu_{s7}^3 a_i^4 d_{13}^2 v_5 N_c, \quad (2.36)$$

where n_7 is the initial density in 10^7 cm $^{-3}$, and v_{s7} is the velocity of the shock in 10^7 cm s $^{-1}$. It is possible to extract $a_1^3 d_{13}^2 N_c$ since both luminosities depend on them. This leads to:

$$\log(L_{H_2O}/L_{\odot}) = -6.5 + \log(L_{mH_2O}/L_{\odot}) + \log(\Delta v_5/n_7 \nu_{s7}^3 a_1). \quad (2.37)$$

The mechanical luminosity of the YSO wind L_{mw} can be related to the mechanical luminosity of the CO outflow, L_{mCO} for momentum-driven flows by:

$$L_{mCO} = L_{mw} \nu_{max}/\nu_w, \quad (2.38)$$

where ν_w is the YSO wind velocity ~ 100 to 200 km s^{-1} (Evans et al., 1987).

As stated earlier, only a fraction ε of the wind pumps the water masers, hence

$$L_{mH_2O} = \varepsilon L_{mw}, \quad (2.39)$$

leading to the relation between L_{mH_2O} and L_{mCO} as:

$$L_{mH_2O} = \varepsilon \nu_w / \nu_{max} L_{mCO}. \quad (2.40)$$

Rewriting equation 2.40 in terms of observable quantities,

$$\log(L_{H_2O}/L_{\odot}) = -6.5 + \log(L_{mCO}/L_{\odot}) + \log(\Delta \nu_5 \varepsilon \nu_w / \nu_{max} n_7 \nu_{s7}^3 a_1). \quad (2.41)$$

Equation 2.41 implies that the water maser luminosity should correlate with the mechanical luminosity of the CO outflow and the maser luminosity should be 6.5 orders of magnitude lower than that of the mechanical luminosity of the outflow. The parameters $\Delta \nu_5$, the pre-shock density n_7 , ν_{s7} and a_1 are intrinsic parameters to the maser and contribute to the maser luminosity; however, their possible range of variability is small, and thus their cumulative effect is not very significant.

In summary, the mechanical luminosity of outflows correlates with water maser luminosities according to the EM model of collisional shock excitation.

Water masers reveal information about the kinematics of the regions producing them. The physical properties of water masers in a region may be determined by the outflow from their associated protostar (Brand et al., 2003).

2.5.4 Precession in jets and outflows

The axis of jets has been known to wander throughout the various evolutionary stages of protostars. Ejected mass from YSOs is expected to travel an approximately linear path as it propagates from the disk unless deflected by a dense clump, a high-density region, or a side wind. This, in essence, suggests that jet wiggles are likely due to variations in ejection angles. Jets are also known to precess (Raga et al., 2012), producing S-shaped point symmetric wiggles or mirror-symmetric wiggles (see Figure 2.3) in the case of a binary system.

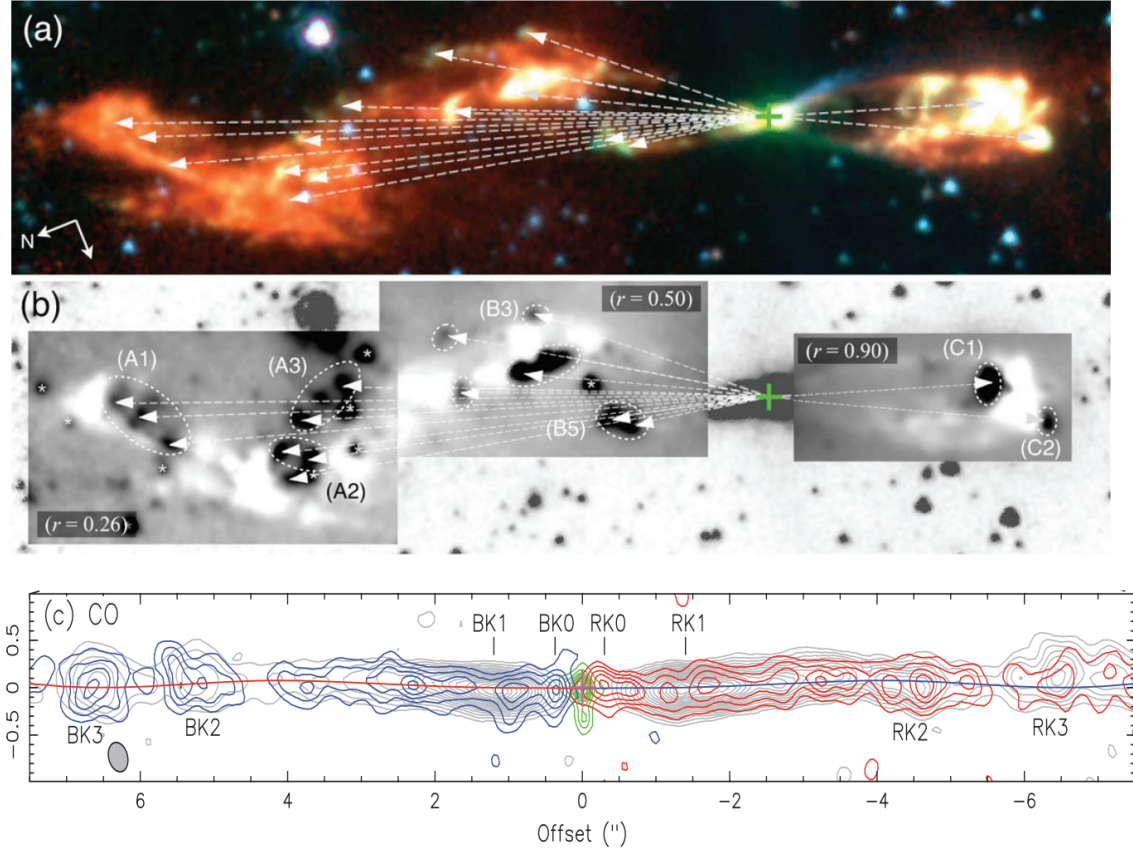


Figure 2.3: Examples of jet precession. Panel (a) is a pseudo-colour image of L1157 from Spitzer. The blue, green, and red represent 3.6 , 4.5 , and $8.0 \mu\text{m}$, respectively). Panel (b) is H₂ map of L1157 showing knots (A1 - C2) connected to the protostar (green cross). Panel (c) is a model of the L1157 jet overlaid on CO and SiO emission knots in the jet. Source: Frank et al. (2014)

The typical precession periods of jets that originate from class 0 or class 1 protostars fall within the range of 400 to 50,000 years (Eisloffel et al., 1996), with axis angle changes extending up to 45° (Cunningham et al., 2009). Jet axis precession is suggested to be a result of the precession of the axis of rotation of circumstellar disks rather than the spin of the protostar axis (Frank et al., 2014).

Jets undergo velocity jumps over years (50 km s^{-1} over 400 years), which are suggested to result from material moving at high velocity catching up with slow-moving material (Raga et al., 2012). The physical causes of the observed quasi-periodic jet variability are unclear. Current theories revolve around stellar magnetic cycles, perturbations by unresolved binary companions, or EXor-FUor accretion bursts.

2.6 Radiation theory

To understand the nature of the incident radiation collected by radio telescopes and the physical properties of the sources emitting the radiation, the understanding of the propagation of radiation through space, particularly the interstellar medium, is crucial. The theory of radiative transfer characterises how the intensity of radiation changes as it travels through an absorbing and/or emitting medium. The photons collected by radio telescopes carry information about their emitting sources such as magnetic field intensity and orientation of circumstellar disks around young protostars. The treatment of radiation theory and radiative transfer presented here is taken from Sasao and Fletcher (2006) and Rybicki and Lightman (1986).

Electromagnetic waves carry energy, and the energy conveyed by the waves is defined by:

$$E = h\nu, \quad (2.42)$$

where h is Planck constant $\sim 6.626 \times 10^{-34}$ J s.

2.6.1 Quantum theory of radiation

Let us take into consideration a gas cloud consisting of N number of particles of the same species. Each particle occupies a unique quantum state denoted by Z_i , where $i=1, 2, 3, \dots, \infty$, with corresponding energy levels, E_j , where $j=1, 2, 3, \dots, \infty$. For two states, Z_m and Z_n , with energy states, $E_m < E_n$, a particle can transition from a lower state Z_m to the higher state Z_n by absorbing radiation energy equivalent to the difference in energy of the two states $E_n - E_m$. Inversely, the particle can move to a lower state Z_m from Z_n by emitting the same differential amount of energy $E_n - E_m$.

From equation 2.42 the frequency of the resulting radiation will be:

$$h\nu_{mn} = E_n - E_m. \quad (2.43)$$

Figure 2.4 is an illustration of the energy levels and the transitions generating emission and absorption.

In general, three main transitions can occur between two energy states, namely spontaneous emission, absorption, and stimulated (or induced) emission.

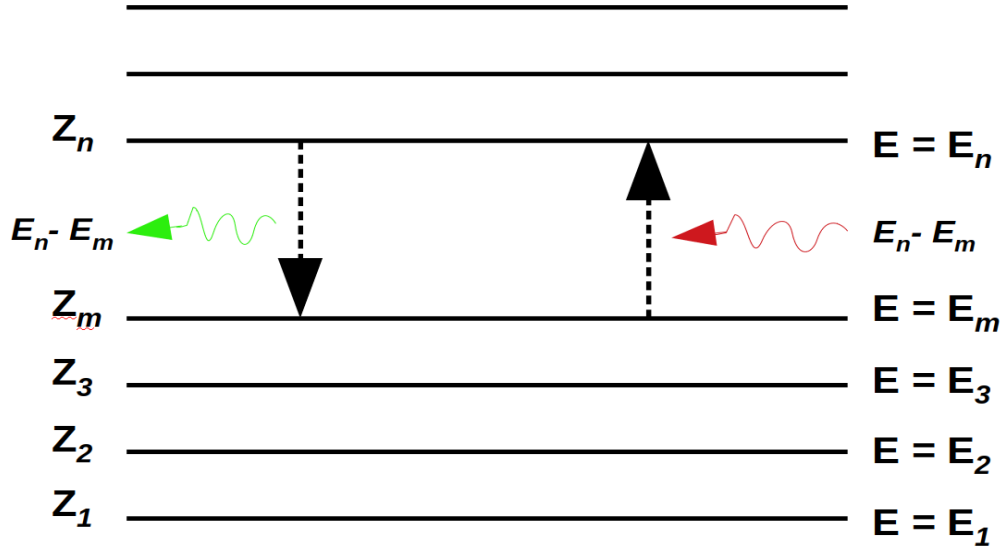


Figure 2.4: Quantum energy levels and energy transitions showing emission and absorption (red and green arrows, respectively) of radiation.

Figure 2.5 illustrates the three main transitions outlined below:

- Spontaneous emission (Figure 2.5 (a)) refers to when a particle moves from a higher energy level to a lower energy level without any external influence.
- A particle may absorb external radiation (Figure 2.5 (b)) passing through it, engendering a transition from a lower energy state to a higher state.
- Incident radiation with a specific frequency may stimulate or induce the movement of a particle(s) from a higher energy level to a lower energy level which leads to the emission of a new radiation (green arrow in Figure 2.5 (c)) with the same properties of the incident radiation (frequency and direction).

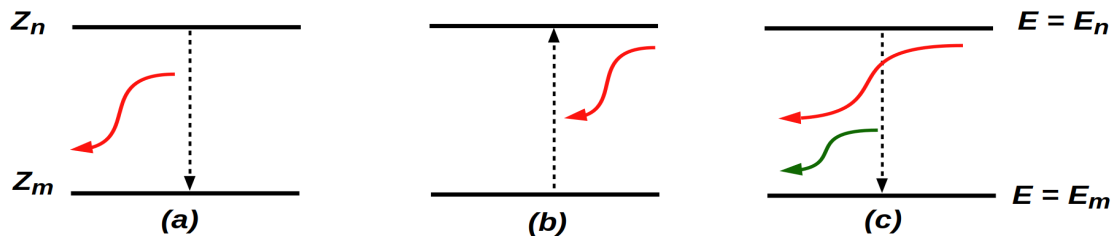


Figure 2.5: Illustration of the three main types of transitions; spontaneous emission (a), absorption (b), and stimulated (induced) emission (c) of radiation. The green arrow in (c) represents the induced emitted photon.

A transition from one energy level to another, which results in the emission of photons with a wide range of energies equal to the difference between the initial and final energy levels, produces a continuous emission spectrum (continuum). The properties of the continuum emission, such as its intensity, shape, and spectral distribution, depend on the specific mechanisms responsible for the transitions and the physical conditions within the emitting source.

2.7 The Einstein coefficients

Spontaneous Emission

Spontaneous emission occurs when a particle spontaneously transitions from a higher energy state Z_n to a lower energy state Z_m without the influence of an external stimulus, emitting a photon in the process (See Figure 2.6 (a)). Let df_{sp} be the probability of a photon to be emitted spontaneously without any external influence within an infinitesimal time interval dt into an infinitesimal solid angle $d\Omega$, in a direction $-\mathbf{s}$, within a small frequency bandwidth $d\nu$ at the frequency ν_{mn} . The bandwidth $d\nu$ of the emitted photon is determined by the decay rate of the excited state of the emitting particle. df_{sp} is proportional to $d\nu d\Omega dt$:

$$df_{sp} = \alpha_n^m d\nu d\Omega dt, \quad (2.44)$$

where α_n^m is a proportionality coefficient known as a differential Einstein coefficient.

Absorption

A gaseous medium may absorb external radiation (Figure 2.6 (b)) passing through it, which triggers a transition of particle(s) from the lower energy state Z_m to the higher state Z_n around a specific frequency ν_{mn} .

The probability of the absorption process occurring df_{st} , in time interval dt , in a specific direction inside a solid angle $d\Omega$, in an infinitesimal frequency bandwidth $d\nu$, should be proportional to $d\nu d\Omega dt$ and the energy density per unit solid angle $U_\nu(\mathbf{s})$ of the incident photon. This introduces another coefficient of proportionality β_m^n :

$$df_{ab} = \beta_m^n u_\nu(\mathbf{s}) d\nu d\Omega dt \quad (2.45)$$

Stimulated (induced) emission

Incident radiation with a frequency ν , incoming from a direction ($\mathbf{s}$), may stimulate/induce transitions of particles to migrate from upper energy levels to lower energy levels which leads to the emission of a new radiation (See Figure 2.6 (c)).

The emitted photon will possess the same characteristics as the incident photon, such as direction and frequency. The probability of this process occurring df_{st} , in a time interval dt , in a particular direction inside a solid angle $d\Omega$, in an infinitesimal frequency bandwidth $d\nu$, should be proportional to $d\nu d\Omega dt$ and the energy density per unit solid angle $U_\nu(\mathbf{s})$ of the incident photon given as:

$$df_{st} = \beta_m^n u_\nu(\mathbf{s}) d\nu d\Omega dt \quad (2.46)$$

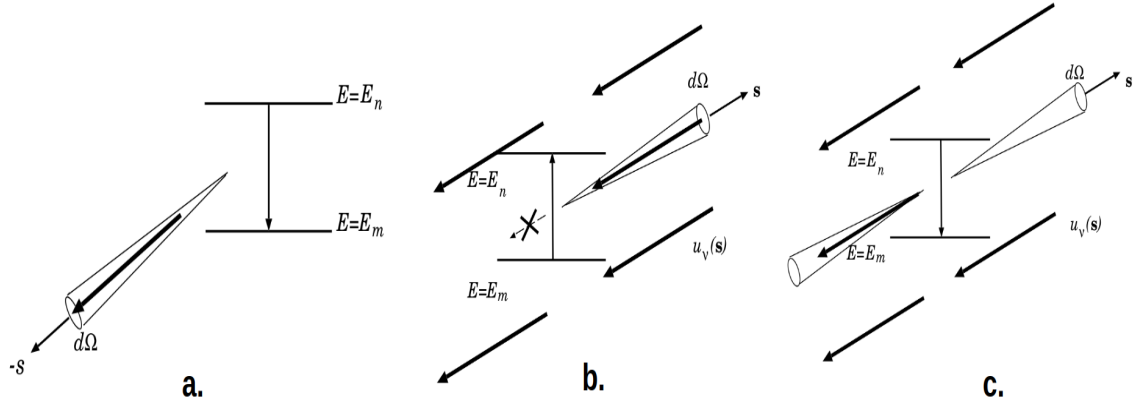


Figure 2.6: Illustration of the propagation of radiation during the three main types of transitions; spontaneous emission (a), absorption (b) and stimulated (induced) emission (c) over an infinitesimal solid angle. Adapted from Sasao and Fletcher (2006).

The proportionality coefficients α_n^m , β_n^m , and β_m^n in equations 2.44, 2.45, and 2.46 describe the probabilities of the three transitions, are isotropic, and are known as the differential Einstein coefficients. For particles in an isotropic radiation field, the transition probabilities dW_i for absorption, spontaneous emission, and stimulated emission, respectively, were originally described by Einstein (1917):

$$\begin{aligned} dW_{ab} &= B_m^n U_\nu dt, \\ dW_{sp} &= A_n^m dt, \\ dW_{st} &= B_n^m U_\nu dt, \end{aligned} \quad (2.47)$$

where U_ν is the spectral energy density defined by; $U_\nu = \int u_\nu(\mathbf{s}) d\Omega$, in units of $Jm^{-3}Hz^{-1}$.

A_n^m , B_m^n , and B_n^m are the Einstein coefficients. The differential Einstein coefficients and the Einstein coefficients are related by:

$$\begin{aligned}\alpha_n^m &= \frac{A_n^m f(\nu)}{4\pi}, \\ \beta_n^m &= B_m^n f(\nu), \\ \beta_m^n &= B_n^m f(\nu),\end{aligned}\tag{2.48}$$

where $f(\nu)$ is the probability distribution of frequency in a spectral line.

2.8 Radiative transfer

2.8.1 Photon number density

An important quantification of particles in interstellar space is the number density, which represents the total number of particles per unit volume of a column of gas in the ISM. Taking n_m and n_n to represent the number densities in a pair of states Z_m and Z_n , respectively, a transition $Z_n \rightarrow Z_m$ within time interval dt , into an infinitesimal solid angle $d\Omega$, in a specific direction $-\mathbf{s}$, per a specific bandwidth $d\nu$, the number density of photons emitted, will be:

$$n_n(df_{sp} + df_{st}) = (\alpha_n^m + \beta_n^m u_\nu) d\nu d\Omega dt.\tag{2.49}$$

In the case of the absorption during $Z_m \rightarrow Z_n$ transition, the number density will be:

$$n_m df_{ab} = n_m \beta_m^n u_\nu d\nu d\Omega dt.\tag{2.50}$$

In the course of both absorption and emission, the infinitesimal variation in the number density of photons in solid angle in direction $-\mathbf{s}$, per unit bandwidth ν_{mn} will be:

$$dn_p(\mathbf{s}, \nu) d\nu d\Omega = -n_m \beta_m^n u_\nu + n_n [\alpha_n^m + \beta_n^m u_\nu(\mathbf{s})] d\nu d\Omega dt.\tag{2.51}$$

Finally, the photon density variation with time will be:

$$\frac{dn_p(\mathbf{s}, \nu)}{dt} = (n_n \beta_n^m - n_m \beta_m^n) u_\nu(\mathbf{s}) + n_n \alpha_n^m.\tag{2.52}$$

2.8.2 The radiative transfer equation

The photon density variation describes how the photon number density changes with time. However, there is a need to quantitatively characterise the transfer of the intensity of the exiting radiation. From equation 2.52, the following relations hold:

$$\begin{aligned} dl &= c dt, \\ I_\nu(\mathbf{s}) &= c u_\nu(\mathbf{s}), \\ u_\nu(\mathbf{s}) &= h\nu n_p(\mathbf{s}, \nu), \end{aligned} \tag{2.53}$$

where I_ν is the intensity and c is the speed of light in vacuum. Using the components in equation 2.53, equation 2.52 can be transformed to:

$$\frac{dI_\nu}{dl} = -(n_m\beta_n^m - n_n\beta_m^n)\frac{h\nu}{c}I_\nu + h\nu n_n \alpha_n^m. \tag{2.54}$$

Further, if we denote $(n_m\beta_n^m - n_n\beta_m^n)\frac{h\nu}{c}$ from equation 2.54 as k_ν and $h\nu n_n \alpha_n^m$ as ϵ_ν , we can rewrite 2.54 as:

$$\frac{dI_\nu}{dl} = -k_\nu I_\nu + \epsilon_\nu, \tag{2.55}$$

which is known as the radiative transfer equation, where k_ν and ϵ_ν are frequency-dependent coefficients. The coefficients of the radiative transfer equation represent physical quantities that describe the interaction of radiation with matter and may vary depending on the system under study. They describe how radiation is absorbed, emitted, scattered, and transmitted through a medium. In this instance, k_ν is the absorption coefficient and ϵ_ν is the emission coefficient. k_ν represents the fraction of the radiation that is absorbed per unit distance travelled in the medium, and is proportional to the product of the material's absorption cross-section and density. ϵ_ν represents the amount of radiation emitted per unit volume and unit frequency interval by the medium, and is dependent on the temperature and composition of the material.

The radiative transfer equation conceptually represents the variation in intensity dI_ν that exiting radiation which entered and propagated through a cylindrical column of gas of infinitesimal length dl will experience and it will be a sum of contributions from both absorption and emission. Figure 2.7 shows a simple illustration of this effect.

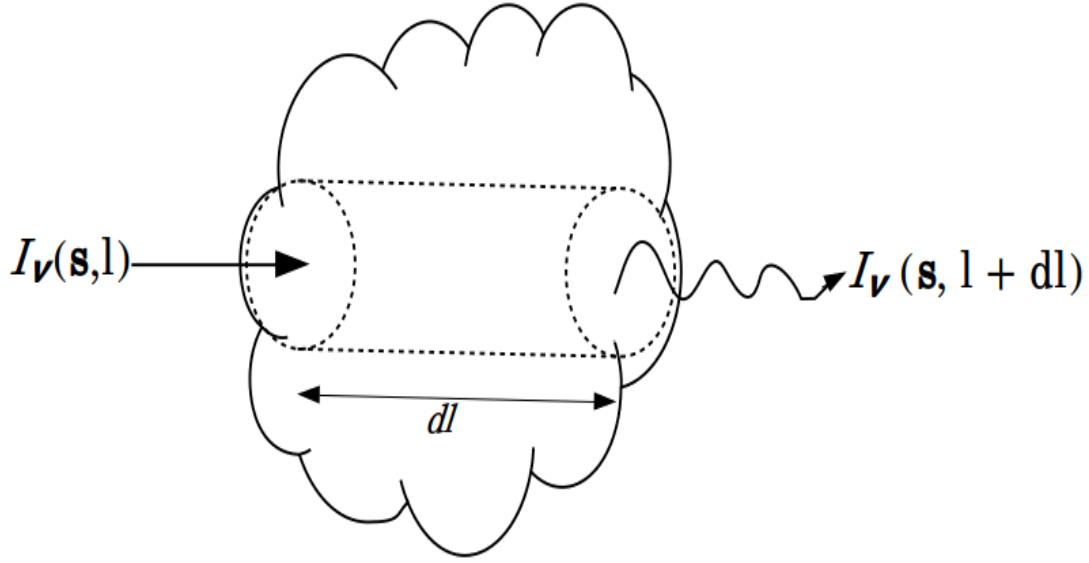


Figure 2.7: Radiative transfer through a cylindrical column of gas of infinitesimal length dl .

2.8.3 Solutions to the radiative transfer equation

The radiative transfer equation has simple solutions under some conditions. To arrive at these simple solutions, we have to consider two conditions:

1. When $k_\nu = 0$, that is in the case of no opacity in the medium;

The solution to the radiative transfer equation will be:

$$I_\nu(l) = I_\nu(0) + \int_0^l \epsilon_\nu(l') dl'. \quad (2.56)$$

2. When $\epsilon_\nu = 0$;

$$I_\nu(l) = I_\nu(0) e^{[-\int_0^l k_\nu(l') dl']}. \quad (2.57)$$

Furthermore, in the case of $k_\nu = \text{constant}$ everywhere, the solution changes to:

$$I_\nu(l) = I_\nu(0) e^{-k_\nu l}. \quad (2.58)$$

These solutions enable inferences about the properties of the medium through which the radiated photon traversed before reaching the observer.

2.8.4 Opacity

The opacity k_ν , of the medium defined as $(n_m\beta_m^m - n_n\beta_n^n)\frac{h\nu}{c}$ contains contributions of emissions due to the factor $h\nu n_n\alpha_n^m$, which is ϵ_ν . Accordingly, equation 2.66 can be substituted to redefine k_ν as:

$$k_\nu = \beta_m^n(n_m - \frac{g_m}{g_n}n_n) h\nu/c. \quad (2.59)$$

If $g_n = g_m$, equation 2.68 reduces to:

$$k_\nu = \beta_m^n(n_m - n_n) h\nu/c. \quad (2.60)$$

The opacity will have a negative value if the upper energy level is more populated than the lower level ($n_n > n_m$). Further, this negative-opacity, assuming homogeneity (equation 2.66), will lead to exponential growth, leading to maser amplification and emission. On the other hand when the opacity is positive ($k_\nu > 0$), exponential decay will occur, which will arise from regular absorption.

2.9 Black body radiation

For a system in thermodynamic equilibrium, under stationary conditions, the number of upward transitions $Z_m \rightarrow Z_n$ and the number of inverse transitions $Z_n \rightarrow Z_m$ must be equal. This can be described as:

$$n_m \beta_m^n u_\nu(\mathbf{s}) = n_n [\alpha_n^m + \beta_n^m u_\nu(\mathbf{s})], \quad (2.61)$$

where n_m and n_n are the number densities in the lower Z_m and upper Z_n states, respectively. α_n^m and β_n^m are the differential Einstein coefficients for spontaneous emission and absorption, respectively. $u_\nu(\mathbf{s})$ is the spectral density per unit solid angle.

The Boltzmann distribution relates the probability of a system of particles to their energies. It is expressed as the probability of finding a particle with energy E in a system of non-interacting particles, given the temperature T of the system. The Boltzmann distribution is used to calculate the occupation number of a particle in a given energy state.

The Boltzmann distribution can be expressed as the probability df_n of a particle occupying the state Z_n :

$$df_n = g_n e^{-\frac{E_n}{kT}}, \quad (2.62)$$

where k is the Boltzmann constant $\sim 1.381 \times 10^{-23} \text{ J K}^{-1}$, E_n is the energy of state Z_n , and T is the absolute temperature in Kelvin. g_n represent the statistical weight (degree of degeneracy of the state).

Denoting n as the total number density of particles in the medium, the probability df_n statistically must be equal to the ratio of the number density n_n and n_m of particles at Z_n and Z_m levels, respectively. Equation 2.62 for both levels can thus be written as:

$$\frac{n_n}{n} = g_n e^{-\frac{E_n}{kT}}, \quad (2.63)$$

$$\frac{n_m}{n} = g_m e^{-\frac{E_m}{kT}}. \quad (2.64)$$

Substituting equations (2.63) and (2.64) into (2.61), we have:

$$e^{-\frac{E_m}{kT}} g_m \beta_m^n u_\nu(\mathbf{s}) = e^{-\frac{E_n}{kT}} g_n [\alpha_n^m + \beta_n^m u_\nu(\mathbf{s})], \quad (2.65)$$

where T is the absolute temperature in Kelvin, g_m and g_n represent the statistical weight that is the degree of degeneracy of the Z_m and Z_n states, respectively. β_m^n and β_n^m are coefficients of absorption for transitions $Z_n \rightarrow Z_m$ and $Z_m \rightarrow Z_n$, respectively.

If the energy density per solid angle of the thermal radiation $u_\nu(\mathbf{s})$ approaches infinity ($u_\nu(\mathbf{s}) \rightarrow \infty$) and the absolute temperature T of the medium also moves to infinity ($T \rightarrow \infty$), Equation 2.65 reduces to:

$$g_m \beta_m^n = g_n \beta_n^m. \quad (2.66)$$

Rewriting 2.65 gives:

$$(e^{\frac{E_n - E_m}{kT}} - 1) \beta_n^m u_\nu(\mathbf{s}) = \alpha_n^m, \quad (2.67)$$

where α_n^m is the coefficient for emission. Substituting equation 2.43 into 2.67 and ignoring the direction ($\mathbf{s}$) since thermal radiation is isotropic, the energy density per solid angle u_ν can be rewritten as:

$$u_\nu = \frac{\alpha_n^m}{\beta_n^m} \frac{1}{e^{\frac{h\nu}{kT}} - 1}. \quad (2.68)$$

The energy density follows the Rayleigh-Jeans radiation law (Rybicki and Lightman, 1986):

$$u_\nu = \frac{2\nu^2}{c^3} kT, \quad (2.69)$$

where ν is the frequency, k is the Boltzmann constant $\sim 1.381 \times 10^{-23} \text{ J K}^{-1}$, and T is the absolute temperature in Kelvin. In the case $h\nu \ll kT$:

$$\frac{\alpha_n^m}{\beta_n^m} = \frac{2\nu^2}{c^3}. \quad (2.70)$$

Substituting equation 2.70 into 2.68, we obtain Planck's formula for blackbody radiation:

$$u_\nu = \frac{2h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad (2.71)$$

The energy density, U_ν , measured by radio telescopes, is the integral over the solid angle:

$$U_\nu = \oint u_\nu d\Omega = 4\pi u_\nu = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1}. \quad (2.72)$$

The Planck formula (Equation 2.71) implies that for any frequency range, the measured intensity of a hot blackbody is always higher than the intensity of a colder body. Interstellar gas clouds, despite colder temperatures, are still bright at radio frequencies due to their large angular sizes. The total intensity I_{total} of thermal radiation from a blackbody of temperature T , over the entire frequency range, is given by:

$$I_{total} = \int_0^\infty I_\nu d\nu = \int_0^\infty \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} d\nu = \frac{1}{\pi} \sigma T^4, \quad (2.73)$$

where σ is the Stefan-Boltzmann constant $\sim 5.6697 \times 10^{-8} W m^{-2} K^{-4}$.

2.10 Basic quantities in radio astronomy

Certain quantities are commonly used in radio astronomy to characterize specific components of interstellar radiation, these quantities are presented in this section and will be used throughout the text.

2.10.1 Intensity I_ν or Brightness B_ν

The intensity I_ν or brightness B_ν in radio astronomy refers to the amount of power from an astronomical source dW , in the form of radiation, arriving from a specific direction $\mathbf{s}$, per unit cross-section of area $d\sigma$, which is inclined at an angle θ from $\mathbf{s}$, per unit time, per unit solid angle $d\Omega$, per unit frequency bandwidth $d\nu$ with centre frequency ν . In terms of monochromatic intensity I_ν , it is given by:

$$dW = I_\nu(\mathbf{s}) \cos \theta d\sigma d\nu d\Omega. \quad (2.74)$$

The SI unit for intensity is $\text{W m}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$. The monochromatic intensity remains constant along a ray path and does not depend on distance from the emitting source, assuming there is no absorption or scattering along the path.

2.10.2 Flux Density S_ν or ‘Flux’

The amount of radiation power from an astronomical source incident on a unit cross-sectional area per unit time per unit frequency describes its flux density. Flux density is usually denoted as either S_ν or F_ν and can be expressed in terms of the intensity I_ν by:

$$S_\nu = \iint_{\Omega} I_\nu(\mathbf{s}) \cos \theta \, d\Omega, \quad = \iint_{\Omega} I_\nu(\theta, \phi) \cos \theta \sin \theta \, d\theta d\phi, \quad (2.75)$$

A unit called ‘Jansky’ (Jy), named after Karl G. Jansky, is commonly used for flux density and has a value of $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2}\text{Hz}^{-1}$.

2.10.3 Directional spectral energy density $U_\nu(\mathbf{s})$

The directional spectral energy density $U_\nu(\mathbf{s})$ describes the density of energy, from incident radiation arriving from a specific direction $\mathbf{s}$, per unit frequency bandwidth, per unit solid angle.

Assuming a cylindrical column of gas with length $c dt$ and cross-sectional area $d\sigma$, where c is the speed of light in vacuum, the energy dU_ν per unit frequency bandwidth per solid angle in the cylinder can be defined by:

$$dU_\nu = u_\nu(\mathbf{s}) \, c dt \, d\sigma. \quad (2.76)$$

The SI Unit is $\text{J m}^{-3} \text{Hz}^{-1} \text{sr}^{-1}$.

2.10.4 Spectral energy density U_ν

The spectral energy density U_ν is described as the energy possessed by incoming radiation, arriving isotropically, per unit volume, per unit frequency bandwidth. It is given by the volume integral over the solid angle:

$$U_\nu = \oint u_\nu(\mathbf{s}) d\Omega = \frac{1}{c} \oint I_\nu(\mathbf{s}) d\Omega. \quad (2.77)$$

The SI Unit is $\text{J m}^{-3} \text{Hz}^{-1}$.

2.10.5 Brightness temperature

The brightness temperature of an astronomical radio source is defined by:

$$T_B = \frac{c^2}{2k\nu^2} I_\nu, \quad (2.78)$$

where I_ν is the intensity or surface brightness.

Brightness temperature is described as the temperature quantity of a radio source when the Rayleigh-Jeans approximation has been applied to the collected incoming radiation from the radio source. The unit of brightness temperature is Kelvin. The brightness temperature corresponds to the physical temperature of a hot ($T \gg 10\text{K}$) thermal source if there was no absorption or added emission along the ray path. For non-thermal sources such as masers, the brightness temperature does not correlate with the physical temperature of the source. Masers for example, could have brightness temperatures as high as 10^{14} K but with actual physical masing gas cloud temperatures of only a few hundred Kelvin.

2.11 Maser theory

This section introduces interstellar masers and their mechanism of operation, followed by their properties and a review of water and methanol maser species.

Microwave amplification of stimulated emission of radiation (MASER) refers to amplified emission of radiation, which has been exponentially amplified in an initial direction of propagation in a specific frequency (Humphreys, 2011). This frequency corresponds to transitions between energy levels where the number of particles at a higher energy level exceeds those at a lower energy level, a condition known as population inversion. The amplification is due to the stimulation of an inducing photon (Humphreys, 2011). Figure 2.8 shows a schematic view of the masing mechanism.

Masing occurs in the presence of population inversion ($n_n > n_m$) and maser emission is non-thermal (Humphreys, 2011). If the gas medium is in thermal equilibrium there will be no population inversion $n_n < n_m$ and thus no amplification can occur. There essentially needs to be a mechanism which creates the population inversion for masing to work. This is referred to as the pumping mechanism (Elitzur, 1992a). Infrared radiation (radiative pumping) and collision of gas particles (collisional pumping) are the common pumping mechanism (Elitzur, 1992b). Interstellar masers, among many of their uses also serve as probes of star formation (Elitzur, 1992a). However, the mechanism by which these masers function is still poorly understood.

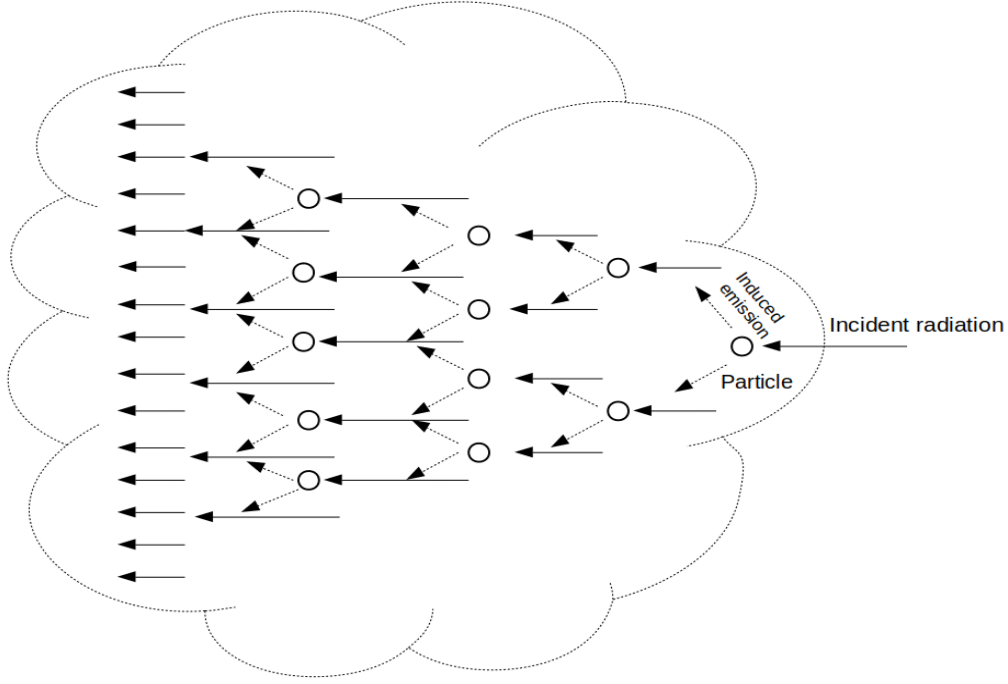


Figure 2.8: Schematic of masing mechanism in a cloud medium. A photon incident on a particle in a gas cloud induces emission from the particle which further produce more photons to generate more particles in the cloud, leading to a cascade of emission. Due to all the induced emissions travelling parallel, a coherent beam is produced and referred as a maser. In the visible spectrum, the same mechanism is known as light amplification of stimulated emission of radiation (LASER).

2.11.1 Pumping of masers

The number of additional molecules arriving at the upper level per unit time and volume from a reservoir of background states is known as the pump rate P_n and can be denoted for the lower energy state as P_m . Reverse pumping can also occur whereby the molecules decay back into the reservoir (Stahler and Palla, 2004). If we denote $n_n\Gamma_n$ and $n_m\Gamma_m$ as loss rates (transitions per unit time back to reservoir) per unit volume, γ_{mn} and γ_{nm} are the coefficients of collisional excitation and de-excitation, respectively, summing all the rates and equating them to zero enables the computation of the steady state population of each level:

$$\begin{aligned} P_n - n_n\Gamma_n - (n_n B_{nm} - n_m B_{mn})\bar{J} - (n_n\gamma_{nm} - n_m\gamma_{mn})n_{tot} - n_n A_{nm} &= 0, \\ P_m - n_m\Gamma_m + (n_n B_{nm} - n_m B_{mn})\bar{J} + (n_n\gamma_{nm} - n_m\gamma_{mn})n_{tot} + n_n A_{nm} &= 0, \end{aligned} \quad (2.79)$$

where $\bar{J}$ is the frequency-integrated mean intensity, and n_{tot} is the number density of the background gas.

Assuming that the two loss rates are equal $\Gamma_n = \Gamma_m = \Gamma$, and the coefficient for spontaneous emission is negligible compared to Γ_n or Γ_m , solving for the populations n_n and n_m , results in:

$$\begin{aligned} n_n &= \frac{(P_n - P_m) + (P_n - P_m)[1 + (2g_n/g_m)(B_{nm}\bar{J} + \gamma_{nm}n_{tot})\Gamma]}{2\Gamma + 2(1 + g_n/g_m)(B_{nm}\bar{J} + \gamma_{nm}n_{tot})}, \\ n_m &= \frac{(P_n - P_m)[1 + 2(B_{nm}\bar{J} + \gamma_{nm}n_{tot})\Gamma] - (P_n - P_m)}{2\Gamma + 2(1 + g_n/g_m)(B_{nm}\bar{J} + \gamma_{nm}n_{tot})}. \end{aligned} \quad (2.80)$$

The population inversion can thus be denoted as the difference Δn :

$$\begin{aligned} \Delta n &\equiv n_n/g_n - n_m/g_m, \\ n_m &= \frac{(P_n/g_n - P_m/g_m)}{\Gamma + (1 + g_n/g_m)(B_{nm}\bar{J} + \gamma_{nm}n_{tot})}. \end{aligned} \quad (2.81)$$

This implies that inversions necessitate a higher pump rate into the upper state at each sub-level than into the lower state since $P_n/g_n - P_m/g_m$. It is still unclear how masers maintain this population inversion over the typical long periods (years) over which they are active.

2.12 Interstellar masers

Maser phenomenon was first discovered in 1965 in interstellar space, specifically in regions of dense molecular gas by Weaver et al. (1965). A suitable physical condition of temperature and density, and an abundance of the relevant molecules are required for a molecular transition to exhibit maser emission (Breen et al., 2013). The most notable maser species associated with star formation are the methanol (CH_3OH) (Barrett et al., 1971), hydroxyl (OH) (Weaver et al., 1965), ammonia (NH_3) (Madden et al., 1986), carbon monosulphide (CS) (Highberger et al., 2000), silicon monoxide (SiO) (Snyder and Buhl, 1974), water (H_2O) (Cheung et al., 1969) and formaldehyde (H_2CO) (Snyder et al., 1969) species.

Interstellar masers aid in determining the presence of circumstellar disks and ionised gas as well as the orientations of outflows. The combination of information on the distribution and kinematics of masers with the radio continuum emission from a star-forming region provides invaluable insight into the characteristics of the protostars in the region. Furthermore, studies of the proper motions of masers imparts understanding into the kinematics

of outflows from young stellar objects (Seth et al., 2002). This study however focuses on water masers as they are the species detected towards NGC 2071-IR during the data collection stage of the research and will include the review of methanol masers.

2.12.1 Water masers

Water masers were first discovered in 1969 by Cheung et al. (1969) in the 22 GHz $6_{15} \rightarrow 5_{23}$ rotational transitions and has since then been found in hundreds of star-forming regions (low, intermediate and high-mass star-forming regions), and around circumstellar envelopes (Menten, 1991a). Water masers are more widespread, relative to other species and have been found around stars at various evolutionary phases. They have detected around evolved stars, near Herbig-Haro objects, supernovae remnants, and the central regions of active galaxies (Breen et al., 2013).

Water masers are known to be collisionally pumped (Elitzur et al., 1989). However, recent studies showed that they also can be radiatively pumped. Setting kinetic temperature, dust temperature and number density as key parameters, simulations by Gray et al. (2022) found a small system of pumping routes through which a 22 GHz transition can be radiatively pumped. Radiative pumping is found to be capable of supplying 50% of inversion under typical radiative pumping conditions. For the radiative pumping to occur, the dust temperature is required to be high ($700 < T_{dust} < 1000$ K), the water molecule number density to be about $3.0 \times 10^6 \text{ cm}^{-3}$, and finally, the kinetic temperature should be less than 350 K. This implies that 22 GHz water masers found in high-mass SFRs may be partly radiatively pumped if the kinetic temperatures are low since the high dust temperatures required are present in those regions (Gray et al., 2022). Gray et al. (2022) referenced the simultaneous flaring of water and methanol species during the 2015 flare in high-mass SFR NGC 6334 (MacLeod et al., 2018) as support, suggesting radiative pumping the likely source of inversion in the water maser.

Nonetheless, the current concurrence is collisional pumping, and maser characteristics, such as line width and line ratio estimates can be explained by the collisional excitation of H_2O molecules by H_2 molecules (Neufeld and Melnick, 1990, 1991). Results from simulations suggest that the pre-shock masing cloud is required to be compressed to densities to the orders of 10^7 cm^{-3} for the pumping of H_2O masers to occur. The current model capable of explaining all the observed galactic water masers including the brightest masers, toward W49 and Orion KL, is the model from Elitzur et al. (1989). The model theorises that water masers form behind dissociative shocks with high velocities, moving through dense molecular clumps, with magnetic pressure being the critical feature determining the nature of the shocks. The sequence of events, according to the model, leading to H_2O maser action is summarised by (Elitzur et al., 1989) as follows:

- Shocks from high velocity ($v_s \sim 30\text{--}200\text{ km s}^{-1}$) outflows/stellar winds/jets interact with pre-shocked gas with a density $\sim 10^7\text{ cm}^{-3}$.
- The pumping energy is provided by the dissipation of the kinetic energies of both shocked and unshocked gas.
- The extremely high post-shock temperatures ($\sim 10^5\text{ K}$) immediately behind the shock, break down all the molecules.
- When cooling post-shock, H_2 reforms on dust grains, releasing chemical energy as heat, which produces a large column of gas with a high H_2O abundance.
- Amplification is achieved in velocity-coherent sheets and filaments produced in the post-shock gas.
- Thermal collisions with H_2 and H and radiative cascading then produce a population inversion and the population of the lowest energy levels.

The critical parameters for the production of water masers according to the model, are the shock velocity and the gas density. If the shock velocities are not high enough ($v_s \leq 30\text{ km s}^{-1}$), H_2 will not be initially dissociated, thus no reformation. If the densities are also not high enough ($\leq 10^6\text{ cm}^{-3}$), H_2O will not be sufficiently produced and the masers will be unsaturated and weak. On the other hand, very high densities ($\geq 10^8\text{ cm}^{-3}$) will thermalise the level populations leading to the deconstruction of the maser.

Water masers are highly variable (Lekht et al., 1982). This variability has been suggested to be related to the luminosity of the star-forming region. Brand et al. (2003), from their study of water masers and their relation to the far-infrared luminosity of the associated protostar, found that the lower the luminosity of the YSO associated with the water masers, the higher the observed variability. Conversely, the higher the luminosity, the stronger and more stable the masers (Brand et al., 2003). Brand et al. (2003) further explained that in lower-luminosity protostars, a smaller number of maser components get excited, and their intrinsic variability dominates the total maser output. In contrast, in higher luminosity protostars, a larger number of maser components get excited, this reduces the effect of the individual variability on the total maser output. Furthermore, as the far infrared luminosity decreases, the conditions for maser amplification become closer to the threshold, causing the maser emission to become more unstable.

Single-dish measurements of water masers obtain spectra representing the average emission of a large ensemble of maser clumps (Menten, 1991a). Water masers were observed to drift in velocity of a few km s^{-1} per year of individual components. Frequent single-dish observations enable tracing of the velocity drifts of individual maser components, and can provide insight into the dynamics in the SFR (Felli et al., 2007). Long-term ($\sim 10+$ years) water maser studies by Brand et al. (2003) have shown that the velocity of the dominant

maser feature in maser spectra is usually close to that of the molecular cloud within which the maser is embedded. Long-term periodic variations (Lekht and Krasnov, 2000; Haschick and Baan, 1990) and cyclical variations (Lekht et al., 2011) have been discovered in water masers. The mechanisms behind these variations are uncertain and remain an active area of research. Water masers are tracers of circumstellar disks or outflow-jet systems (Elitzur et al., 1989), however, they are not ideal for determining the size of jets since they only trace the denser portions of jets (Bayandina et al., 2022).

2.12.2 Methanol masers

Interstellar methanol is formed by the hydrogenation of carbon monoxide (CO) when it freezes on the surface of dust grains, which is then heated into the gaseous phase by young stars (Wiström et al., 2011). Interstellar methanol (CH_3OH) masers were first discovered towards the Orion-KL region at about 25 GHz (Barrett et al., 1971). The methanol molecule has energy levels that emit in several microwave lines due to the molecule possessing an asymmetric rotor which enables internal rotation. Interstellar CH_3OH lines arise from more highly excited energy levels than other molecules and require greater gas densities to maintain a detectable population in energy levels. (Barrett et al., 1971). Methanol masers have been detected towards a vast number of star-forming regions (SFRs) (Batra et al., 1987; Pestalozzi et al., 2005; Breen et al., 2013; Song et al., 2022), and their positions were found in general, to not coincide with the centres of OH and H_2O masers (Ellingsen, 2005). No strong ($\geq 3 \times 10^6$ K) methanol masers are associated with low-mass star formation, however a class II methanol maser has been detected towards NGC 2024:FIR 4, an intermediate-high mass protostar, thereby setting the lower protostellar mass limit for strong methanol masers to $3 M_\odot$ (Minier et al., 2003).

Methanol masers are generally classified into two groups, namely Class I or Class II methanol masers (Menten, 1991a). The Class I CH_3OH maser assemblage includes 9, 25, 44, 84, 95 and 132 GHz lines. The Class II assemblage consists of 6.7, 12, 23, 36, 37, 38 and 107 GHz lines. The major difference between the two classes is that class I methanol masers are usually found to offset from other masers, such as OH or H_2O maser centres, and ultracompact HII regions, while class II are usually found in the same regions as OH masers and close to compact HII regions. To date, class II methanol masers have only been found in high-mass star-forming regions (Sobolev et al., 2007; Breen et al., 2013). The excitation mechanisms of class I methanol masers are fairly understood from the basic properties of methanol though excitation of class II methanol masers is still poorly understood (Menten, 1991a). Class II methanol masers have high brightness temperatures (up to 10^{12} K) and cannot be explained by the collisional pumping mechanism of excitation. Several pumping mechanisms may be contributing to the pumping of a particular maser in a complementary way rather than contradictory one (Liu and Sun, 1997).

2.12.3 6.7 GHz methanol masers

The $5_1 \rightarrow 6_0 A^1$ (6.7 GHz) transition of methanol produces the highest brightness temperatures (up to 10^{12} K) in class II CH₃OH masers (Menten et al., 1992). 6.7 GHz methanol masers have been reported to be exclusively associated with high-mass star formation (Xu et al., 2008; Breen et al., 2013; Paulson and Pandian, 2020). They are often spatially associated with the 12.2 GHz methanol masers and are the second strongest class II main line CH₃OH masers in terms of brightness temperature (Pandian, 2007). 6.7 GHz CH₃OH masers are the strongest and most widespread masers (Breen et al., 2013). They are suggested to arise from dense and warm molecular material surrounding compact ionised hydrogen (HII) regions which are excited by high-mass stars. Hot O and B stars serve as the driving source of gas ionisation and excitation of masers. VLBI observations of 6.7 GHz CH₃OH masers have revealed that they are compact, with their sizes ranging from a few AU to 10 AU. They are often enclosed by diffuse halos which are double the size of the masers (Minier et al., 2002). Due to their compact sizes, 6.7 GHz CH₃OH masers are good traces of the motion of disks and envelopes around stars via the study of their proper motions.

An estimate of the lifetime of 6.7 GHz methanol masers, using initial mass functions, found them to lie between 2.5×10^4 yr and 4.5×10^4 yr. Their lifetimes last, on average, a few 10^4 yr with an uncertainty of 35 % (van der Walt, 2005). However, precisely when exactly 6.7 GHz masers develop during the formation of stars, is still unclear. Not all 6.7 GHz CH₃OH masers observed are associated with detectable radio continuum. This is due to the association of 6.7 GHz CH₃OH masers with the earlier phases of the evolution of high-mass protostars, or that those masers are associated with low-mass stars with UV fluxes insufficient to create HII regions (Pandian, 2007). The latter reason is refuted by studies that found 83 out of 84 masers to be associated with objects with high bolometric luminosities ($10^3 \sim 10^5$), which are indicative of massive stars (Walsh et al., 2003). This further reinforces their suggested exclusive association with massive stars.

While 6.7 GHz CH₃OH masers may originate from circumstellar disks, some are also found to be associated with outflows and shock fronts (Pandian, 2007). It is thought that methanol masers are radiatively pumped (Sobolev et al., 1997; Cragg et al., 2005). This radiation is suggested to be from infrared emission from heated dust grains.

Requisite conditions for pumping of 6.7 GHz methanol masers

The excitation mechanism of 6.7 GHz CH₃OH masers is suggested to be either by collisions from torsional excitation (Breen et al., 2019) or by radiative excitation by a far-infrared continuum from an exciting source (e.g. YSO) (Sobolev and Deguchi, 1994; Cragg et al., 2005). Extensive studies on modelling of these processes to reproduce the observational

results seen in 6.7 GHz methanol masers, have been done. Currently, the prevailing model of excitation/pumping of 6.7 GHz CH_3OH masers is the Sobolev-Deguchi model (Sobolev and Deguchi, 1994). It is the only model to succeed in producing the observed high brightness temperatures ($> 10^{12}$ K). The model requires the hydrogen number density to be in the range of $10^6 \sim 10^8 \text{ cm}^{-3}$, the gas temperatures of masing medium to be ~ 30 K, a methanol column density of $\sim 5 \times 10^{17} \text{ cm}^{-2}$, and a region of warm dust with a temperature greater than 175 K, providing the photons to generate the population inversion (Sobolev and Deguchi, 1994; Sobolev et al., 1997).

The simulations by Sobolev et al. (2007) of the production of bright 6.7 GHz CH_3OH masers suggest the masing medium would have to be close to a hypercompact HII (HCHII) region where non-diluted free-free emission with high turnover frequency ($f_e > 100$ GHz) is present (Sobolev et al., 2007). The dust emission from hypercompact HII regions is dominated by strong free-free emission at high frequencies (up to 300 GHz). Modelling results also revealed that class II methanol masers can be pumped not only by radiation from warm dust but, also free-free emission from an HCHII region with a turnover frequency higher than 100 GHz (Sobolev et al., 2007).

Furthermore, a comparison between the physical environments observed in Class 0 and Class I low to intermediate-mass protostars and the requirements of the Sobolev-Deguchi model (Sobolev et al., 1997) suggests that the conditions around these objects are insufficient for the production of 6.7 GHz CH_3OH masers, despite the presence of copious amounts of methanol. This was explained through the mechanism for the release of the methanol molecules differing from that of high-mass protostars. Around high-mass protostars, the dust temperature in the heated envelopes within a 1000 AU radius from the centre of the core is expected to be higher than 90 K, which is enough to evaporate the methanol from the frozen dust grains and also supply the required photons for population inversion. On the other hand, the dust temperatures around low-mass protostars at a distance of 500-3000 AU from the core centre are less than 90 K, which is insufficient to separate the methanol from the frozen dust grains via evaporation. The separation is suggested to occur from the collision of dust grains in shocked layers produced by jets and outflows which would not be enough to provide residual photons sufficient for population inversion (Minier et al., 2003). The presence of the physical conditions proposed by the current models will be required in a star-forming region for the production of 6.7 GHz CH_3OH masers until more accurate models are developed.

Variability and periodicity of 6.7 GHz methanol masers

Variability has been discovered in some 6.7 GHz CH_3OH masers. This observed variability is exhibited in the light curves in monotonic, quasi-periodic, and periodic ways (Goedhart et al., 2004, 2007). The driving source of the observed variability is still uncertain. The

most interesting of all the variability profiles is the periodic variability. The two most common periodic profiles which manifest in the light curves of periodic 6.7 GHz masers are 1) a steep increase in intensity from a steady state which is followed by an exponential decrease known as a flare profile, and 2) a type of flare profile characterised by a slow increase in intensity which is superseded by a gradual decrease in intensity similar to a ‘bunny hop’ profile which can be approximated by $|\cos(\omega t)|$ function (Szymczak et al., 2015; Morgan et al., 2021; MacLeod et al., 2021). The discovery of periodicity from these methanol masers has inspired the development of theoretical models which seek to explain the phenomena (van der Walt et al., 2009; Araya et al., 2010; van der Walt, 2011; Parfenov and Sobolev, 2014). The colliding-wind binary model and the periodic accretion models propose explanations for the aforementioned periodic lightcurve profiles. In the colliding-wind binary (CWB) scenario (van der Walt, 2011), the orbital motion of binaries regulates the mass production of abundant ionising photons produced by hot-shocked gas ($\geq 10^6$ K). The ionising photons are thus produced in a ‘pulse’ rhythm. The ionised photons propagate almost unrestricted through the ionised gas to the ionisation front. The ionisation front expands, thereby increasing the electron density in the ionised plasma, against which the maser extends. The increase in free-free emission is amplified by the maser, which subsequently decays exponentially as the ionised plasma begins to recombine to reach equilibrium. The ionisation flux of the massive protostar in the system governs the decay process (van der Walt, 2011). Figure 2.9 is an illustration of the CWB scenario.

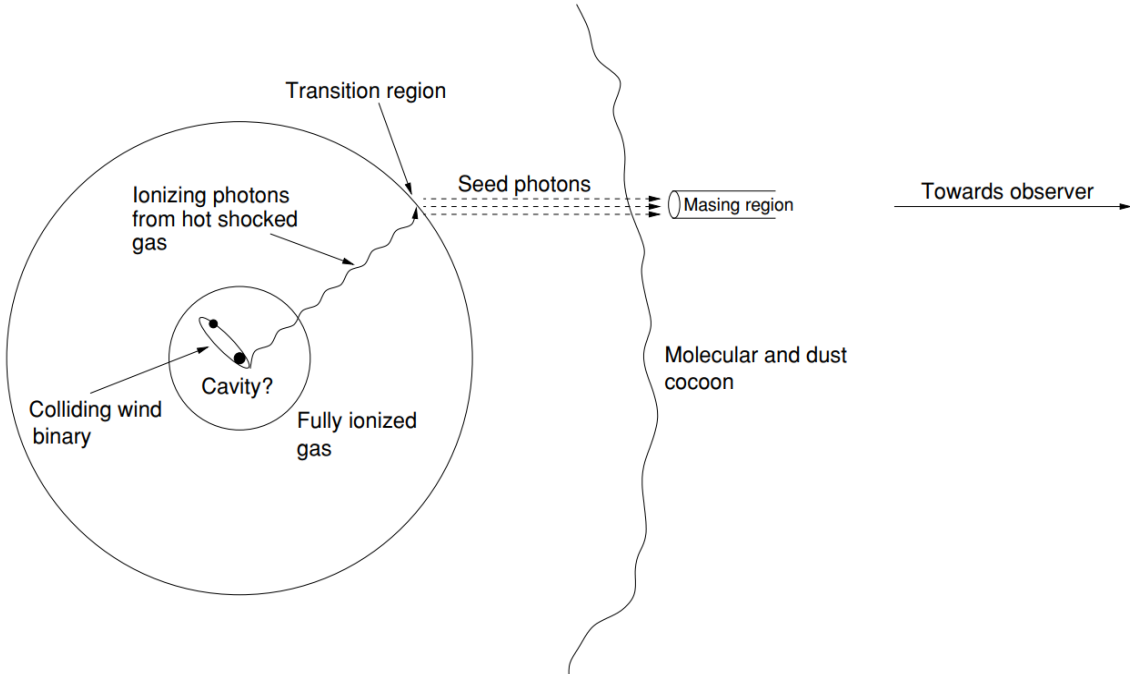


Figure 2.9: Illustration of CWB scenario. The observer sees a flare in the maser intensity which is modulated by the orbital motion of the binary system (van der Walt, 2011).

On the other hand, the periodic accretion model proposes a scenario where periodic accretion of matter from the circumbinary disks onto the protostar heats the dust particles, thus leading to an increase in the infrared radiation background. This leads to an increase in microwave amplification due to increase in the gain of the maser. This scenario would then explain both the observed timescales for the periodic masers and the duration of flares (Araya et al., 2010). According to the model, in binary systems, the periodic accretion could produce a periodic flare profile, which would be essentially dependent on the eccentricity of the binary system. Ignoring optical depth effects, a characteristic lightcurve is expected. van der Walt et al. (2016) suggested that the radiation illuminating a particular point on the inner edge of the circumbinary disk, e.g. the line of sight of an observer, is modulated by the orbital motion of the star as well as other emitting structures associated with the system. The modulation will be entirely geometric due to the time-dependent variations of $1/d^2$, where d is the distance between each star and the observer. The expected lightcurve is presented in Figure 2.10 in solid black lines.

Lightcurves have features describing a flared profile characterised by the gradual rise in amplitude from the first minimum to a maximum before gradually decreasing back to a second minimum. These flares appear to follow a Gaussian profile and are separated by periods of smaller flares with similar profiles. The second light curve, shown in the red line in Figure 2.10 traces a lumination made by a trailing spiral shock produced by the orbital motion of the stars. The light curve of this shock exhibits a slow rise in flux to a peak and then followed by a rapid decrease to a minimum. The peak is offset from the peak of the light curve produced by the star (van der Walt et al., 2016). The light curve resulting from the combination of both lightcurves is the dashed black line in Figure 2.10.

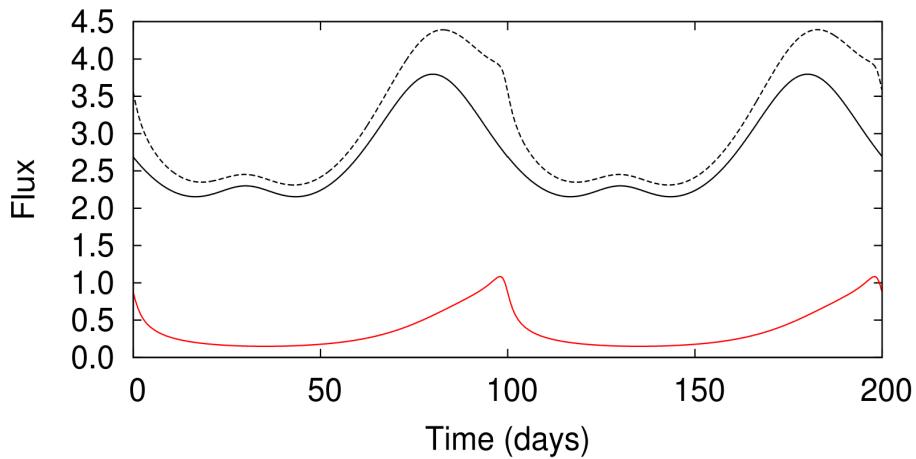


Figure 2.10: Expected lightcurve of periodic masers in a binary system as observed by an observer inclined at 70° . The solid black line shows the lightcurve of the maser. The red line shows the expected light curve due to illumination from a spiral shock produced by the orbit of the stars. The dashed black line is the expected maser lightcurve adding contributions from both illuminating sources (van der Walt et al., 2016).

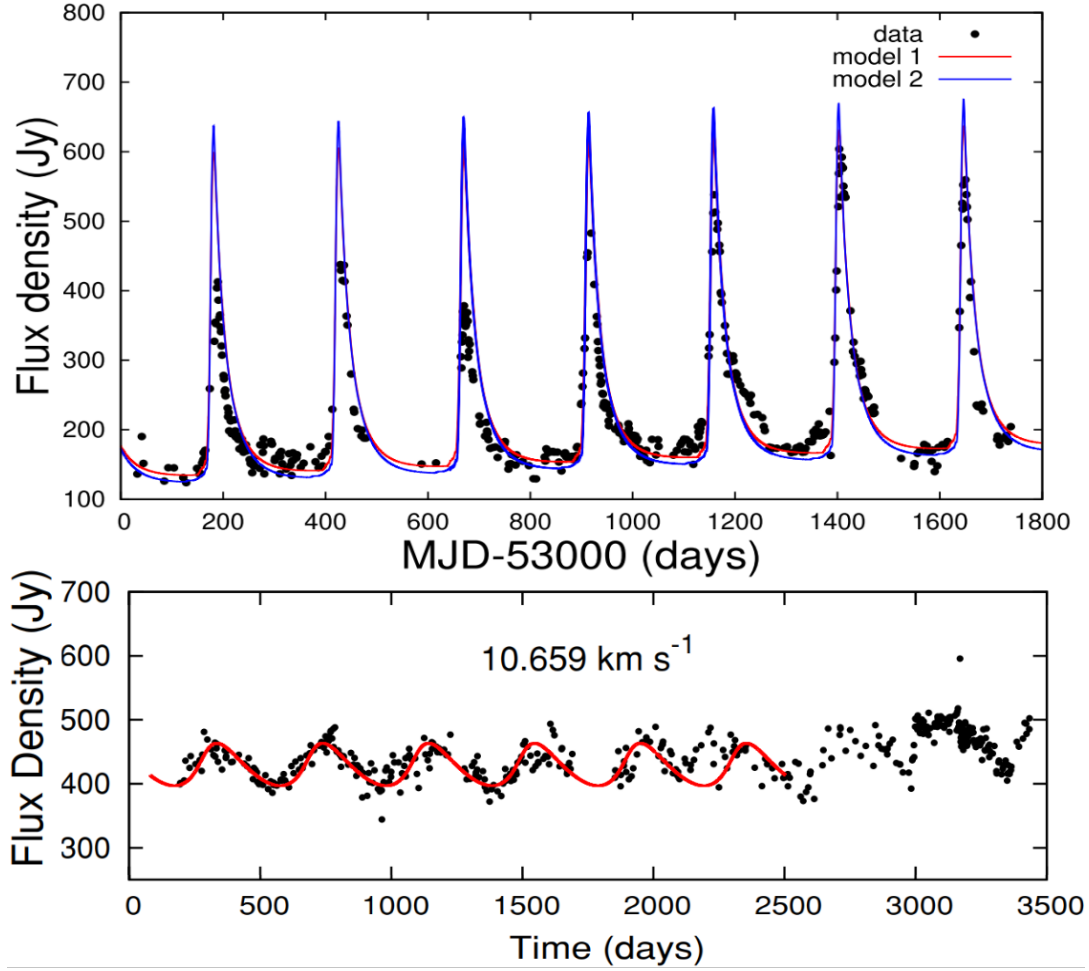


Figure 2.11: (Top panel) Lightcurves of class II methanol maser G9.62+0.20E showing the steep rise and exponential fall periodicity. The black points are the observed data. The blue and red lines are fits of the model based on CWB (van den Heever et al., 2019). Two CWB models have been fitted to the observational data. (Bottom panel) The lightcurve of 10.659 km s^{-1} feature of G188.95+0.89, showing a bunny hop profile. The red line is the fit of the CWB model to the observational data (obtained and adapted from van der Walt (2011)).

Parfenov and Sobolev (2014) also proposed a model to explain the periodic behaviour of methanol masers. The model is based on an accretion disc surrounding a binary system and rotating spiral shocks in the central cavity. These spiral shocks periodically change the radiation field in the disc and cause variations in dust temperature. The variations affect the pumping of methanol masers and produce maser variability. The radiation luminosity decreases as the spiral shock rotates and gas density decreases. However, this model has been disputed by van der Walt et al. (2016), arguing that it fails to accurately reproduce the observed light curves in many periodic methanol masers. A successful model would be required to explain and account for the light curve profiles of multiple periodic methanol masers.

Chapter 3

Radio telescopes and observational techniques

This chapter presents an overview of radio telescopes and how they operate. Single-aperture telescopes and the observational techniques relevant to them are covered, focusing on the HartRAO's 26-m telescope. The principles and techniques of radio interferometry and aperture synthesis are also introduced. The interferometers from which the data for this study was obtained are described in detail herein.

3.1 Fundamentals of radio telescopes

The construction of what is considered the first radio telescope was by Karl Jansky of Bell Laboratories in 1928. He built a directional radio antenna intended to locate the source of radio frequency noise present in long-distance telephone calls. Jansky discovered the noise was of extraterrestrial origin (Jansky, 1933). Inspired by Jansky's discovery, Grote Reber, a professional engineer, constructed a 30-foot parabolic antenna in 1937 and with it succeeded in mapping radio emission from the galaxy at 160 MHz (Sullivan, 2005). Generally, a radio telescope intercepts and measures the power of incoming radiation from astronomical sources, usually separating the radiation into two polarisation components. Radio telescopes are often characterised by their designs, particularly the shape of the reflectors, their optical layout, mounting systems, and their observing wavelengths. The primary reflectors of most modern radio telescopes are parabolic in shape, allowing for efficient collection and concentration of radiation. The paraboloid shape focuses all incident photons striking the reflector's surface onto a single point known as the telescope's focus. The most common optical configurations for parabolic primary reflector radio telescopes are the front feed/prime focus, the off-axis/offset feed, Gregorian, and Cassegrain configurations. Figure 3.1 shows some of the most common optical designs of radio telescopes.

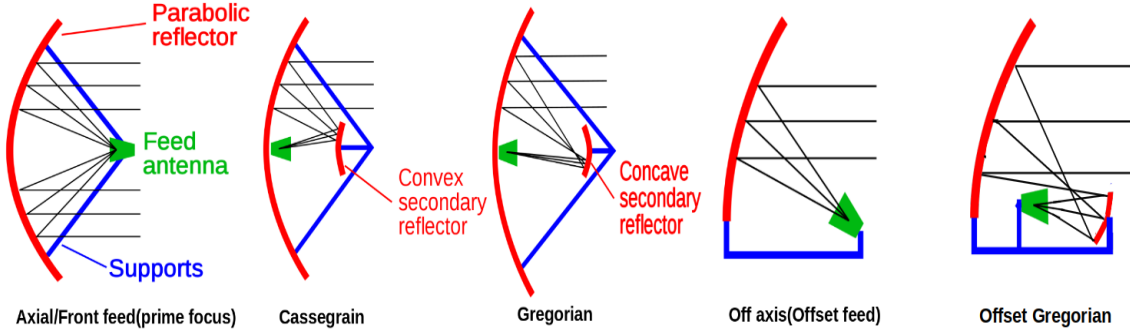


Figure 3.1: Common optical designs of radio telescopes (dapted and modified from Reeves (2022)).

The front feed system/prime focus telescope employs a parabolic primary reflector which focuses incoming radiation into a feed placed at its focus. The feed is often held in place by support structures. Front-end receivers and amplifiers can also be in tandem with the feed at the focus. Telescopes of Cassegrain design employ an additional reflector known as the sub-reflector. The sub-reflector, having a convex shape, is usually located at the focus of the primary reflector. Its purpose is to focus and redirect the focused radiation from the primary reflector into the feed, located at the centre of the primary reflector, or behind the primary reflector which will have an aperture at its centre. The Gregorian configuration is designed similar to the Cassegrain but with a major difference in the shape of the sub-reflector. The Gregorian configuration employs a concave sub-reflector to redirect the focused radiation into the feed.

The offset feed configuration employs an asymmetrical segment of the parabolic shape as its primary reflector. The feed is located to one side of the reflector and held in place by a support structure. Offset feed telescopes have the advantage of low blockage since the feed system is removed from the beam path. The offset Gregorian follows a similar design as the Gregorian but differs by its employment of a concave sub-reflector. The concave sub-reflector is located to one side of the primary reflector and refocuses the incoming radiation from the primary reflector onto the feed. The feed system in offset Gregorian configuration is located between the primary reflector and the sub-reflector.

The offset Gregorian system is now the most popular design, with next-generation telescopes such as MeerKAT, the SKA, and ngVLA all employing this configuration. The offset Gregorian configuration provides the collecting area with the least amount of obstruction. The discussion of the radio telescopes will now focus on prime-focused parabolic telescopes since all the telescopes used in this study employ this configuration.

A single-aperture prime-focused radio telescope often, referred to as a ‘single-dish’ telescope, consists of a primary reflector (dish), a transmission line, a receiver, and a computer for storing recorded signals for further analysis (Marr et al., 2020). Figure 3.2 depicts the basic setup of a prime-focus telescope and its components.

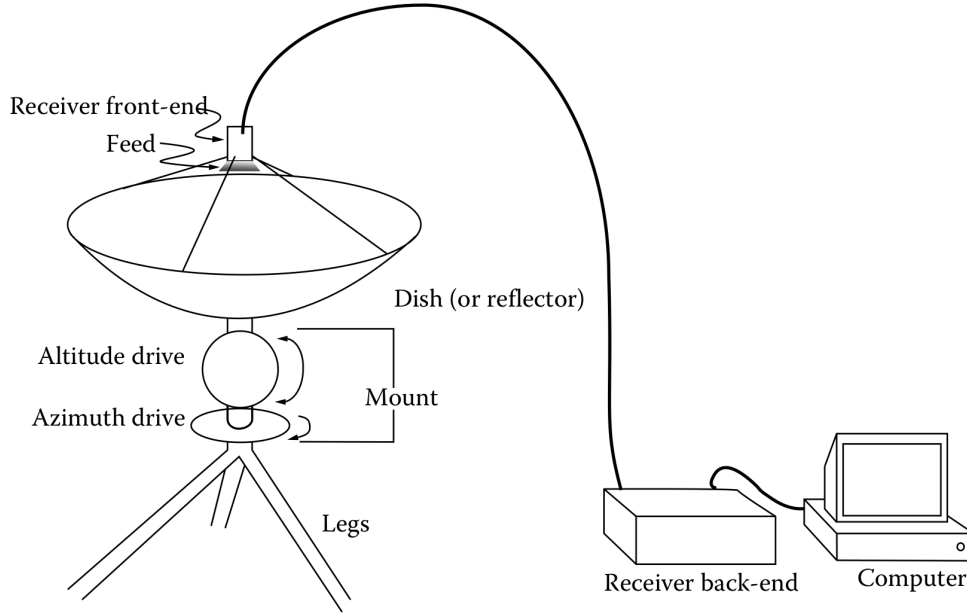


Figure 3.2: Basic components of a radio telescope (Obtained from Marr et al. (2020)).

A radio telescope’s mount system refers to how the telescope is oriented towards the sky and how it rotates on its axes. The equatorial mount and the azimuth-elevation (AZ-EL) mount systems are the most common telescope mount systems. Equatorial mounts rotate about the polar axes and the declination axes, while AZ-EL mounts rotate about the azimuth and elevation axes. Equatorial systems use the rotation of the Earth to track sources (Kitchin, 1995). A Feed couples electromagnetic radiation from free space into confined waves that are transmitted to the receiver via a transmission line. Transmission lines, usually made of coaxial cables or waveguides, can transmit EM waves along their lengths, allowing the electric and magnetic fields to oscillate sinusoidally in time and position along the lines, just as in free space. Since the feed already polarises the waves, two lines are required to provide the full received power (Wilson et al., 2013).

The receiver systems of radio telescopes can be separated into front-end and back-end components. The front-end systems are usually composed of splitters, filters, and mixers, while the back-end system is usually made up of converters, digitizers and correlators (Marr et al., 2020). Both parts contain several amplifiers. In operation, incident waves are focused onto a feedhorn where a polarisation splitter separates the waves into two circular polarisation components- the left circular polarisation (LCP) and the right circular polarisation (RCP). The polarised signals follow separate paths but undergo the same

processes. To simplify the discussion, we will focus only on one polarisation-RCP. The front-end receiver contains an amplifier which increases the amplitude of the waves by a value referred to as gain G . The gain is defined in terms of power by:

$$G = \frac{P_{out}}{P_{in}}. \quad (3.1)$$

The amplified signals are then converted into a lower frequency by a mixer. The local oscillator (LO) in a mixer generates a lower frequency wave at a fixed frequency and amplitude known as LO frequency. This wave is then ‘mixed’ with the incoming RF signal to produce a lower frequency wave than the input RF, but still retains all the properties of the input RF. This output frequency is in the form of a band known as the Intermediate frequency (IF) (Marr et al., 2020). Figure 3.3 illustrates the process of mixing.

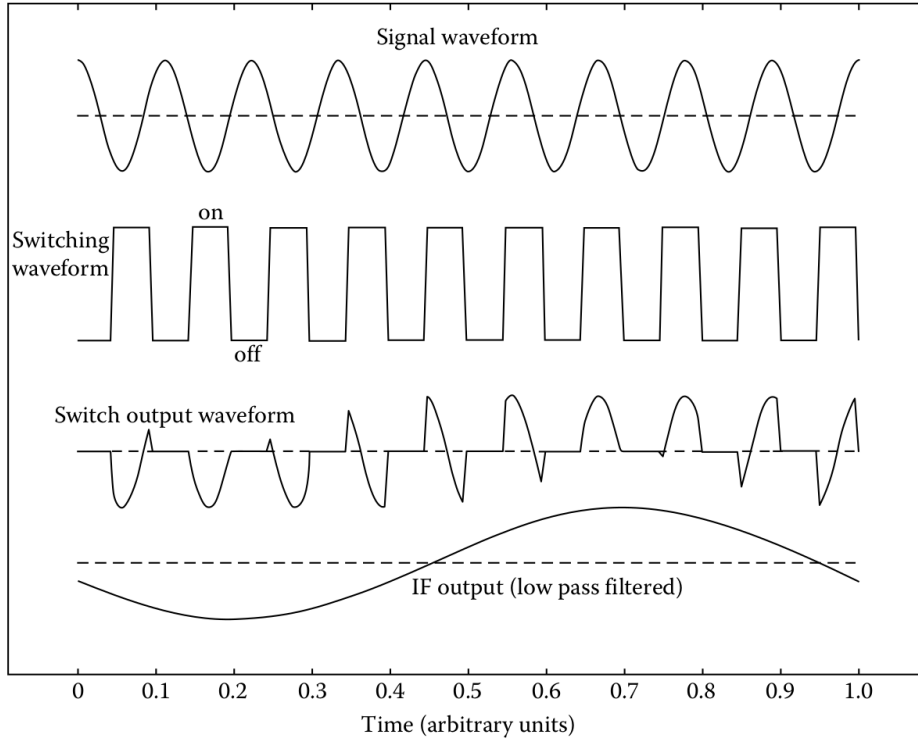


Figure 3.3: Schematic of an ideal mixer. The switching waveform is generated by the LO. The resulting mixed waveform (IF) is jagged and only smoothed by passing it through a low pass filter (Obtained from Marr et al. (2020)).

The back-end receiver system contains a radiometer and/or a spectrometer and a band-pass filter which defines the frequencies of interest and attenuates undesired signals. The radiometer comprises a square-law detector that produces currents proportional to the square of the electric field of the input wave (Burke and Graham-Smith, 2014). Current is passed through a resistor and the resulting voltage is determined by Ohm’s law, $V = E^2$. Assuming an EM wave of single frequency $E_o \cos(\omega t)$ enters the square law detector,

from Ohm's law:

$$V \propto (E_o \cos(\omega t))^2, \quad (3.2)$$

where V is the voltage, E_o is the amplitude of the electric current, ω is the angular frequency, and t is time. Applying trigonometric identity $\cos^2(A) = \frac{1}{2}[1 + \cos(2A)]$,

$$V \propto E_o^2 \frac{1}{2}([1 + \cos(2\omega t)]). \quad (3.3)$$

This output signal from the square law detector is then passed through a low-pass filter which removes the high-frequency variations (2ω) leaving just E_o^2 . The output voltage is then:

$$V = \alpha P, \quad (3.4)$$

where P is input power and α is the constant of conversion (responsitivity of detector).

The power measured from an astronomical source is usually denoted by its temperature equivalent referred to as antenna temperature (T_A). The sum of all the unwanted power is known as the system temperature (T_{sys}). The power generated by the receiver components which is often undesired is referred to as noise temperature (T_N).

Spectrometers are used for spectral line observations. Spectrometers divide the passband of line features into narrow frequency band channels. A spectrum is then produced which contains the measured full power in each band channel. There are two main types of spectrometers-analogue filterbank spectrometers (AFBS) and digital spectrometers (Wilson et al., 2013). Spectrometers are characterised by their bandwidth and spectral resolution:

$$\delta\nu \sim \frac{1}{\Delta t_{Interval}}, \quad (3.5)$$

where $\delta\nu$ is an infinitesimal length of bandwidth, and $\Delta t_{Interval}$ is the time interval.

Digital spectrometers measure the electric field of electromagnetic waves in time or frequency. They function by Fourier transforming (deconstructing) time variations in electric fields. The incoming signals are divided into two groups and sampled. After that, they are quantized and digitised. The digital data, which is a time series, is then Fourier transformed to obtain electric field variations with frequency $E(\nu)$, which is then squared to obtain the power spectrum, $P(V)$:

$$P(V) \propto [E(\nu)]^2. \quad (3.6)$$

The electric field must be sampled at minimum a rate twice the bandwidth of the radio waves, a method known as Nyquist sampling (Nyquist, 1928). Longer intervals contain more samples but are computationally intensive. Autocorrelation spectrometers overcome this challenge by implementing an autocorrelation function which 'auto' (self) correlates the electric field functions with itself. Output voltages are stored in computers or recorders for further processing and analysis (Burke and Graham-Smith, 2014).

3.2 Calibration of radio telescopes

3.2.1 Beam pattern

The antenna response or beam pattern is one of the key parameters that characterise a radio telescope. The beam pattern depicted in figure 3.4 represents the telescope's sensitivity as a function of the angle to the pointing direction. Beam patterns are non-uniform due to the directional variation in the telescope's ability to capture the incoming radiation power. The central part of the sensitivity pattern is known as the main beam, and the angular width measured at the point where the received power falls to one-half of the on-axis value, known as the half power beamwidth (HPBW) or full width at half maximum (FWHM) (Marr et al., 2020).

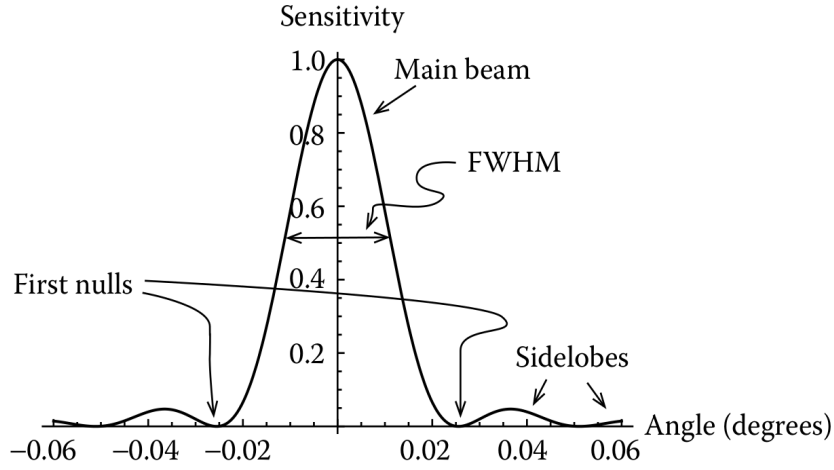


Figure 3.4: Sample sensitivity pattern for a circular 40-m telescope. The function is symmetric and normalized to unity where the telescope has maximum sensitivity (Obtained from Marr et al. (2020)).

The FWHM determines the angular resolution of a radio telescope. The observing wavelength, the feed illumination, and the diameter of the primary reflector determine the FWHM.

In practice, the main beam pattern, also known as an Airy pattern, can be approximated as a Gaussian profile by:

$$P_{main}(\theta) = \exp \left[-4 \ln 2 \left(\frac{\theta}{\theta_{FWHM}} \right)^2 \right], \quad (3.7)$$

where θ_{FWHM} is the FWHM of the main beam. The Gaussian function is analytically simpler and is a closer approximation to the main beam than a Bessel function.

The Fourier transform of a Gaussian function also produces a Gaussian function. The widths of Gaussian Fourier transform pairs are inversely related, thus the beam size is inversely related to the diameter of the primary reflector. Smaller beam sizes are normally required for discerning detailed structures and distinguishing sources with very small angular separation in the sky (Burke and Graham-Smith, 2014). Interferometry discussed in section 3.5 provides the highest angular resolutions in radio astronomy.

3.2.2 Pointing calibrations

A radio telescope's pointing accuracy degrades over time due to various factors such as wear and tear in gears and bearings of the mounting system, deformations of the primary reflector's shape and surface panels and support structure due to gravity, and non-uniform thermal expansion and contraction. As a result, the actual pointing position of the telescope and the intended position differ by a factor known as a pointing offset. The drift scan method (see section 3.3.1) can be used to correct these pointing offsets. Using the data from a drift scan, a pointing correction factor is derived, and applied to the measured amplitudes to obtain accurate flux density measurements. At HartRAO, drifts scans are used for calibration measurements, using only two pointing offsets - the north and south pointings.

The most common pointing correction method is the *five-point position correction observation* or simply a *five-point scan*. It is used for improving pointing accuracy on spectroscopic observations. During the five-point scan, the telescope is pointed at a total of five positions around and on a compact astronomical source, and antenna temperatures are recorded. These positions are North (T_A^n), South (T_A^s), East (T_A^e), West (T_A^w) and lastly On-source (T_A^{on}) position. The array of measurements is then fitted in two dimensions with a Gaussian function. The positions of the peak of the fitted function relative to the expected position are the pointing corrections. The pointing correction factor is computed with:

$$PC = \exp\left\{\frac{4 \ln 2}{HPBW^2} ([T_A^{ns}]^2 + [T_A^{ew}]^2)\right\}, \quad (3.8)$$

where HPBW is the half power point of the beamwidth (see section 3.2.1) and T_A^{ns} and T_A^{ew} is derived from the following formulae:

$$\begin{aligned} T_A^{ns} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^s}{T_A^n}\right|\right]^2\right\}, & T_A^{ew} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^w}{T_A^e}\right|\right]^2\right\}, \\ T_A^{ns} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^s}{T_A^{on}}\right| + \ln 2\right]^2\right\}, & T_A^{ew} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^w}{T_A^{on}}\right| + \ln 2\right]^2\right\}, \\ T_A^{ns} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^{on}}{T_A^n}\right| - \ln 2\right]^2\right\}, & T_A^{ew} &= T_A^{on} \exp\left\{\frac{1}{16 \ln 2} \left[\ln \left|\frac{T_A^{on}}{T_A^e}\right| - \ln 2\right]^2\right\}. \end{aligned} \quad (3.9)$$

Pointing correction depends on elevation hence radio telescope operators usually develop and automatically apply a *pointing model* that corrects the pointing offsets as a function of elevation as well as taking other factors as well into consideration. Over time, the pointing model degrades and is required to be updated regularly. For very long baseline interferometry (VLBI) observations, the most effective way to ensure accurate pointing is to observe a compact calibrator source close to the target source at the start of each observation and regular intervals throughout the observation (Maswanganye, 2018), and it is strictly applied to all VLBI observations. This is not strictly required for single-dish observations.

3.2.3 Sensitivity and flux density

A radio telescope's sensitivity or gain is an important factor in determining its ability to achieve a specific scientific goal. The sensitivity of a single-aperture telescope is known as its point-source sensitivity (PSS). It is given by the number of Kelvins measured per polarisation per flux density of the source, often having the units of Kelvin per Jansky (K Jy^{-1}) (Burke and Graham-Smith, 2014). For both circular polarizations, the PSS will be given as;

$$PSS_i = \frac{S_\nu/2}{K_s T_A^i}, \quad (3.10)$$

where S_ν is the observed flux, T_A^i is the antenna temperature, K_s is the source correction factor (1 for astronomical masers), and i is either *lcp* or *rcp*.

In practice the PSS is measured by observing bright continuum sources whose flux density is known. These bright continuum sources are often compact and are known as calibrators. Some examples of flux calibrators used for obtaining PSS values from single-dish telescopes are Virgo A, Hydra A, 3C123, and Jupiter (particularly for 22 GHz maser observations). Good calibrators have stable flux densities over long periods. The PSS enables the conversion of measured antenna temperatures to flux densities by :

$$S_\nu = \frac{2 * T_A K_s PSS}{2}. \quad (3.11)$$

Sensitivity can be improved through the upgrade of electronics such as receivers and spectrometers, as well as reflector surface upgrades.

3.2.4 System equivalent flux density (SEFD) and signal-to-noise ratio (SNR)

The power measured by a radio telescope is the summation of the signal from the astronomical source and the total receiver noise power. However, there are additional unwanted signal contributions. The term “noise” here refers to electrical signals generated

by electronic components that propagate through the receiver but are unrelated to the astronomical signal. A radio telescope's capacity to detect a given signal is largely determined by whether the signal is strong enough compared to the system noise. In Radio astronomy, the signal is required to be at least three times the root mean square (RMS) of the noise (3σ detection) (Wilson et al., 2013). This ratio is known as the signal-to-noise ratio (SNR). For switched observations, the uncertainty in power measured $\sigma(T_A)$ is:

$$\sigma(T_A) = 2 \frac{T_{sys}}{\sqrt{\Delta t_{obs} \Delta \nu}}, \quad (3.12)$$

where Δt_{obs} is the total observation time, T_{sys} is the system temperature, and $\Delta \nu$ is the bandwidth of the observation.

Not all light incidents on a primary reflector make it into the transmission lines, some of the signals are lost via shadowing, blockages due to feed system supports, surface irregularities, and spillover. A dimensionless quantity, known as the antenna efficiency, is used to quantify the total surface area that effectively focuses radiation into the feed system. This surface area is referred to as the antenna's effective collecting area (A_{eff}) and is always smaller than the antenna's geometric area (Wilson et al., 2013). The RMS uncertainty; in the antenna temperature can be converted into RMS uncertainty in the flux density, $\sigma(F_\nu)$ with:

$$\sigma(F_\nu) = \frac{2k}{A_{eff}} \left[2 \frac{T_{sys}}{\sqrt{\Delta t_{obs} \Delta \nu}} \right], \quad (3.13)$$

where A_{eff} is the antenna's effective collecting area.

Before planning an observation, the minimum SNR that will meet the science goal(s) is determined. This can then be scaled to a minimum flux density that can be detected for a given SNR with:

$$F_\nu(min) = SNR \left(\frac{4k}{A_{eff}} \frac{T_{sys}}{\sqrt{\Delta t_{obs} \Delta \nu}} \right). \quad (3.14)$$

An alternative way of estimating the minimum detectable flux density is through the system equivalent flux density (SEFD). SEFD is a quantity that can be described as the flux density a compact astronomical source must have to produce an antenna temperature which is double the system temperature (Wrobel and Walker, 1999). It is given by:

$$SEFD = \frac{2k}{A_{eff}} T_{sys} = \frac{k}{A_{eff}} (2T_{sys}). \quad (3.15)$$

Equation 3.14 can then be written in terms of SEFD as

$$F_\nu(min) = SNR \left(2 \frac{SEFD}{\sqrt{\Delta t_{obs} \Delta \nu}} \right). \quad (3.16)$$

The SEFD combines the intrinsic sensitivity of the telescope with the measure of the noise in the observation T_{sys} , which depends on frequency, weather, and receiver temperature.

The SEFD allows for setting parameters A_{eff} and T_{sys} during the planning of observations. The system noise can be significantly reduced by cooling the receivers. Six of the seven HartRAO 26-m telescope's receivers are cryogenically cooled.

3.3 Single-dish observation techniques

There are two major observational configurations for single-dish observations, namely single-dish observations and interferometric observations. The techniques of single-dish observations are introduced and discussed in this section.

3.3.1 Drift scans

In practice, a drift scan (Figure 3.5) is performed by positioning the telescope in the sky but at an hour-angle ahead of a source's position, where the target source will transit or 'drift' through the telescope's beam after a short time due to the rotation of the Earth. The result is a one-dimensional slice pattern (T_{ant} vs Time) that can be described by a sinc or Gaussian profile. A noise diode with a known temperature is turned on and off before the source enters the telescope's beam. When the source passes through the centre of the beam, the maximum power is measured. Because the noise diode's temperature is known, the measured temperatures can be converted to Kelvin.

3.3.2 Bandpass calibration

During spectral-line observations, the shape of the receiver's bandpass spectrum is usually not levelled. This is due to contributions from electronic noise and changes in weather conditions. However, to have accurate flux scaling, the bandpass needs to be flattened. The process of flattening the bandpass response is known as bandpass calibration. The position and frequency switching techniques discussed herein allow for bandpass calibration. To perform bandpass calibration, a 'baseline' is subtracted from the difference spectrum. Often a linear function of frequency such as an n th-order polynomial is fitted and subtracted from the data. For bandpasses with curvature, second or higher-order polynomials are fitted. The total power can then be multiplied by the PSS to obtain flux densities.

Position switched observations

Noise dominates the power measured by a single-dish radio telescope. Noise generated by the receiver's electrical components, background radiation from the sky such as the cosmic microwave background (CMB), noise due to the wavelength of observation, thermal

radiation from the ground, radiation from the dish itself, and other observation particulars all adds up to the total power measured.

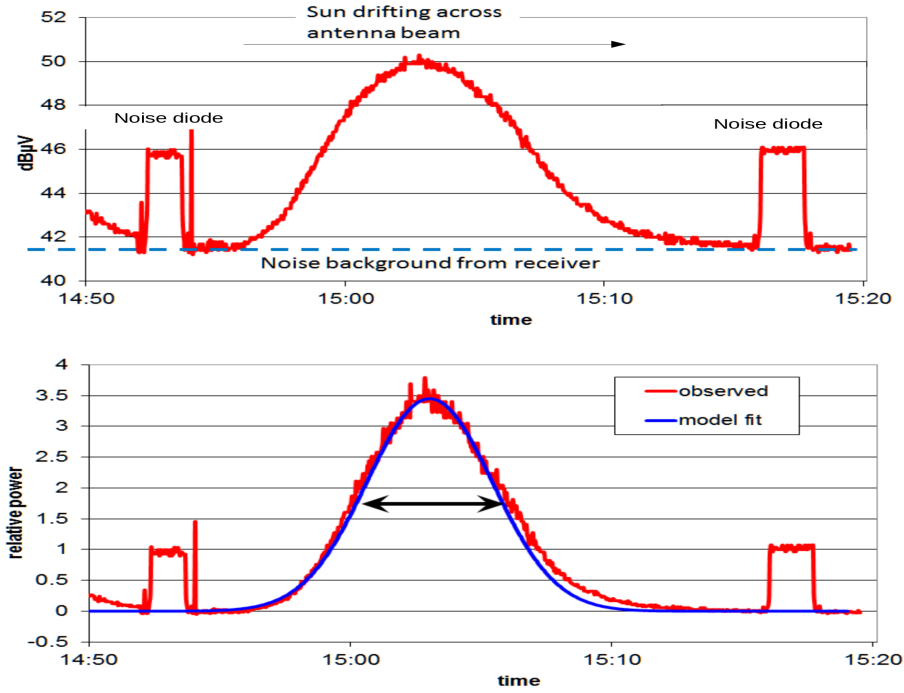


Figure 3.5: (Top) Sample continuum drift scan of the sun observed at 11 GHz with 1.2-m ESA-Dresden Radio Telescope. The noise diode calibrator is shown switched on and off at the start and end of the observation. Measured power does not start from zero due to the contributions of the system temperature T_{sys} . These contributions are eliminated by fitting a suitable polynomial to the baseline and subtracting it from the data. (Bottom) Gaussian model fit of the data with the HPBW indicated with black arrows (<https://portia.astrophysik.uni-kiel.de/koeppen/ue7e/sundrift.html>).

To correct this and determine the amount of power solely due to the target source, noise and other sources of unwanted radiation must be subtracted (Crane and Napier, 1986). Position switching is a technique in which the antenna's direction is alternated between the target source and a nearby region of sky free of emission. If we denote the voltage recorded when the antenna is pointed on-source as V_{on} and the voltage recorded when the antenna is pointed off-source as V_{off} , the V_{on} and V_{off} can be expressed as:

$$V_{on} = \alpha G k \Delta\nu (T_A + T_{sys}), \quad \text{and} \quad V_{off} = \alpha G k \Delta\nu T_{sys}, \quad (3.17)$$

where α is the responsivity of the detector and has units of V/W, G is the dimensionless total receiver gain, k is Boltzmann's constant, and $\Delta\nu$ is the observing bandwidth.

Subtracting Equation V_{off} from V_{on} ,

$$V_{on} - V_{off} = \alpha G k \Delta\nu T_A. \quad (3.18)$$

To determine T_A , only the conversion factor $\alpha k \Delta \nu$ must be determined to convert between temperature and voltage, which is accomplished by calibrating the system temperature. The gain G varies throughout the observing period. Consequently, due to $V_{on} - V_{off}$ being a tiny fraction of the V_{on} , small variations in G which can cause a small change in V_{on} translate to large errors in $V_{on} - V_{off}$. Regular V_{off} and V_{on} observations mitigate the large error generation caused by gain variations. Switching must occur faster than any power variations. There are two main types of switching, namely, position switching and beam switching. During position switching, the entire telescope is moved to point in a blank patch of the sky (an area free of strong emission) and then moved back onto the source's position. During beam switching only the sub-reflector is moved slightly, resulting in the pointing direction veering off the source. Switching times are strongly influenced by the frequency and observing conditions. Position switching is usually done on $10 \sim 30$ s timescales, while beam switching is done on sub-second timescales (Marr et al., 2020).

Frequency switched observations

Changing the pointing direction during observations by moving the telescope as in the case of position switching can consume valuable observing time. Instead of moving the telescope on and off-source, the frequency switching method works by slightly shifting the observing frequency via changing the LO frequency on and off the spectral line. This can be done rapidly and without affecting the observation since spectral lines are only present in a narrow range of frequencies. System noise and atmospheric contributions can be easily identified and removed since they contribute equally to both frequency settings. In the case of a very narrow linewidth, absence of other lines and wide receiver bandwidth, the spectral line does not have to be shifted out of the observing passband but rather to another part of the passband. This allows for the *on*-and-*off* observations in one part of the passband to be the *off*-and-*on* observations in the other part, respectively. The *on* and *off* channels alternate between containing spectral lines, acting as *on*-scans, and containing only noise, acting as *off*-scans, which increases the sensitivity of the observations.

Frequency switching can lead to a doubling in *on*-source time and is often a factor of $\sqrt{2}$ more sensitive than position-switched observations (Marr et al., 2020). Frequency switching was employed in all the HartRAO maser observations used in this study. The central observing frequency was shifted left and right. This generates corresponding power measurements P_l and P_r respectively. To obtain the total power spectrum the two are combined to;

$$P_{Total} = \frac{P_l - P_r}{P_r} T_{sys}, \quad (3.19)$$

where T_{sys} is in the units of Kelvin and converting total power to Kelvins.

3.4 Design and operation of the HartRAO 26-m telescope

The Hartebeesthoek Radio Astronomy Observatory (HartRAO) is located in the valley of the Witwatersrand mountain range 65 km from Johannesburg in South Africa. HartRAO is equipped with a 15-m diameter Azimuth-Elevation mounted telescope and a 26-m equatorial mount Cassegrain-type radio telescope built by Blaw Knox in 1961. This discussion will be limited to the 26-m telescope since it was the only HartRAO telescope used in this study. The 26-m telescope was initially part of NASA's deep-space tracking network until 1975 when it was converted into an astronomical telescope. The primary reflector is parabolic; having a 3-m diameter hyperboloid sub-reflector mounted at its focus by four quadrupod legs serving as a secondary reflector. Figure 3.6 shows the HartRAO 26-m telescope.

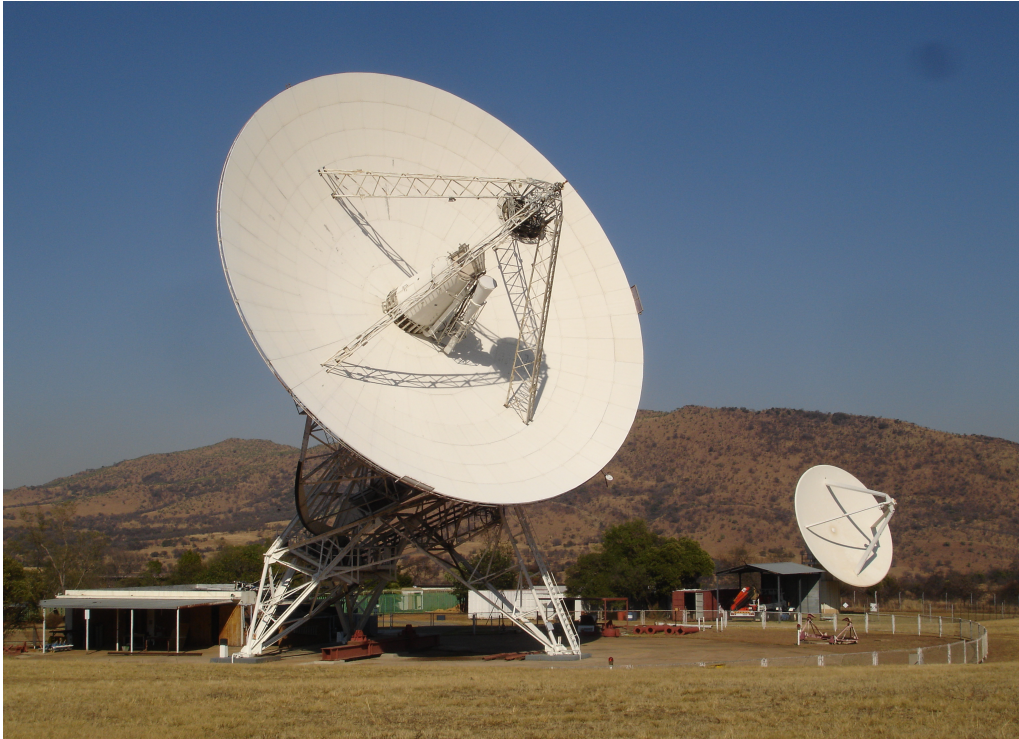


Figure 3.6: The HartRAO 26-m telescope with the HartRAO 15-m telescope by its side. Source: <http://www.hartrao.ac.za/gallery/>

The telescope is fitted with seven receivers, six of which are cryogenically cooled high electron-mobility transistor (HEMTS) receivers operating at 1.3, 4.5, 5, 6, 13 cm and 18 cm wavelength (MacLeod et al., 2021). The 2.5 cm receiver is an uncooled pseudomorphic high electron-mobility transistor (pHEMT) receiver. The receivers are dual circularly polarised into two feeds per receiver (RCP and LCP). The 1.3 cm and 4.5 cm receivers are mainly used for observing 22 GHz and 6.7 GHz methanol masers, respectively. Table 3.1 contains the specifications of the HartRAO 26-m telescope.

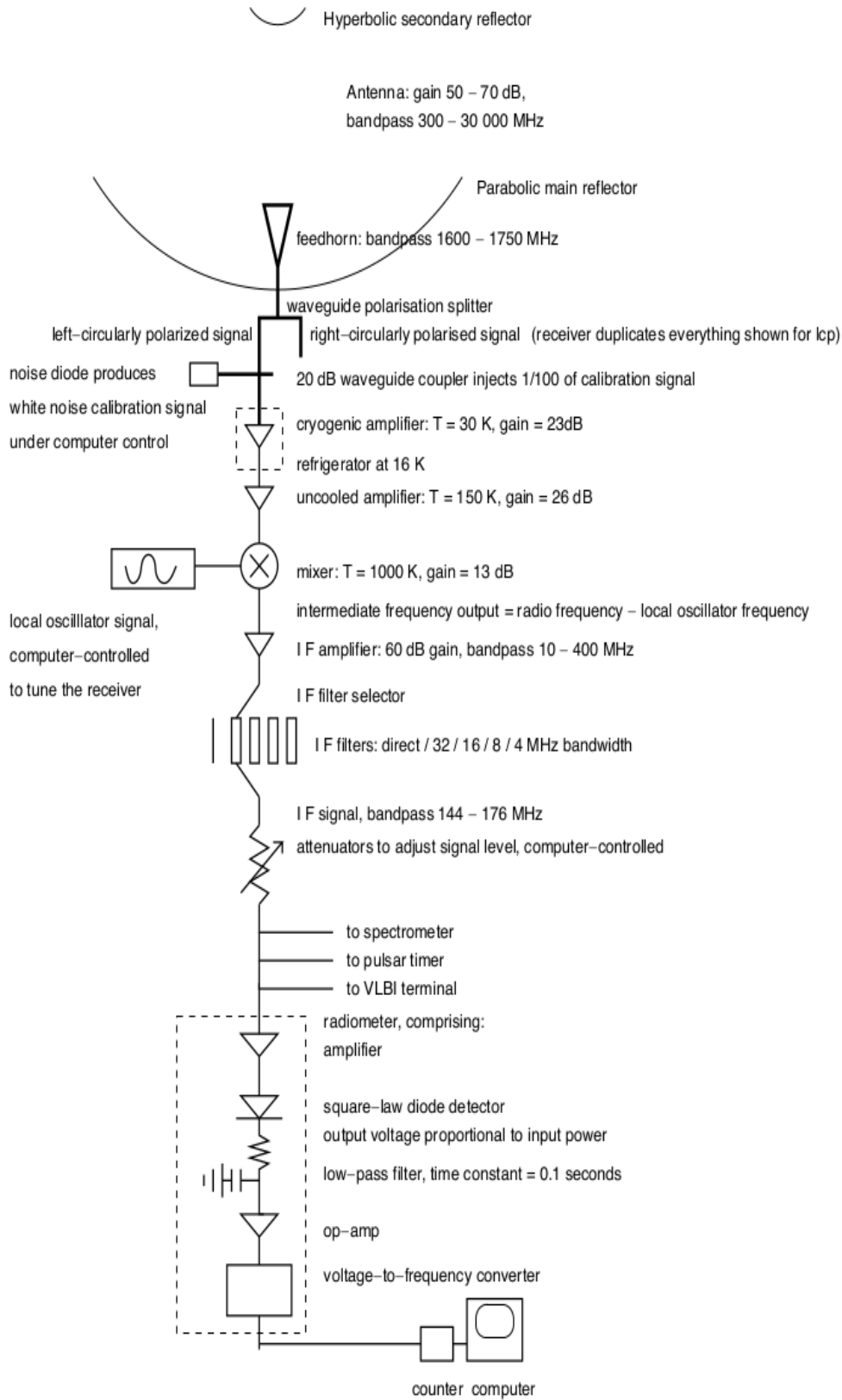


Figure 3.7: Typical signal processing chain of a single-dish radio telescope. A hydrogen maser is used as a frequency standard for the HartRAO 26-m telescope (Gaylard, 2010)

Table 3.1: Specifications of the HartRAO 26-m radio telescope.

Parameter	Value
Diameter	25.914 m
Receiver Feed	Cassegrain
Focal length	10.886 m
Focal Ratio	0.42
Main reflector Surface Accuracy (RMS)	0.5 mm
Mount Type	Offset Equatorial
Pointing resolution	0.001°
Pointing repeatability	0.004°
Short Wavelength Limit	1.3 cm
Slewing rate on each axis	0.5° s ⁻¹

In operation, the signal processing chain of the HartRAO 26-m telescope follows a path similar to the one illustrated in Figure 3.7. Incoming radiation from a source is collected by the primary reflector and focused onto the secondary reflector. The signal is focused onto a feedhorn and waveguide polarisation splitter, which separates the signal into RCP and LCP. White noise is injected into both polarised signals as a calibration signal. The signal is fed into a mixer which couples each signal, with a signal produced by a local oscillator (LO), in a process known as downconversion. Downconversion reduces signal attenuation as it travels through coaxial cable transmission lines. The output signals, in the form of intermediate frequencies (IFs), are then filtered and amplified again before being dispatched for additional mixing and filtering in a room located at the base of the 26-m main reflector known as the dec room. The signal is transferred from the dec room to a control room, which houses a radiometer, a spectrometer, a VLBI terminal, and a pulsar timer. For maser observations, a radiometer and a spectrometer are used. The radiometer is a square-law diode detector that produces a proportional output voltage by squaring the amplified input signals from both polarisations. The spectrometer converts the voltages to frequencies before segmenting the passband into narrow frequency ranges and measuring the power in each channel. Finally, the signal is further amplified and fed into a counter, which records the voltages as ‘counts’ and stores them in a computer.

The 26-m telescope’s data acquisition system consists of a Digital Base Band Converter (DBBC) terminal and an e-transfer-capable MARK5B+ magnetic recorder. The data is usually stored in the Flexible Image Transport System (FITS) (Wells et al., 1981) format. HartRAO’s spectroscopic research focuses on observing and monitoring astronomical masers (Gaylard and Nicolson, 2007). HartRAO’s ongoing maser monitoring programs regularly observe 6.7 GHz methanol masers, 4.7 and 6 GHz hydroxyl masers, and 22 GHz water masers. Between 1999 and 2003, a 256-channel spectrometer was upgraded to a 1024-channel spectrometer. The primary reflector’s surface was also upgraded between 2003 and 2004, increasing the telescope’s sensitivity (Goedhart et al., 2007). Table 3.2 lists the specifications of HartRAO’s 1.3 cm and 4.5 cm receivers used in this study.

Table 3.2: Specifications of 4.5 cm and 1.3 cm receivers of the HartRAO 26-m telescope

Band	4.5 cm	1.3 cm
Feed horns	1 × diagonal + parallel-plate polarizer	1 × circular
Amplifier and polarization	cryogenic HEMT, LCP & RCP	cryogenic HEMT, LCP & RCP
Standard Frequency (MHz)	6670	23000
Lower and upper-frequency limits (MHz)	6008, 6682	22000, 24000
Receiver Bandwidth (MHz)	660	2000
Beamwidth: full width at half max. (degrees)	0.113	0.033
Minimum system temperature at Zenith (K)	57	45
Point Source Sensitivity per polarization (Jy/K/Pol)	5.1	6.17
System Equivalent Flux Density SEFD (Jy)	700	900
Beamwidth: between first nulls (degrees)	0.32	0.073

3.5 Interferometry and image synthesis

High angular resolution observations are essential to the study and understanding of star formation. However, due to cost and available technology, there is a limit on the constructibility and size of extra-large single-dish telescopes (Marr et al., 2020). The development of radio interferometers helped overcome this handicap. Interferometry refers to the technique of combining two or more radio telescopes separated by an accurately known distance, called a baseline $\vec{b}$, to observe the same source and measure the Fourier transforms of the source, which is then inverted to produce maps of brightness distributions (Wilson et al., 2013). The light collected by each antenna is combined with that collected by other antennas, which generates interference and a beam pattern known as the synthesised beam. The resolution of an interferometer is given by:

$$\theta \approx \frac{\lambda}{\vec{b}_{max}}, \quad (3.20)$$

where λ is the central observing wavelength and $\vec{b}_{max}$ is the baseline vector of the maximum separation between the telescopes. The maximum baseline $\vec{b}_{max}$ will determine the highest angular resolution of the interferometer. An interferometer's ability to detect faint astronomical sources depends on the total area available to collect incoming radiation, which is the sum of the effective collecting areas of all antennas in the array (Crane and Napier, 1986). To highlight the fundamental principles, only a two-element interferometer will be discussed from this point onward. Figure 3.8 illustrates a two-element interferometer.

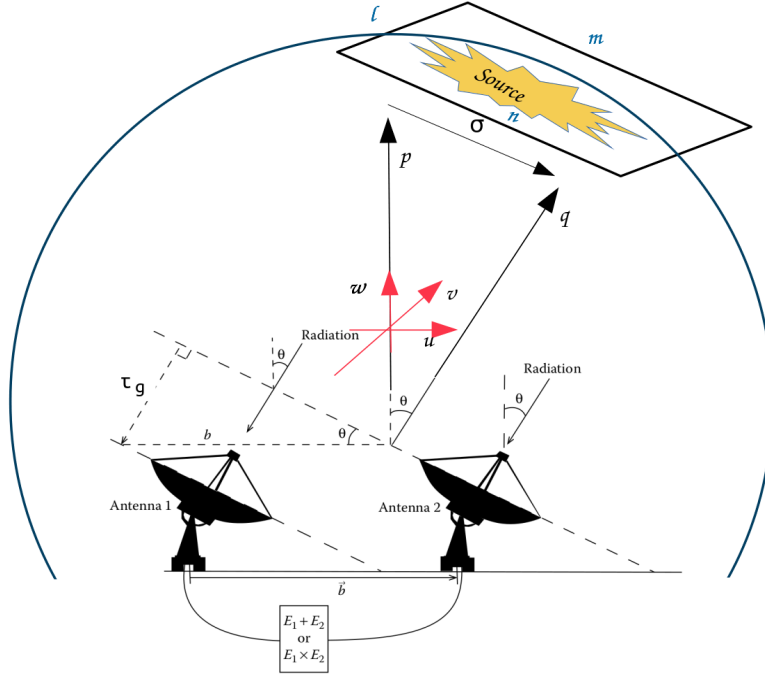


Figure 3.8: Schematic of a two-element interferometer. The u , v , w axis is the telescope's plane and the l , n , m plane is the sky plane (Modified from Marr et al. (2020)).

A radio source at a position l, m , and n in the sky, will produce an electric field $\vec{E}(t)$ that varies with time. The interferometer located on the ground has coordinates u, v , and w . The voltages measured by the two antennas respectively are:

$$V_1 = v_1 \cos 2\pi\nu(t - \tau_g) \quad \text{and} \quad V_2 = v_2 \cos 2\pi\nu(t), \quad (3.21)$$

where v_1 and v_2 are the amplitudes of the wave, τ_g is the geometric delay, which is the delay due to geometry defined by $\tau_g = \vec{b} \cdot (p + \sigma)/c$, p is the phase referencing position, and σ is the offset vector.

There are two main signal combination methods by interferometers. Signals can be combined by adding ($E_1 + E_2$) and averaging the signals in time (additive interferometer), or signals are cross-correlated where the product of the two signals ($E_1 \times E_2$) are averaged in time (cross-correlating interferometer). Although the outputs of both methods are similar, cross-correlated outputs have a significant advantage over additive interferometers hence most modern correlators are cross-correlation type (Burke and Graham-Smith, 2014).

The measured voltages are multiplied and averaged in time by the correlator. The correlation of electric fields at different locations is called complex visibility, given by;

$$\mathbf{V}_{1,2} = \iint I(l, m) \frac{e^{-2\pi i \nu [ul + vm]}}{[1 - l^2 - m^2]^{\frac{1}{2}}} dl dm. \quad (3.22)$$

The intensity $I(l, m)$ is the Fourier transform of the complex visibilities $\mathbf{V}$. For more than two element interferometers, the complex visibilities of each baseline will be $V_{i,j}$. $S(u, v)$ is the sampling function of the visibilities $\mathbf{V}(u, v)$ arising from the gaps in the u - v plane. The Fourier transform of the sampling function and the visibility is known as the dirty image (Crane and Napier, 1986), given as:

$$I^{(Dirty)}(l, m) = \iint \mathbf{V}(u, v) S(u, v) e^{2\pi i \nu [ul + vm]} du dv, \quad (3.23)$$

where $I^{(Dirty)}$ is the dirty image, $\mathbf{V}(u, v)$ is the visibility, and $S(u, v)$ is the sampling function.

Furthermore, the convolution theorem (Briggs et al. (1999)), which states that the Fourier transform of the product of functions or signals is the convolution of the Fourier transforms, implies that the dirty beam is the convolution of the sky intensity distribution, I , and the synthesized beam, which is also known as the point spread function (PSF);

$$I^{(Dirty)} = I \otimes PSF, \quad (3.24)$$

where the PSF of the sampling function is:

$$PSF(l, m) = \iint S(u, v) e^{2\pi i \nu [ul + vm]} du dv. \quad (3.25)$$

In practice, the u - v coverage is the sampling function of the sky and is formed as the baselines in the u - v plane track the target source in the l - m plane, using the earth's rotation. Sampling functions can be improved by adding more telescopes or increasing the number of scans (Marr et al., 2020). Calibrators, typically compact point sources with stable flux densities and known distances and positions (e.g. quasars), are observed during interferometric observations. They allow for the amendment of expected anomalies such as phase delays, radio frequency interference, and atmospheric aberrations. A flux calibrator (primary calibrator) is used to scale the amplitude. A phase calibrator (secondary calibrator) is used to determine the amplitude and phase variations of baseline-based complex gains. For calibrating the bandpass, a bandpass calibrator is observed (Fomalont, 1999). Figure 3.9 shows the u - v track and resulting Point Spread Function (PSF) of the Korean VLBI Network (KVN) and VLBI Exploration of Radio Astrometry (VERA) combined array known as the KAVA telescope array located in Korea and Japan. A better sampling function will produce higher-quality images as seen in Figure 3.9.

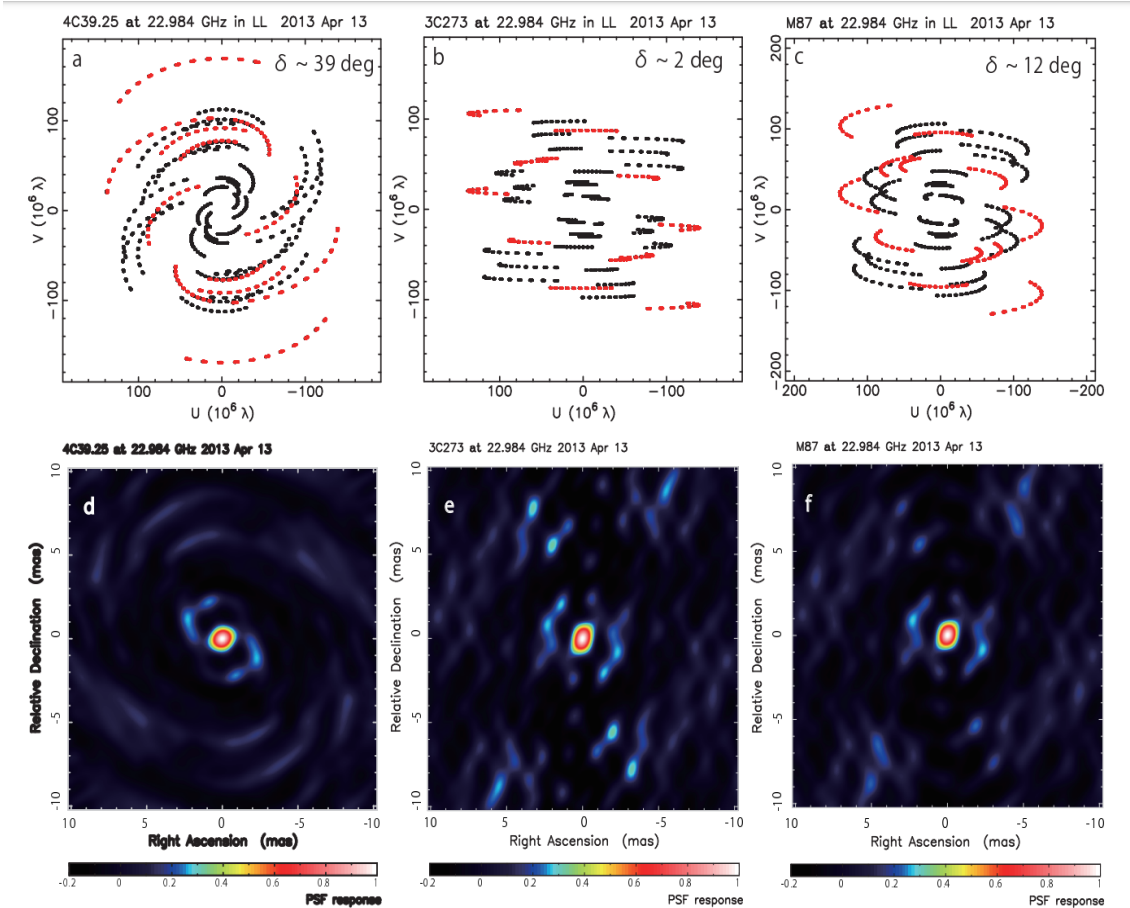


Figure 3.9: KAVA uv -coverage at various elevations (top) derived from observing 4C39.25, 3C 273, and M87 at 23 GHz at elevations 39, 2, and 12 degrees and the resulting point spread function (PSF). Red points in uv -track are those derived from the VERA array only. The observations were performed by 11 scans 6 minutes in length and at intervals of 30 minutes for a total observing time of 6 hours. Figure taken from Niinuma et al. (2014)

3.5.1 Deconvolution and imaging

Interferometric data is edited and calibrated prior to imaging to remove anomalous sections of the data, after which the dirty image is deconvolved to produce the actual sky intensities. Högbom's CLEAN algorithm (Högbom, 1974) is commonly used for deconvolution. The Högbom algorithm's deconvolution process can be divided into six main steps:

1. Locating the position and value of the peak intensity in dirty image.
2. Generates a point source from the product of the dirty beam, peak strength, and damping factor.
3. Subtracts the point source from the dirty image at the peak position.
4. An accumulation model of intensity is then generated, which consists of the position and point source.
5. Steps 1-4 are repeated in sequence until a peak strength threshold, specified by the user, is reached in the dirty image.
6. Finally, a CLEAN image is produced from the convolution of the accumulated model.

A dirty image residual is generated and added to the clean image, which can provide information on noise and sidelobe levels. There are other CLEAN algorithms like Cotton-Schwab (Briggs et al., 1999) and Clark (Clark, 1980) that improved Högbom's algorithm. The most common software for calibrating and deconvolving radio interferometric data are MIRIAD (Sault et al., 2011), AIPS (Greisen, 2003), and CASA (McMullin et al., 2007). Radio interferometers currently offer the highest angular resolution of any ground-based telescope. Low angular resolution is incapable of resolving young stellar objects (YSOs) due to the clustering of protostars in their natal clouds. Interferometers provide the needed high resolution and sensitivity for studying the core sizes of a few astronomical units (Dall'Olio, 2020). Interferometers, such as ALMA, will be described in the next section and are able to provide sub-arcsecond resolutions, enabling observations of circumstellar disks (1 AU scales) around protostars.

3.6 Radio interferometers utilised in this study

This section introduces the interferometers used in the study, including their design and capabilities.

3.6.1 Design and signal processing of ALMA

The Atacama Large Millimetre/submillimetre Array (ALMA) is a re-configurable radio interferometer located on the Chajnantor plateau of the Atacama desert in Chile at an elevation of 5000 m. Construction began in 2002 and achieved its first light in 2011 (Wootten and Thompson, 2009). The location of ALMA is conducive for sub-millimetre observations due to insignificant water vapour precipitation and cloud cover, which, when present, will attenuate millimetre and sub-millimetre wavelength radiation. The location is also advantageous for being free of light pollution and radio interference due to human activity (Dall’Olio, 2020). ALMA’s wavelength range is 0.3-10 mm (950 GHz-30 GHz). ALMA consists of 66 high-precision antennas spatially distributed in various configurations. ALMA consists of two key observing arrays. A compact array consisting of 16 fixed antennas known as the ALMA Compact Array (ACA) and an extended array consisting of 50 movable 12-m antennas. ALMA in a compact and extended configuration, offer maximum baselines of 150 m and 16 km, respectively (Hills and Beasley, 2008). Out of the 16 antennas of ACA, 12 are 7 m in diameter and 4 are 12 m in diameter. All ALMA antennas have altitude-azimuth mounts with quadripod mounting for sub-reflectors (Iguchi et al., 2009). The baseline range of ACA is 9-32 m. Figure 3.10 shows the layout of ALMA with the top right panel, showing the compact distribution of ACA’s antennas.

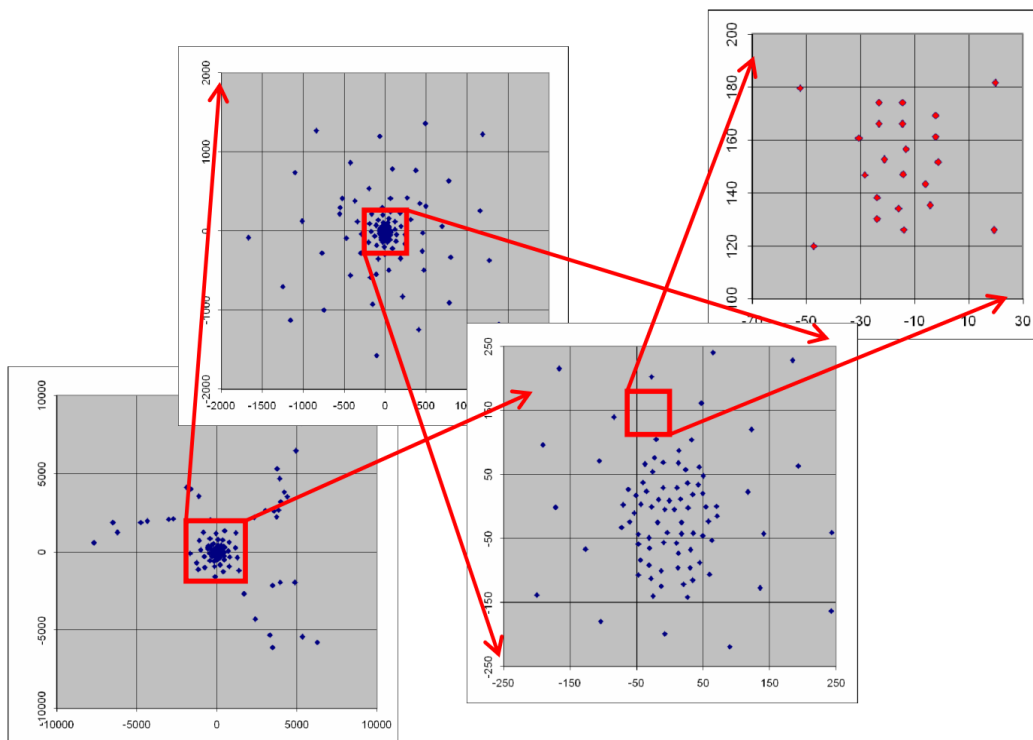


Figure 3.10: ALMA’s antenna layout: combined array (bottom left) and red points (top right) showing ACA antenna positions. The scales are in meters. Figure obtained from Hills and Beasley (2008).

ACA enhances the sensitivity of ALMA to low brightness and extended sources. ACA is useful for resolving faint components which cannot be observed with the extended array. Four ACA antennas are total power antennas equipped with special rapid-moving sub-reflectors which enable sky subtraction. The surface accuracy of the ACA's antennas is kept below 25μ rms, with their pointing accuracy maintained at $2''$ rms (Wootten and Thompson, 2009). Table 3.3 shows the specification of the ALMA antennas.

Table 3.3: ALMA antenna specifications.

Parameter	12-m antenna	7-m antenna
Main reflector diameter	12 m	7 m
Number of elements	54	12
Sub-reflector diameter	0.750 m	0.4569 m
Primary focal length	4.800 m	2.5717 m
Geometric blockage	$< 3\%$	$< 5\%$
Surface accuracy	$< 25\mu\text{m rms}$	$< 20\mu\text{m rms}$
Aperture efficiency at 675 GHz	> 0.45	> 0.50
Offset pointing	$< 0''6\text{ rms}$	$< 0''6\text{ rms}$
Max angular resolution	$0.015'' \times \lambda(mm)$	$5'' \times \lambda(mm)$
Spectral channels	4096 per IF	4096 per IF
Total collecting area	6600-7700 m ²	462 m ²

ALMA is fitted with cryogenically cooled dual-polarisation receivers. ALMA's full frequency band is split into 10 bands; each band has a bandwidth of $\sim 25\%$. The receiver noise is in the range of 0.2 to 0.3 K times the observing frequency. ALMA's 64-element array utilises an XF correlator (correlation before Fourier), which produces complex spectra, including 4 Stokes parameters (Hills and Beasley, 2008). ACA has a dedicated FX correlator (Fourier before correlation). Before the cross-correlation of signals, time delays resulting from geometric paths from the antenna to the correlator location are done by inserting variable time offsets in the digital sampler clocks. Further, digital filtering is then carried out to divide every 2 GHz wideband into 32 sub-bands of 62.5 MHz widths. At the filter outputs, the signals are re-quantised to 2 bits or 4 bits for cross-correlation. The data is then integrated for multiples of 16 ms. Autocorrelation data are integrated with multiples of 1 ms (Wootten and Thompson, 2009). ACA antennas are capable of observing together with the extended array and the signals from both arrays can be correlated (Hills and Beasley, 2008).

The scientific goals of ALMA are to study the early phases of star formation and the assemblage of massive galaxies at high redshifts. ALMA is capable of imaging molecular line emissions with a high spatial resolution (1 AU) and sufficient spectral resolution. ALMA data is curated online on the ALMA science archive with publicly released datasets available for download. This study uses three observational datasets from the ALMA archives.

3.6.2 Design and signal processing of VLA

The Very Large Array (VLA) is a reconfigurable radio interferometer located in Socorro in the United States of America. The VLA is made up of 28 (27 always-operational, 1 spare) 25-m altitude-azimuth mounted Cassegrain-type telescopes. Constructed in 1980, the VLA generates 351 unique baselines. The VLA's antenna sub-reflectors are modified hyperboloids whose focal point moves around a circle of 0.97 m radius when rotated about the axis of the main reflector. Feeds are placed on this circle, and changing between frequency bands is achieved by rotating the sub-reflector (Thompson et al., 1980). The VLA is capable of observing in 10 bands (L, P, C, S, Q, Ku, K, Ka, and X bands), with the K-band (18-26.5 GHz) of special interest for maser and star formation research. In K-band, VLA can observe 32 molecular and thermal lines such as H_2O , CH_3OH , CS, H_2CS , NH_3 , and SO_2 with a velocity resolution of 0.2 km s^{-1} (Dougherty and Perley, 2010). The antennas can operate in the 74 MHz to 50 GHz (400 cm - 7 mm) frequency ranges and are arranged on three equiangular arms, each 21 km long, with nine antennas in a Y shape (Bradt and Padmanabhan, 2005). The VLA is reconfigured using standard gauge train tracks and a total of 72 antenna stations, each with three concrete piers on which antennas can be mounted. The major configurations of the VLA are A, B, C and D. The A configuration is the most extended and D is the most compact configuration (Thompson et al., 1980). Figure 3.11 shows the VLA in A configuration.

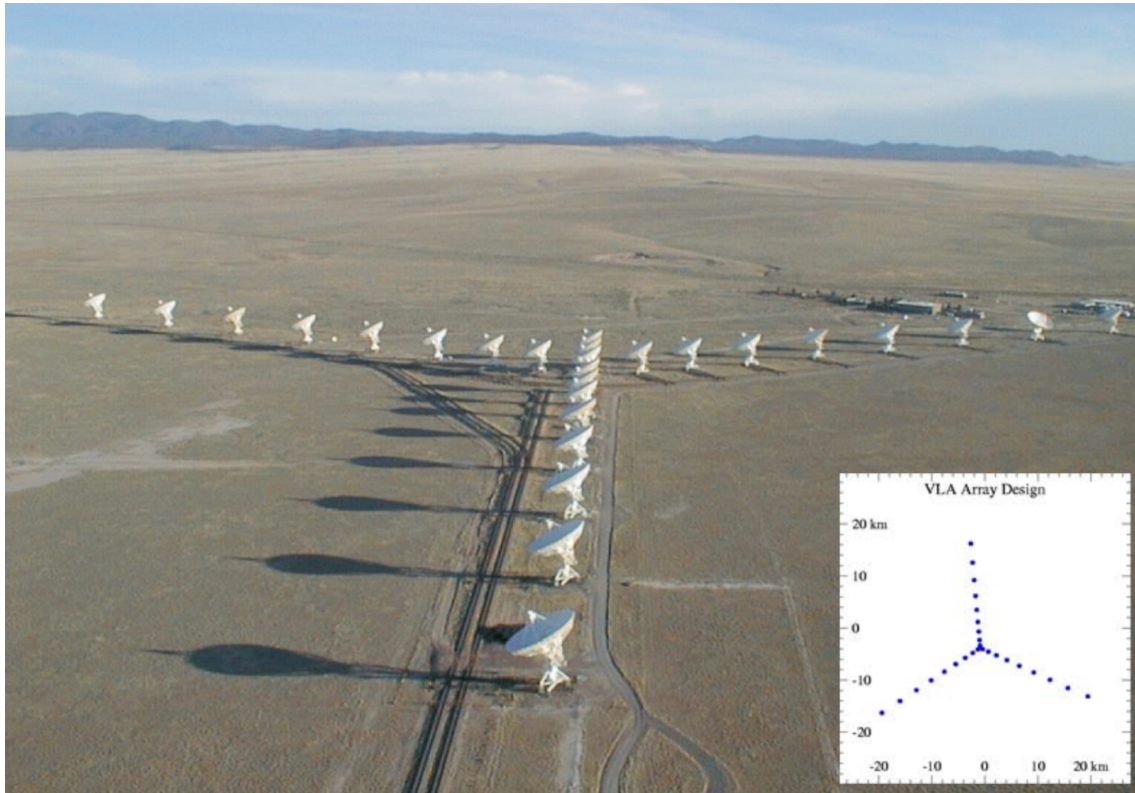


Figure 3.11: VLA telescope in A configuration. Source: <https://public.nrao.edu/VLA>.

The VLA's digital correlator was capable of providing 512 spectral channels split into 3 MHz divisions per baseline in a single polarization. VLA is capable of observing with a bandwidth of 100 MHz per polarisation in four frequency bands and capable of imaging all four Stokes parameters. The angular resolution of the VLA ranges from $1.4''$ to $0.04''$ for observations between 1.4 GHz and 50 GHz. VLA's antenna electronics were upgraded in 2011 and are now capable of processing 8 channels up to 2 GHz and sample data at 8 GHz bandwidth per polarization. A wideband correlator was installed which is capable of producing 16,384 spectral channels per baseline (Factor of 1092 improvement). A new control system for the array capable of real-time control was also installed and a high-level software system was also integrated (Perley et al., 2011). Table 3.4 shows the performance comparison between the VLA and the upgraded version known as the Expanded Very Large Array (EVLA). The continuum sensitivity increased by a factor of 10 after the upgrades.

Table 3.4: VLA and EVLA performance comparison (Dougherty and Perley, 2010).

Parameter	VLA	EVLA
Continuum sensitivity (1σ , 9 hr) ,	$10 \mu\text{Jy}$	$1 \mu\text{Jy}$
Maximum bandwidth in each polarization	0.1 GHz	8 GHz
Number of channels at maximum bandwidth	16	16,384
Maximum number of frequency channels	512	4,194,304
Coarsest frequency resolution	50 MHz	2 MHz
Finest frequency resolution	381 Hz	0.12 Hz
Number of full-polarization sub-correlators	2	64
Log (frequency coverage over 1 - 50 GHz)	22%	100%

The VLA's new wideband digital correlator (WIDAR) is 10 petaflops 32-bit/s special-purpose correlator. It is capable of processing cross-power spectral visibilities for all 351 baselines. WIDAR with an input of 16 GHz can produce 64 independent spectral windows with a variable width from 128 MHz to 31 kHz. The spectral resolution is in the range of 0.12 Hz to 2000 kHz. WIDAR is capable of providing full polarisation on all baselines and channels. Some of the standard observing modes of the VLA include HI spectral line or polarisation observations, low-frequency continuum, and high-frequency continuum. Data from VLA can be reduced with an automated pipeline or with astronomical packages such as Astronomical Image Processing Software (AIPS) (Greisen, 2003) or Common Astronomical Software Applications (CASA) (McMullin et al., 2007). Typical image dynamic range of continuum images from EVLA are 10^6 with standard post-processing efforts. The VLA's primary scientific goals include studying stellar nurseries, magnetic fields and radio transients. The VLA has proven to be an excellent instrument in the observation of disk-YSO-outflow systems due to the transparency of dust at centimetre wavelengths. VLA provides high angular resolution, and sensitivity for the observation of the environment of young stellar objects (Torrelles et al., 1998).

3.6.3 The Kanata/HONIR optical and near-infrared telescope

The Kanata telescope is a 1.5-m Ritchey-Chretien telescope located at Higashi-Hiroshima Observatory in Japan, and it is operated by Hiroshima University. The Kanata telescope has three focal ports, one Cassegrain port and two Nasmyth ports for the attachment of additional instruments. A Wide-field one-shot optical polarimeter (HOWPol), capable of optical imaging, spectroscopy and full-stokes simultaneous polarimetry, is also attached to the Kanata telescope (Sakimoto et al., 2012). The major specifications of the Kanata telescope are listed in Table 3.5.

Table 3.5: Specifications of the Kanata telescope (Sakimoto et al., 2012).

Primary mirror diameter	1.5 m
Type	Ritchey-Chretien
Field of view	15'
Focal number	F/12.3
Plate scale	11.148"/mm
Focal ports: attached instruments	Cassegrain port: HONIR Nasmyth port 1: HOWPol Nasmyth port 2: High-speed camera

The Hiroshima Optical and Near-InfraRed camera (HONIR) is a 1-m class near-infrared (NIR) telescope, attached to the Kanata telescope. Built in 2007, HONIR is attached to the Cassegrain port of Kanata and replaces the TRISPEC instrument. HONIR is capable of simultaneous imaging and spectrography. The polarimetry function of HONIR enables three colour imaging at ranges of 0.5 - 1.0 μm , 1.15 - 1.35 μm , and 1.45 - 2.40 μm . The telescope has a $10\times 10'$ field of view with a spatial sampling of $0''.29$. The optical components are mounted on a cryogenically cooled optical bench placed in a vacuum chamber which keeps the temperature of the components in the range of 60 - 70 K. HONIR is capable of cycling the optical elements due to four rotating turrets on which the components are mounted. HONIR can observe in the J, H, and Ks bands with typical resolutions of $1.7''$ and $0.9''$ FWHM at optical and NIR bands. The photometric accuracy of HONIR is ~ 0.02 mag at Ks and 0.01 mag at J and H bands. Image distortion is below 0.18% and 0.19 % at the H, Ks and J bands, respectively. A slit mask mounted on the focal plane of HONIR is used in tandem with a set of grisms for spectroscopy. At the pupil plane, a Wollaston prism is used as a polarization beam splitter. A Wollaston prism divides an incident beam into two separate perpendicularly polarized beams. HONIR is dedicated to optical and NIR observations of transient or variable astronomical objects (Akitaya et al., 2014). The specifications of the HONIR camera are presented in Table 3.6. The schematic diagram of HONIR is illustrated in Figure 3.12, and an image of the camera system and its schematic is shown in Figure 3.13.

Table 3.6: Specifications of the HONIR camera.

Wavelength coverage (μm)	0.5 - 1.0 , 1.45 - 2.40, 1.15 - 1.35
Sampling rate (arcsec/pixel)	0.29
Focal number	F/12.3
Plate scale (arcsec/mm)	11.148
Field of view (arcmin)	10×10
CCD pixel number	2048×4096
HgCdTe pixel number	2048×2048
Filters	J, H, Ks, B, V, z' , Y, R_C , I_C
Operating Temperature	85 K

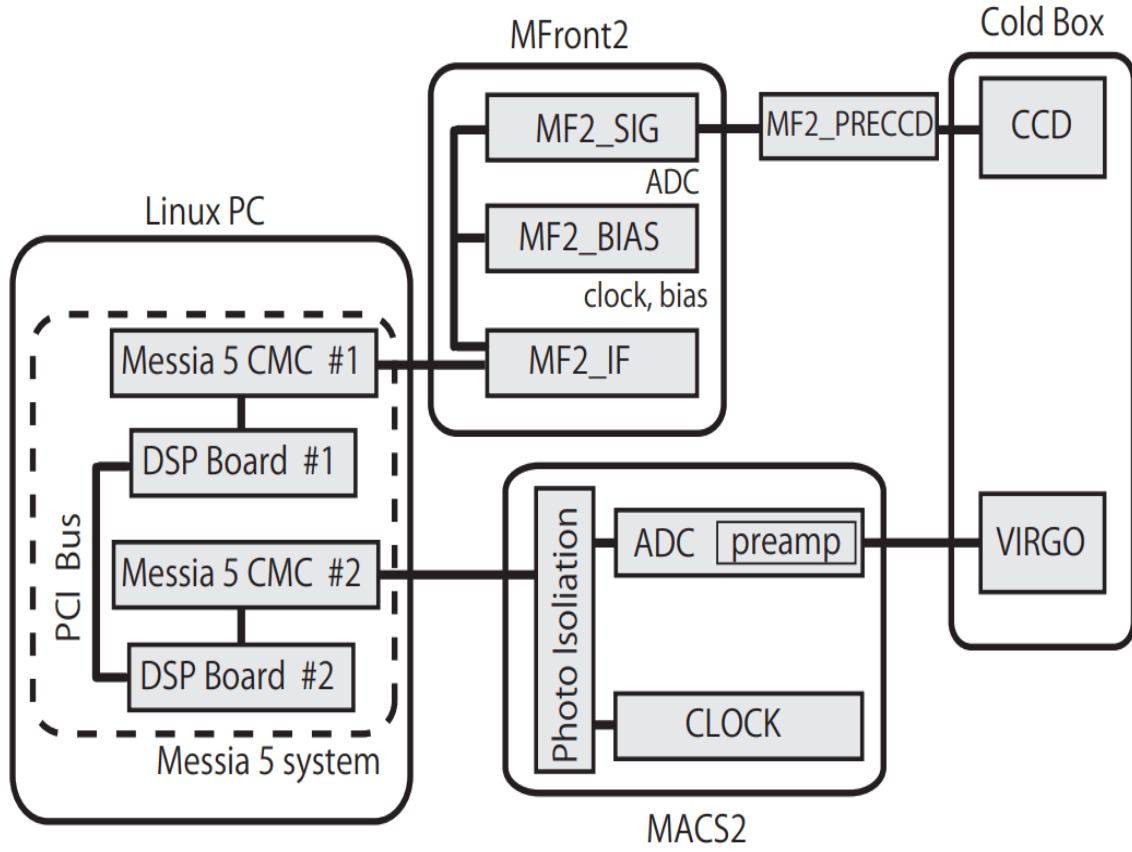


Figure 3.12: Block diagram of HONIR detector. Source: Sakimoto et al. (2012).

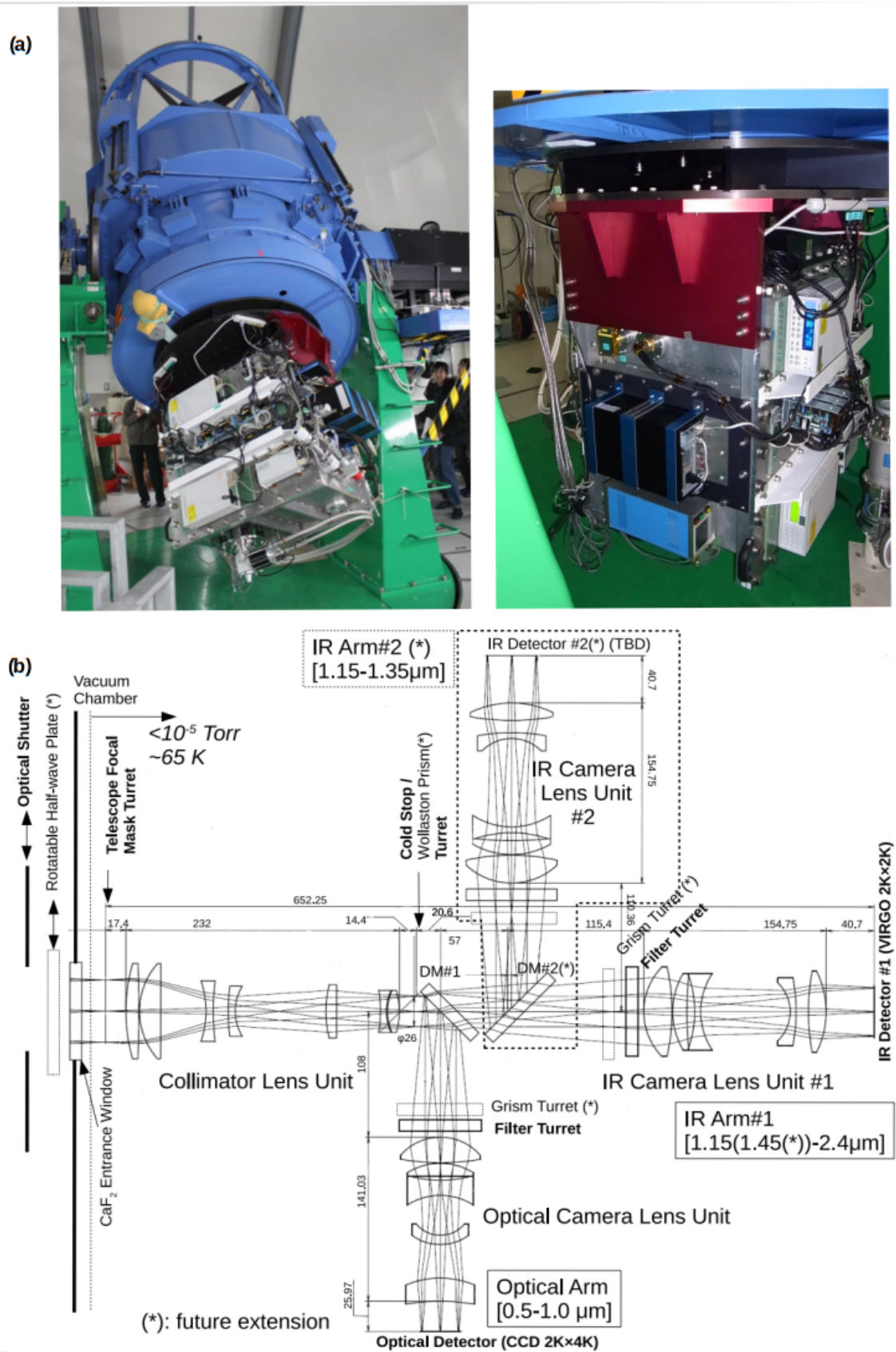


Figure 3.13: Picture and schematic diagram of the Hiroshima Optical and Near-Infrared camera (HONIR). Top figure (a) is HONIR affixed to the Kanata optical telescope. On the left is a close-up of HONIR. Bottom (b) is the schematic diagram of HONIR showing its optical design and layout (Sakimoto et al., 2012).

Chapter 4

Observations and Data Reduction

This chapter discusses the observations that produced the data sets used in this study and the data reduction procedures. The target source NGC 2071-IR is presented first, followed by the observations, data reduction and analysis.

4.1 Target source: NGC 2071-IR (HOPS-361)

NGC 2071-IR also called HOPS 361 (Fischer et al., 2017) is located in the Lynds 1630 dark cloud in the Orion molecular cloud complex which is the nearest active star formation region in the Milky Way galaxy, located at a distance of 400 parsecs (Kounkel et al., 2017; Zucker et al., 2019). The Orion star-forming complex can be delineated into two distinct regions, the Orion A cloud and Orion B molecular cloud. NGC 2071-IR is an active star-forming region located north of the reflection nebula NGC 2071, about 4 arcminutes north of the Orion B molecular cloud complex (Walther and Geballe, 2019). The dense subgroup NGC 2071-IR cluster covers an area of $\sim 80 \text{ arcmin}^2$, with a bolometric luminosity of NGC 2071-IR of $\sim 500 L_{\odot}$ (Butner et al., 1990). NGC 2071-IR appears as a dark patch in the optical, indicating substantial dust extinction, which suggests that the young stellar objects in NGC 2071-IR are still in the early phases of their evolutionary sequence (Torrelles et al., 1998). NGC 2071-IR was observed in infrared and four infrared sources were identified. Subsequent high-resolution interferometric observations resolved NGC 2071-IR into a cluster of eight far infrared (FIR)/continuum sources (Lekht et al., 2011; Cheng et al., 2022). At J, H, and K_s bands, the colour composite image of NGC 2071-IR in Figure 4.1 shows multiple cores with eight NIR sources labelled IRS 1 to 8. IRS 1 and IRS 3 dominate the emission in the region, which suggests they are the more evolved cores (Walther and Geballe, 2019). NGC 2071-IR is reported to be associated with water masers (Schwartz and Buhl, 1975; Campbell, 1978; Torrelles et al., 1998). Several water maser components have been detected towards the region, indicating that the masers are

clustered. The Herschel Orion Protostellar Survey (HOPS) (Fischer et al., 2017) designated the NGC 2071-IR region as HOPS 361. Three of the YSOs, NGC 2071-IRS3 to the north, NGC 2071-IRS1 to the southwest, and VLA-1 located centrally, are resolved in (sub)millimetre continuum images in the HOPS 361 region. ALMA observations of NGC 2071-IR presented in Chapter 5 reveal (sub)millimetre dust emission at locations that coincide with the location of the three IRS sources.

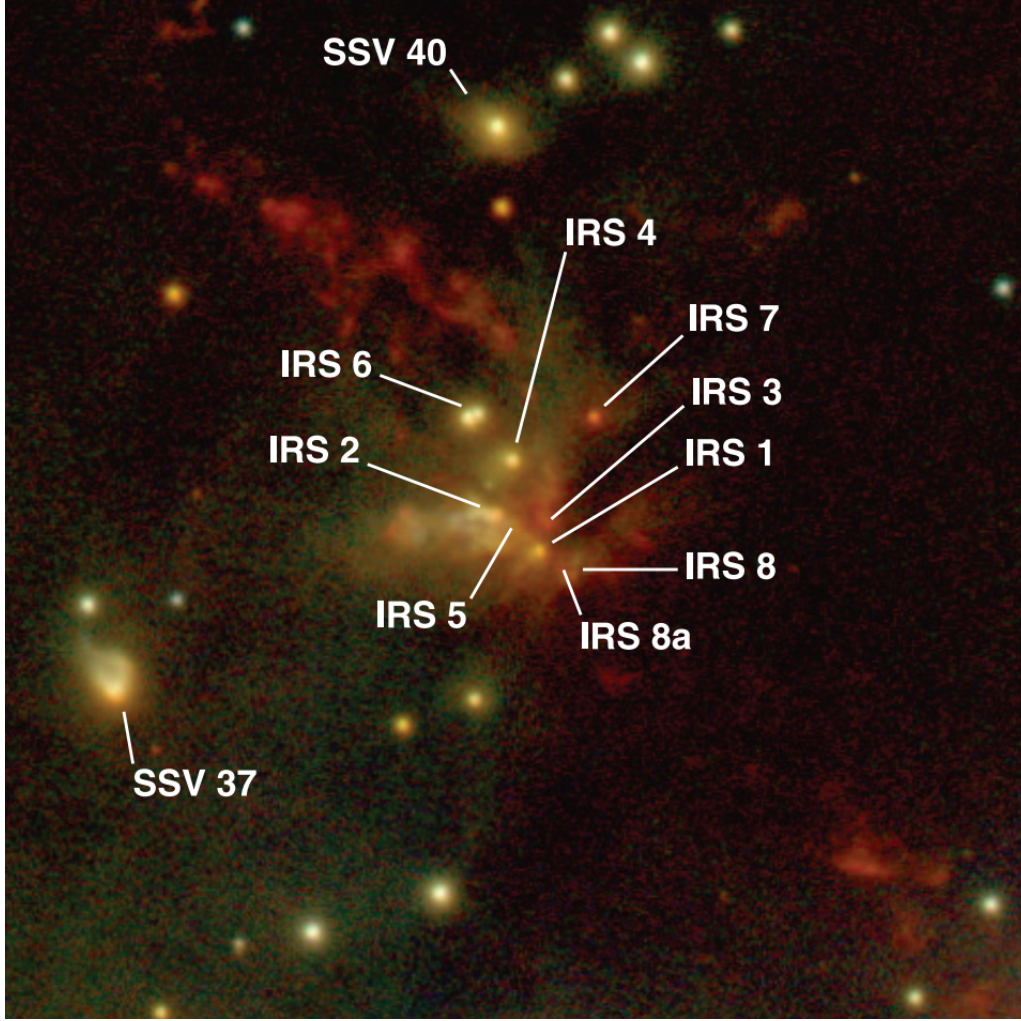


Figure 4.1: $1.25\ \mu\text{m}$ (J band), $1.63\ \mu\text{m}$ (H band), and $2.14\ \mu\text{m}$ (K_s band), (blue, green, and red, respectively) colour composite of NGC 2071-IR region taken with the SIRIUS camera on the 1.4-m IRSF telescope in South Africa. Location of infrared sources of interest to this study, IRS 1 and IRS 3 are indicated with other IR sources. The field of view is $4' \times 4'$. The image is taken from Tamura et al. (2007).

NGC 2071-IRS1 region is suggested to possess a wide velocity profile similar to those previously seen in the core of the Orion molecular cloud after shock excited H_2 (1-0) was detected and mapped towards the region by Walther and Geballe (2019). Both IRS 3 and IRS 1 are reported to be associated with high velocity bipolar outflows. Observations of

CO millimetre lines showed a large-scale outflow emanating from IRS 3 in the northeast-southwest direction, and an east-west oriented outflow from IRS 1 (Walther and Geballe, 2019). The outflow from IRS 1 has been estimated to be $1.5'$ in width and $5'$ in length (Lane and Bally, 1986). Three HII regions suggested to be formed via collisional ionisation of hot gas have been found towards the region, with two of them coinciding with IRS 3 and IRS 1 positions (Smith and Beck, 1994). It must be noted that these are not the photo-ionized HII regions found in massive star-forming regions.

4.2 Single-dish observations of NGC 2071-IR

The HartRAO’s 26-m telescope monitors NGC 2071-IR as part of the M2O project (Burns, 2021). At HartRAO, NGC 2071-IR is monitored under the project ‘Monitoring Flaring Masers Associated with NGC 2071’. Multi-epoch observations of 6.7 GHz methanol masers towards NGC 2071-IR were carried out from January 2019 to June 2020, and 22 GHz water maser observations from January 2019 to May 2022 were obtained from HartRAO. The frequency of the monitoring observations ranged from daily to once a week. Table 4.1 summarises the NGC 2071-IR observations with the HartRAO 26-m telescope.

Table 4.1: Summary of HartRAO NGC 2071-IR observations.

Molecule	Frequency (GHz)	Flux calibrator	HPBW ($^{\circ}$)	Velocity resolution (km s^{-1})	RMS Noise (K)	RMS Flux density (Jy)
CH ₃ OH	6.7	3C123	0.116	0.04	0.34	1.4
H ₂ O	22	Jupiter	0.031	0.10	0.57	1.0

4.2.1 HartRAO NGC 2071-IR 6.7 GHz methanol maser observations

From 14 January 2019 to 3 June 2020, 51 unique 6.7 GHz methanol maser observations were made towards NGC 2071-IR with the HartRAO 26-m telescope. The telescope was pointed at the coordinates RADEC (J2000) 05:47:04.80 +00:21:42.80. The total integration time per scan was 90 s and 360 s per observation. The total bandwidth of the backend receiver was 10 MHz and was centred at $V_{lsr} = 12.5 \text{ km s}^{-1}$. The number of spectrometer channels was 1024. Data was recorded in LCP and RCP using a cryogenically cooled 4.6 cm dual polarisation receiver to obtain the full power. Three observations were discarded due to corrupt data, leaving 30 observations made in 2019 and 18 observations in 2020 for reduction. The Point Source Sensitivity (PSS) values of the HartRAO 26-m telescope was measured routinely by observing compact radio galaxy 3C123 (J0437+296). The PSS observations of 3C123 were reduced for the period between 1 January 2019 and 3 September 2020. The 6.7 GHz methanol maser observations were halted in June 2020 due to constant non-detection.

4.2.2 HartRAO NGC 2071-IR 22 GHz water maser observations

A total of 460 unique H₂O maser observations with the HartRAO 26-m telescope spanning from January 2019 to May 2022, were made. The telescope was pointed at the coordinates RADEC (J2000) 05:47:04.8 +00:21:47.8. A total of 36, 232, 136, and 56 unique observations were made in 2019, 2020, 2021, and 2022, respectively. Figure 4.2 shows the distributions of the H₂O maser observations. The spectra were divided into four groups based on the Julian calendar year of observation. The 2019 observations were sporadic whilst 2020 and 2021 were high-cadence observations. The V_{lsr} ranged from -14.57 km s^{-1} to 39.36 km s^{-1} . The total spectrometer bandwidth was 8 MHz centred at $V_{lsr} = 12.5 \text{ km s}^{-1}$ with 1024 spectrometer channels. To obtain the total power, the data was recorded in LCP and RCP using a cryogenically cooled 1.3 cm dual polarisation receiver. The Frequency-switching technique described in subsection 3.3.2 was employed during the 22 GHz H₂O masers observations. The noise level in the spectra is about 1.5 Jy. The integration time per scan was 30 s and per observation was 360 s.

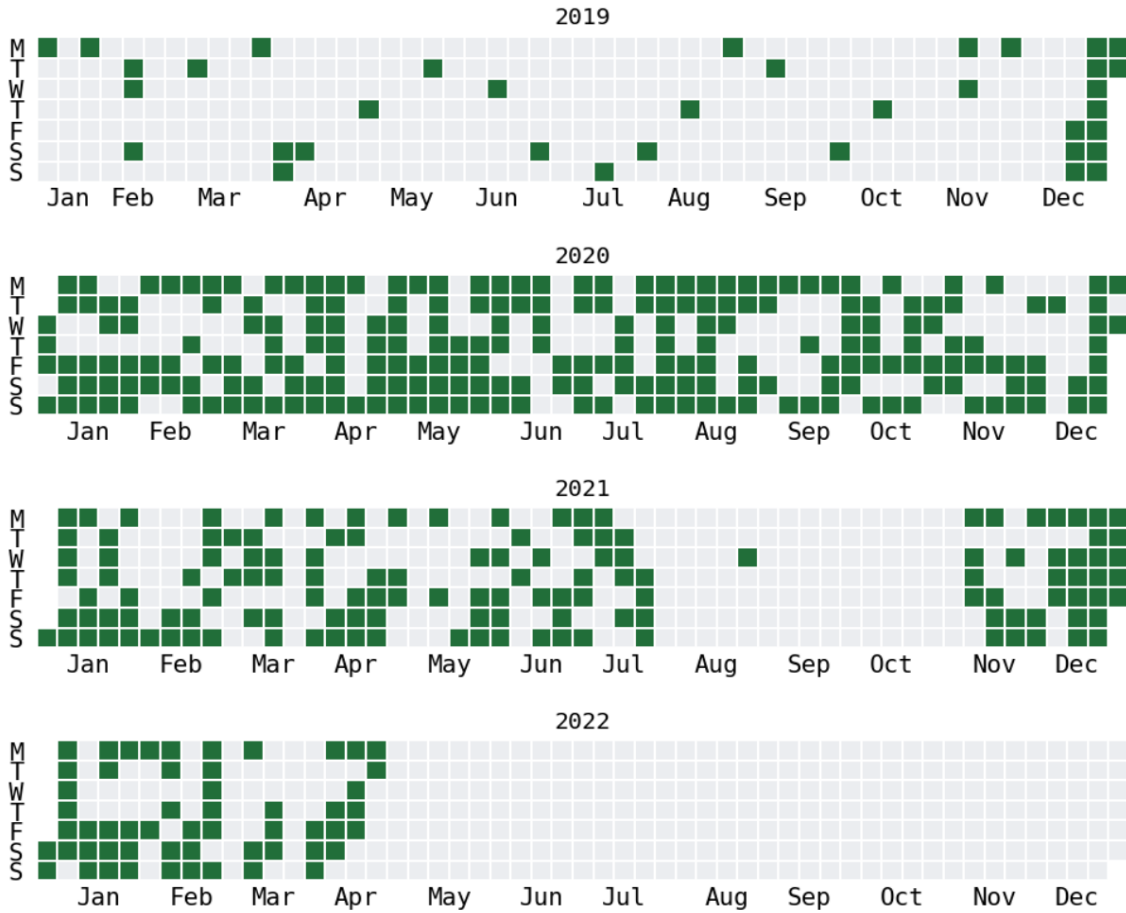


Figure 4.2: Calendar distribution of the 22 GHz H₂O maser observations towards NGC 2071-IR with the HartRAO 26-m telescope. Observations in 2019 were sparsely conducted. The pause from July to November 2021 was due to the telescope conducting scheduled VLBI observations.

4.2.3 Calibration processes of HartRAO 26-m data

Processing of point source sensitivity (PSS) values

Jupiter was observed as a flux calibrator for the 22 GHz H_2O masers towards NGC 2071-IR. Jupiter has a high but stable flux density making it an ideal calibrator for 22 GHz H_2O masers.

The Jupiter PSS values obtained from HartRAO exhibited periodic variations in the form of a recurrent increase in PSS values as shown in Figure 4.3. The jumps occur during the South African summer months (December to March).

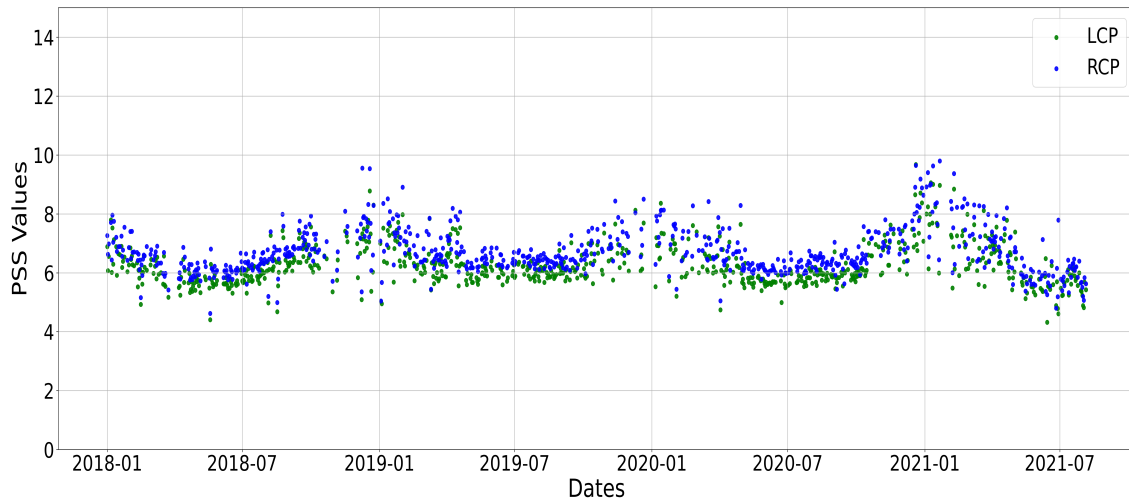
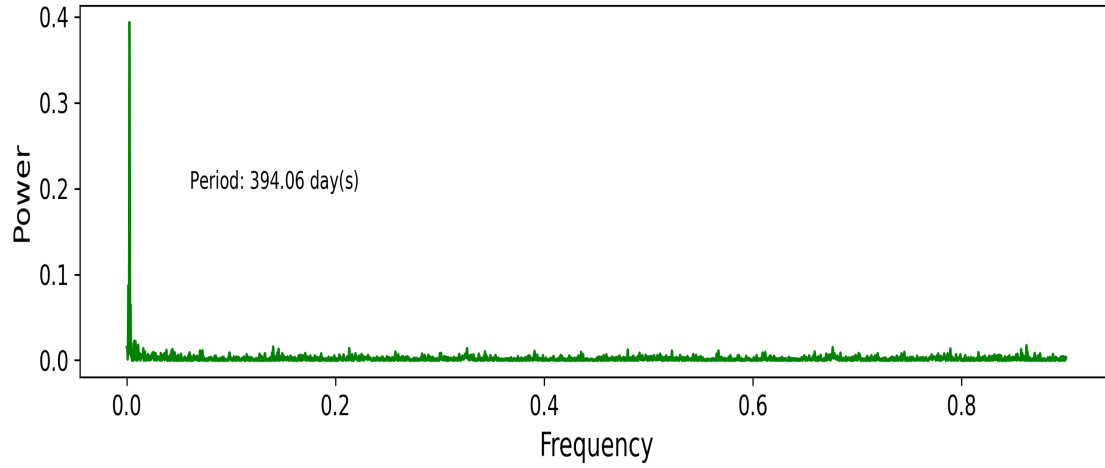
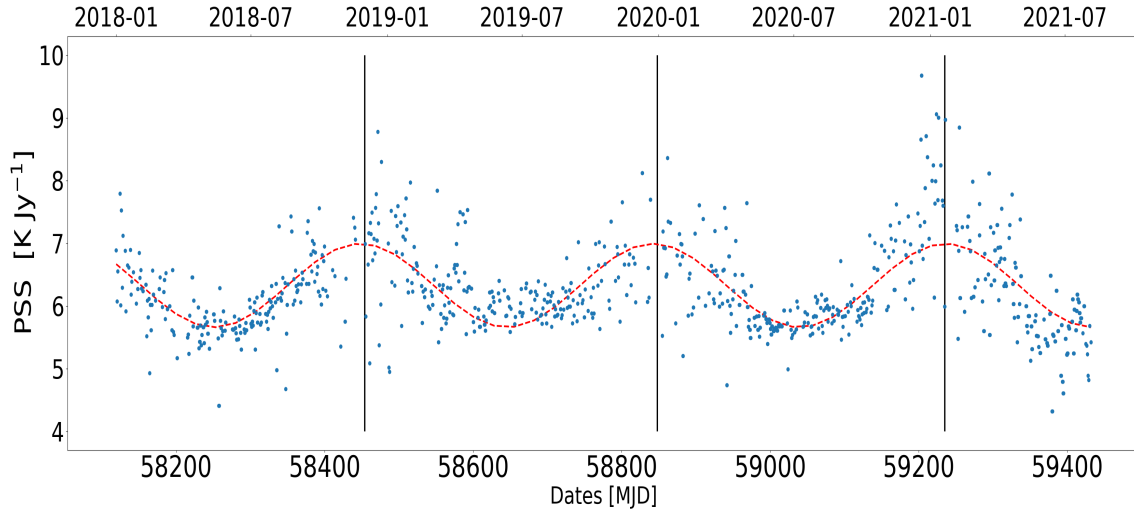


Figure 4.3: PSS values (Jupiter) from HartRAO. Jumps in PSS values can be seen at the first month of each year.

A plausible explanation for the jumps is the effect of the orbital motions of the Earth and Jupiter around the Sun and as well as the varying distance between the two planets. The Lomb-Scargle periodogram algorithm (Press and Rybicki, 1989; Lomb, 1976; Scargle, 1982), a statistical tool designed to detect periodic signals in irregularly spaced observations, was utilized to fit the PSS data, revealing a 394-day period for the jumps. This is close to the synodic period (time interval between two successive conjunctions of Jupiter and the Earth) which is about 398.88 days (Pizzella and Ricci, 2011; Tan and Cheng, 2013). This supports the explanation of the orbital variations causing the jumps. An increase in water vapor content during summer months, which attenuates radio signals as they travel through the atmosphere, may also contribute to the jumps in the PSS values. Therefore, the jumps are likely the result of a combination of both phenomena. Further investigation would be needed to robustly confirm the source of the periodic jumps in the Jupiter PSS values.



(a) Lomb-Scargle periodogram fit result with a period of 394 days.



(b) Jupiter LCP-PSS Values from HartRAO with Lomb-Scargle fit (red dashed lines) showing periodicity. Vertical black lines indicate 394-day intervals.

Figure 4.4: Lomb-Scargle fit results on Jupiter PSS data from HartRAO.

The PSS data was split into five sections 1, A, 2, B and 3, as shown in Fig 4.5. Data points from sections labelled 1, 2, and 3 were counted and the values were discarded. PSS values outside the range of 4-10 were considered outliers and removed before splitting data into sections. Histograms of data from sections labelled A and B were plotted. The data from sections A and B were combined, and the mean value of the resulting data was calculated.

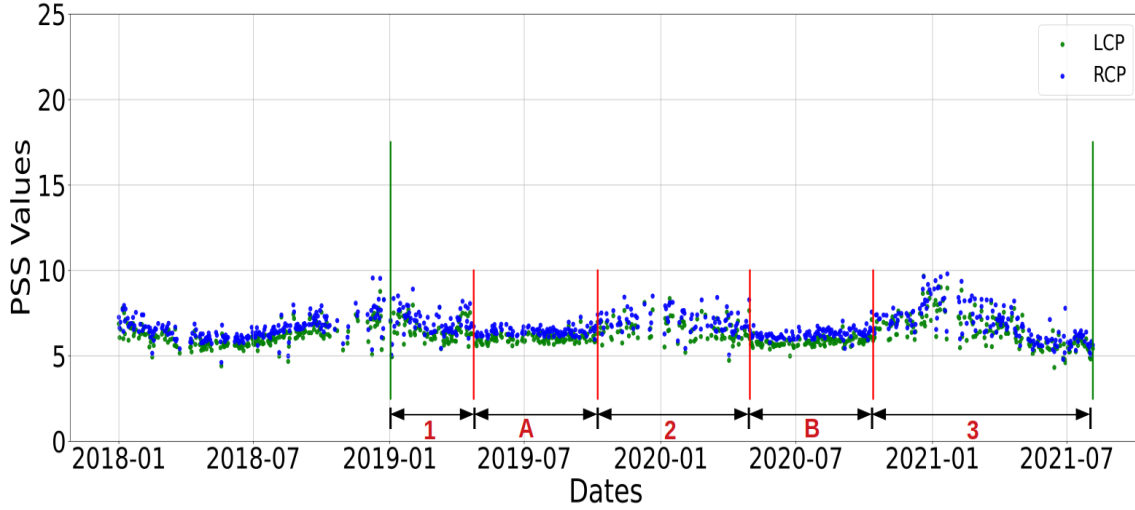


Figure 4.5: PSS Values split into sections 1, A, 2, B, and 3.

The *truncnorm* controlled random number generator from the *Scipy* package of the Python programming language was then used to generate numbers to replace the PSS values from sections 1, 2, and 3. The truncnorm number generator is a standard normal truncated to the range $[a, b]$, where a and b represent the minimum and maximum number respectively (the domain). The domain was set to 2σ from the mean for the generation. The process was iterated until the mean of the generated numbers was close or equal to the mean of the concatenated data from sections A and B, as well as checking the distribution closest to the histogram distribution of the concatenated data of sections A and B. The process is done separately for LCP and RCP. Figure 4.6 shows the histogram distributions of the concatenated HartRAO PSS data from sections A and B.

The PSS values from sections 1, 2, and 3 were then replaced with the generated values. Figure 4.7 shows the PSS values from HartRAO and the PSS values with the jumps replaced with the generated values. The average PSS of the 26-m HartRAO telescope for both right circular polarisation (RCP) and left circular polarisation (LCP) derived from observing Jupiter at a central frequency of 22 GHz between January 2019 and April 2022 is 6.40 Jy K^{-1} and 5.94 Jy K^{-1} , respectively.

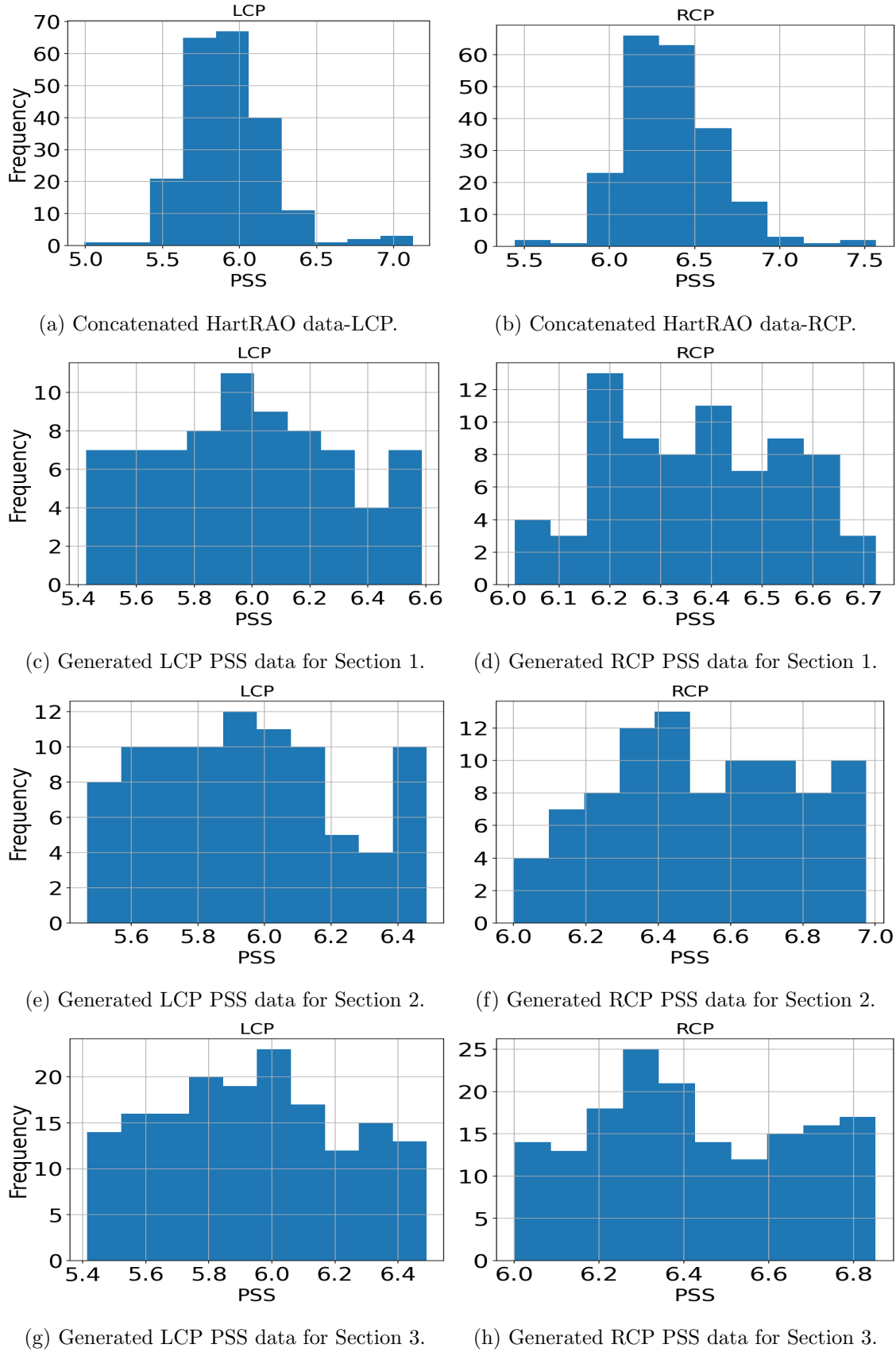
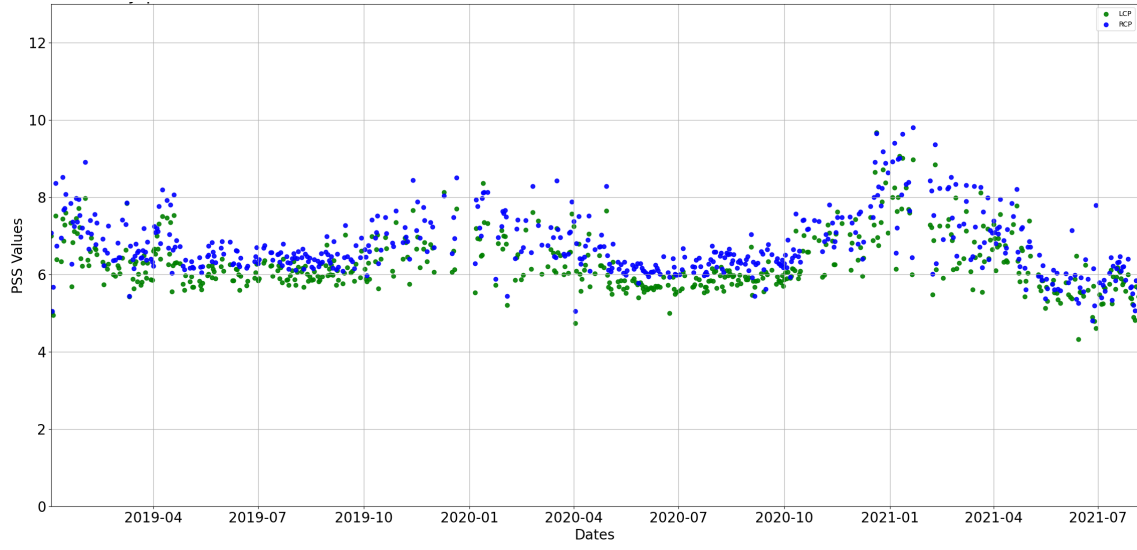
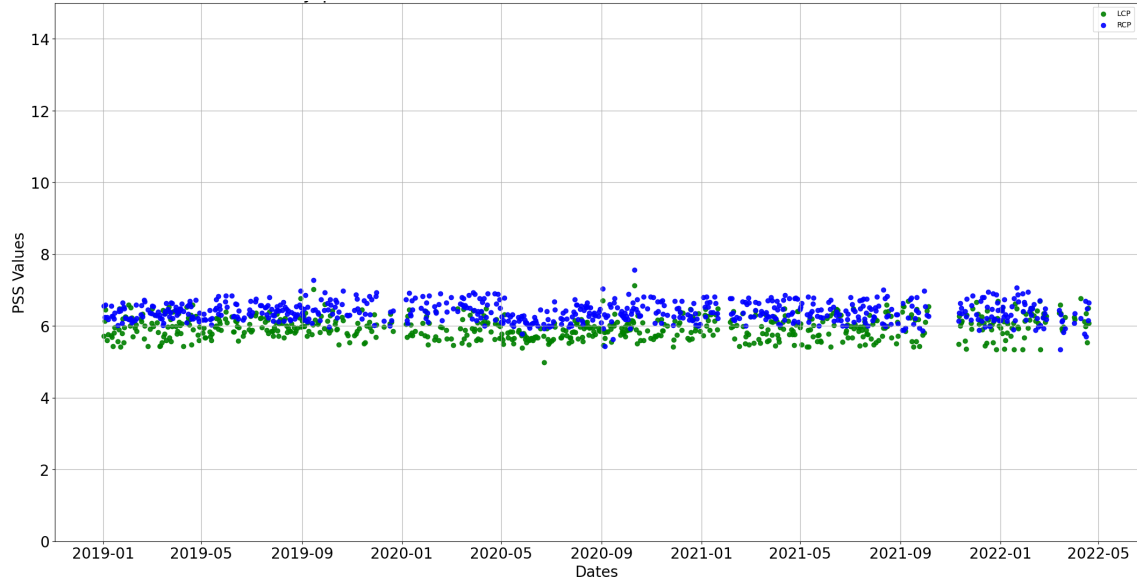


Figure 4.6: Histograms showing distributions of PSS values for concatenated data from sections A and B (a,b) and generated values (c-h) to replace the values from sections 1, 2 and 3. These distributions were the closest to the concatenated data.



(a) HartRAO Jupiter PSS data with periodic jumps.



(b) HartRAO Jupiter PSS data with regions of periodic jumps replaced with generated PSS values.

Figure 4.7: Pre- (a) and post- (b) processed Jupiter PSS data from HartRAO.

HartRAO NGC 2071-IR H₂O maser data reduction

Four raw scans were made on Jupiter for each polarisation using the drift scan method described in section 3.3.1. Figure 4.8 shows the raw half-power beam width (HPBW) point scans, as well as one *on-source* scan through the centre of the telescope's beam.

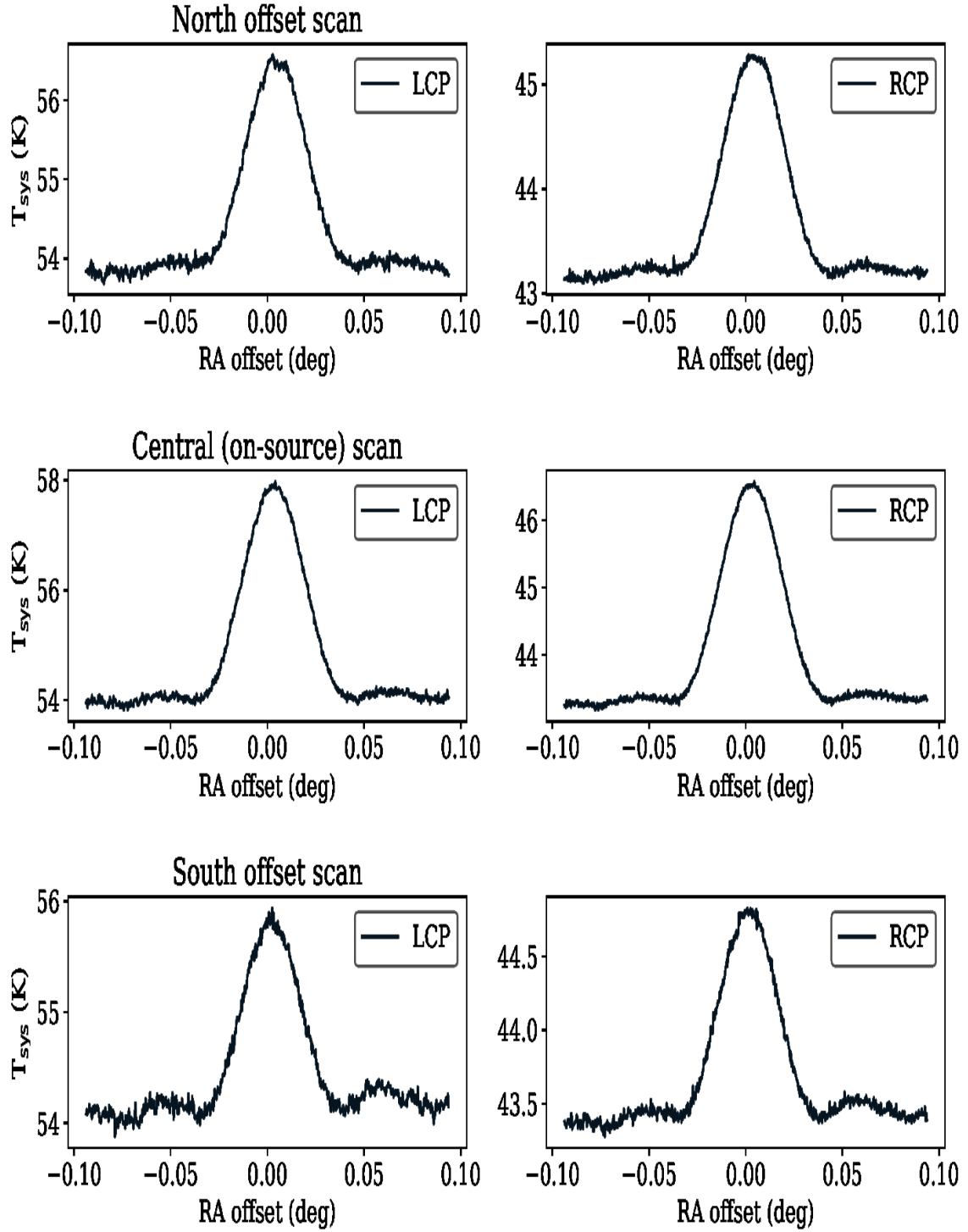
Figure 4.8: Drift scans on Jupiter for determination of T_A .

Table 4.2 contains a list of the Jupiter observation parameters from the observations. For each observation, Jupiter was observed for 45.44 s. The frequency switching maser observations of NGC 2071-IR also used the five-pointing offset technique. Figure 4.9 shows a sample of the five-point observation offsets for a single maser observation.

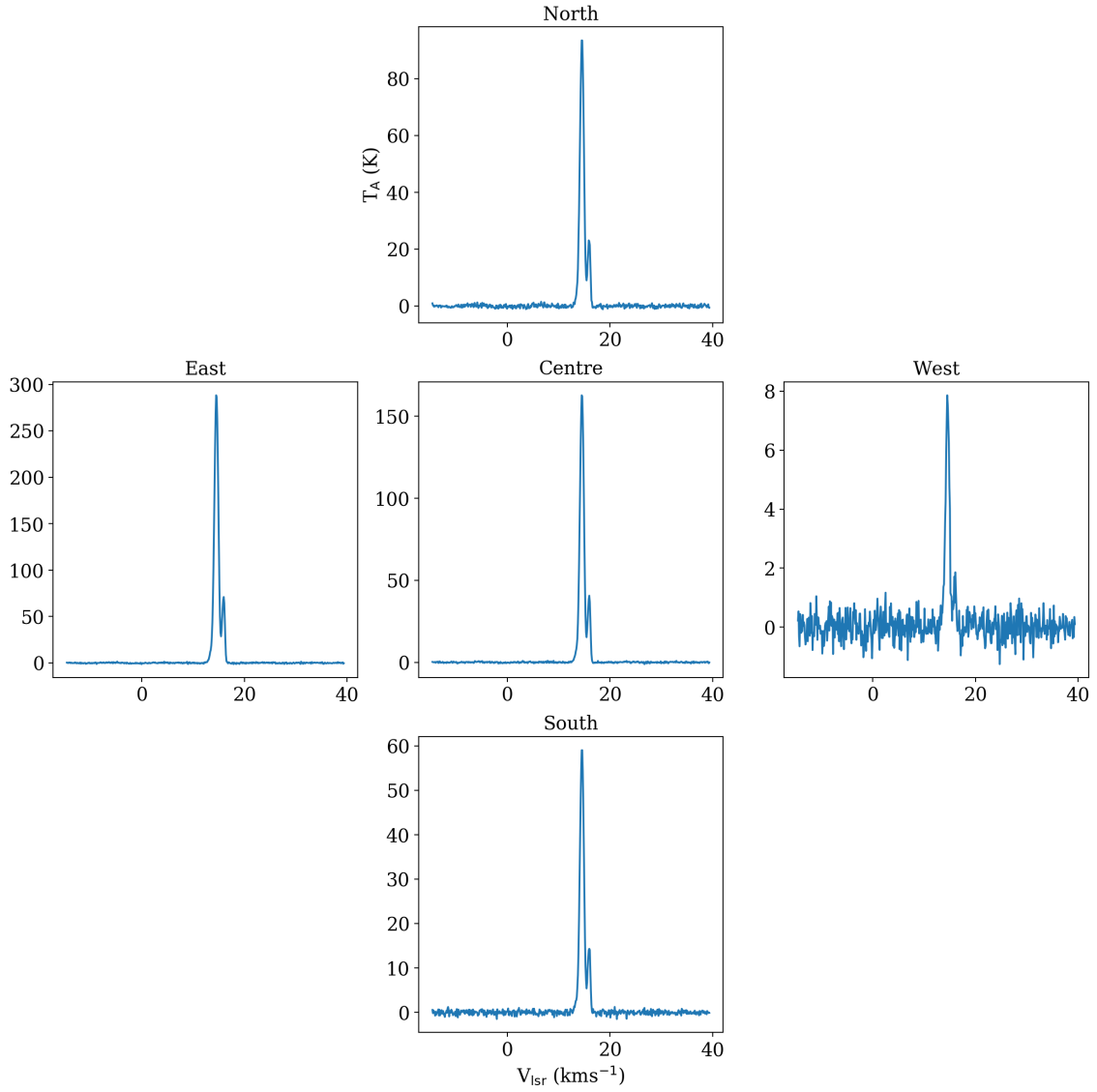
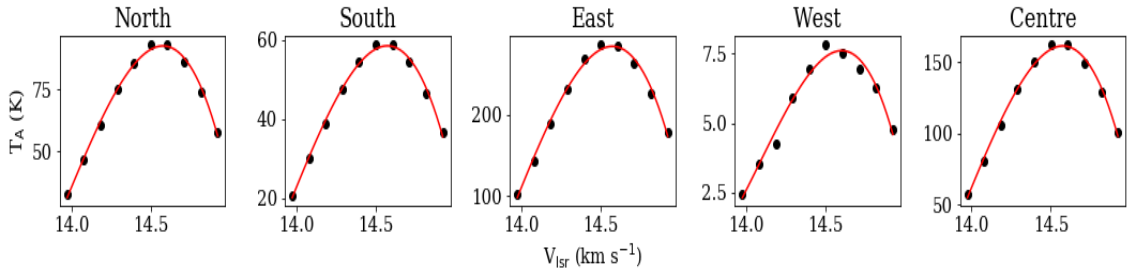
Figure 4.9: Drift scans on Jupiter for determination of T_A .

Figure 4.10: Amplitude fitting of maser peaks to derive pointing offsets.

For the reduction of the water maser data, the maser spectra were also fitted with suitable order polynomials. The polynomial order varied due to short timescale variations in the

maser profiles as well as the number of features present in the spectra. To improve the SNR, the North & South power values measured were averaged. The same method was applied to the East & West power values. The maser features with the largest amplitudes were fitted with a suitable order polynomial to derive the pointing errors (see sample in Figure 4.10). Pointing offsets were then derived and applied to the on-source pointing (central source) to obtain the total power.

Table 4.2: Jupiter observation parameters.

Parameter	Value
Scan type	Drift scan
Half Power Beam Width	0.031 degrees
longitude	263.2 °
Latitude	−22.6 °
Ambient temperature	290 K
Atmospheric pressure(mbar)	864.8
Humidity (%)	85%
backend receiver centre frequency	22235.12 MHz
Bandwidth of backend receiver	64 MHz
Noise diode Temp.(K) : LCP, RCP	34.1, 39.5

To correct for the bandpass response and flatten the baseline, a spectrum retrieved from the frequency-switched observations is subtracted from the main maser spectrum. The left circular polarisation (LCP) values and the right circular polarisation (RCP) with common velocities are summed. Baselines were then fitted linearly to remove remnants of variations in the baseline. Each polarisation of the maser spectrum was then multiplied with its date-corresponding PSS value derived from the drift scans, thus converting the antenna temperature from Kelvin (K) to flux density in Janskys (Jy). For missing PSS values, an average of the previous and next day’s PSS values is calculated and used for the reduction. Lastly, the polarised spectra (LCP and RCP) now in units of Jansky are summed to obtain the total intensity, since each polarisation contains only half of the intensity (See section 3.1). The maser data reductions were carried out utilising Python programming packages and libraries.

4.3 ALMA archival data of NGC 2071-IR

Publicly available ALMA data for NGC 2071-IR (HOPS 361/361-N) was obtained from the ALMA Science archive*. Two unique datasets were obtained in total from the ALMA database. An additional dataset was obtained from the VANDAM database[†]. One in the

form of a fits image and the other a continuum subtracted self-calibrated measurement set (MS). A detailed overview of the ALMA observations is presented herein.

* https://almascience.nrao.edu/aq/?result_view=observation&sourceName=hops-361 † <https://dataverse.harvard.edu/dataverse/VANDAMOrion>

ALMA Band 7 (275 - 373 GHz) observations - 12-m array

The VANDAM survey of Orion protostars (Tobin et al., 2020a) targeted > 300 embedded Class 0, Class I, and flat spectrum young stellar objects in the Orion star-forming region using ALMA in band 7 (345 GHz). At the distance of Orion (400 pc; (Kounkel et al., 2017; Zucker et al., 2019)) the angular resolution attained was $\sim 0.1''$ (~ 40 AU). The survey also observed 148 protostars with the VLA at a wavelength of 9 mm at an angular resolution of $\sim 0.08''$ (32 AU). Each target was observed for ~ 54 s. A dual baseband configured correlator was used with a bandwidth of 1.875 GHz, with two basebands centred at 333 GHz and 344 GHz set to a bandwidth of 1.9 GHz. An additional baseband was used to observe $^{12}\text{CO } J=3-2$ line at 345.8 GHz, setting the total bandwidth to 937.5 MHz with a spectral resolution of 0.489 km s^{-1} per channel. $^{13}\text{CO } J=3-2$ observations at 330.6 GHz were also conducted. The total bandwidth utilized was 234.4 MHz with a spectra resolution of 0.128 km s^{-1} per channel. Continuum at 870 microns was observed with ALMA for 328 protostars in Orion including NGC 2071-IR (HOPS-361). The $^{12}\text{CO } J=3-2$ transition was also mapped with ALMA to search for outflows.

Pipeline-processed and imaged 870-micron continuum image and $^{12}\text{CO } J=3-2$ were obtained from the VANDAM Orion dataverse (Tobin, 2019). The self-calibrated Measurement Set (MS) file for $^{13}\text{CO } J=3-2$ was also obtained from the VANDAM database and imaged using CASA 5.4.0-68, following standard CASA imaging procedures.

ALMA band 6 observations: 211 - 275 GHz

In October 2018, ALMA conducted band 6 observations of protostars using the 12-m array as part of the VANDAM project. A total of 50 protostars were detected including NGC 2071-IR (ALMA source name: HOPS 361-N). Table 4.4 presents details of the band 6 observations. The raw data was calibrated using standard CASA calibrations methods. Five unique measurement sets (MS) containing visibilities were obtained from the ALMA database. Flagging was done to remove bad data points and band edges removed. The antenna positions were updated and the water vapour radiometer corrections were calculated. Flux values were set for all calibrators using CASA task ‘Setjy’. A measurement set for only HOPS-361 was extracted using CASA task ‘mstransform’. Dirty image cubes were made and visually inspected using ‘CASA viewer’ for identification of continuum channels, which were then extracted using CASA task ‘uvcontsub’ and imaged. All five

measurement sets were combined using CASA task ‘concat’ to produce one measurement set for imaging. CASA version 5.7.0-134 was used throughout the calibration and imaging process.

ALMA observations: ALMA Compact Array (ACA) band 7 (275 - 373 GHz)

NGC 2071-IR was also observed with ALMA in its compact configuration. The observations were mosaic observations made between 2 October 2018 and 30 October 2018. The spectral windows were centred on 332.975 GHz and 343.975 GHz for the continuum observations. At each frequency, the correlator provided 2 GHz bandwidths. Integration times were in the range of 4500 to 6000 s. Calibration steps were retrieved from the basic reduction scripts provided for the ALMA pipeline. The reduction of the ACA data was done following the standard CASA calibration and imaging procedures. A measurement set for only field 61 which covered the NCG 2071-IR region was extracted using CASA task ‘mstransform’. The same steps as those outlined in the reduction of the band 6 data were employed for extracting the continuum.

For imaging, Högbom’s CLEAN algorithm (Högbom, 1974) was used as a deconvolver. A standard gridding with robust parameter set to 0.5 and Briggs weighting was employed. The cell size and image size were set to 0.14 arcseconds and 400×400 , respectively. A mask was made manually through interactive implementation of CASA task ‘tclean’, with number of iterations set to 100. Four spectra windows were imaged together. CASA 5.4.0-68 was used throughout the calibration and imaging procedure.

4.4 VLA archival data of NGC 2071

3.6 cm VLA continuum observation of NGC 2071-IR

Carrasco-González et al. (2012) provided a 3.6 cm VLA continuum image of NGC 2071-IR for this study. The observations were conducted with VLA in its most extended configuration (A), with an effective total bandwidth of 200 MHz. The 3.6 cm continuum image was made by concatenating UV data from five observations ranging from August 1995 to July 1999. Table 4.3 below shows the observation parameters of each five epochs. Detailed information on the observations is described in Carrasco-González et al. (2012).

VLA 9 mm dust continuum observation of NGC 2071-IR

Tobin et al. (2020a) during the VANDAM survey conducted observations of Orion protostars with the VLA. A total of 148 protostars were observed.

Table 4.3: Summary of 3.6 cm VLA continuum observations from Carassco-González et al (2012).

Epoch	Obs. Date	Config.	Flux cal.	Phase cal.	S_{Phase} (Jy)	HPBW (Arcsec)	P.A. (deg)	RMS Noise (μ Jy/ beam)
1995.6	12 Aug. 95	A	3C286	J0541–056	1.225 ± 0.003	0.34×0.25	–15	27
1997.0	10 Jan. 97	A	3C48	J0541–056	0.809 ± 0.005	0.31×0.25	7	19
1998.2	27 Mar. 98	A	3C48	J0541–056	0.720 ± 0.004	0.35×0.25	–20	18
1998.4	26 May. 98	A	3C48	J0541–056	0.858 ± 0.008	0.36×0.24	–26	20
1999.5	03 Jul. 99	A	3C48	J0541–056	1.021 ± 0.005	0.34×0.27	–12	19

About 100 individual observations were carried out with VLA in A configuration at a resolution of 0.08 (32 AU). The observations were made between 20 October 2016 and 7 January 2017. NGC 2071-IR (HOPS-361) and 148 protostellar regions were observed. The telescope was pointed at coordinates (J2000) $\alpha = 05^h 47^m 04^s.776$, $\delta = +00^\circ 21' 42''.87$. The observations were conducted using VLA Ka-band receivers in both A and C configurations.

Table 4.4: Summary of ALMA observations of NGC 2071-IR (HOPS-361) used in this study.

Parameter	Band 7	Band 6	Band 7 (ACA)
Project code	2015.1.00041.S	2017.1.00419.S	2018.1.01284.S
Frequency support (GHz)	330.46 - 346.25	218.19 - 234.43	330.55 - 345.91
Wavelength (mm)	0.87	1.30	0.87
Array	12 m	12 m	7 m
ALMA source name	HOPS-361	HOPS-361-N	HOPS-361
Phase center α ,	$05^h 47^m 04^s.780$	$05^h 47^m 04^s.634$	$05^h 47^m 04^s.780000$
Phase center δ	$+00^\circ 21' 42''.840$	$+00^\circ 21' 47''.800$	$+00^\circ 21' 42''.84000$
Obs. Date (YYYY-MM-DD)	2016-09-04	2018-01-07	2018-10-03
Cont. Sens. (mJy/bm)	0.339	0.065	5.499
Min. Res. (KHz, km/s)	141.109, 0.128	61.033, 0.083	35.277, 0.032
Int. Time (s)	48.384	1209.60	18.66
Baseline (Max, Min) (m)	3696.897, 15.065	2516.854, 15.068	48.949, 8.854
Ang. Res. (arcsec)	0.085	0.141	3.335
PWV (mm)	0.790	1.088	0.910
FOV (arcsec)	17.210	25.730	60.146
Flux calibrator	J0510+1800	J0510+1800	J0522-3627
Bandpass calibrator	J0510+1800	J0510+1800	JJ0522-3627
Phase calibrator	J0552+0313	J0532+0732	J0609-1542

A correlator in wide bandwidth mode with 3-bit samplers was utilised. A 4 GHz base-band was centred at 37 GHz and another at 28.9 GHz. The total integration time per target source was 60 seconds. The quasar J0137+3309 was observed as a flux calibrator and the quasar J0319+4130 was observed and used to calibration the bandpass. Quasar J0552+0313 was observed as a complex gain calibrator. To reduce phase decoherence at high frequencies, fast-switching mode of observation was employed.

Before the flux and bandpass calibrators were observed, the pointing corrections were applied. The gain calibrator was observed at hourly intervals throughout the observation period. Reduction of the raw data was done using the VLA pipeline. CASA version 4.4.0 was used throughout the reduction process. The FITS images were obtained from the VANDAM Orion dataverse (Tobin, 2019). The images are presented in chapter 5.

Table 4.5: Summary of 9 mm VLA continuum observation of NGC 2071-IR (HOPS-361) from Tobin et al (2020).

Obs. Date	Config.	Flux Cal.	Bandpass Cal.	Phase Cal.	F_ν (mJy)	Peak I_ν (mJy/beam)	HPBW (arcsec)	P.A. (deg)	RMS Noise (μ Jy)
09 Dec. 16	A	3C48	3C84	J0552–0313	5.446 0.026	3.007	0.10 0.07	64.4	8.8

4.5 KANATA/HONIR observations of NGC 2071-IR and data reduction

Near-infrared observations of NGC 2071-IR were made with the Kanata/Honir telescope (Sakimoto et al., 2012). The observations were made on 28 December 2019 and 3 January 2020. The December observations were in J, H, and Ks bands while the January 2020 observations were only made in Ks band. The exposure time for the observations was 40 s per observation, and the position angle of the half-wave plate was 67.5° . The images were 2048×2048 pixels. Darks (images taken with the shutter closed) were taken and the sky was also observed.

4.5.1 Data reduction and photometry of the KANATA/HONIR data

The raw files were calibrated prior to photometry. Science ready fits files were obtained after a series of calibration steps. The data was calibrated in the following steps:

- The raw fits files were corrected for bad pixels.
- The bad pixel-corrected files were then dark subtracted.
- The dark subtracted files were then pixel-sensitivity normalized (field-flat applied).

- The flattened image then had the NIR sky-background subtracted from them.

Figure 4.11 shows a flow chart for the reduction steps. Photometry was carried out on the calibrated images. Reference stars were selected from the 2MASS image of the field and labelled and their magnitudes were obtained. The magnitudes of the reference stars in the HONIR image were measured using IRAF task ‘phot’ in the ‘noao’ commands package. The aperture was set to 7.0 pixels. Magnitudes were also checked for aperture sizes of 8.0 and 9.0 pixels for consistency for the 2019 observations. IRAF version V2.16 with SAOImage DS9 was used throughout the reduction and photometry process (Tody, 1986). The images from the Kanata/HONIR observations are presented in the next chapter.

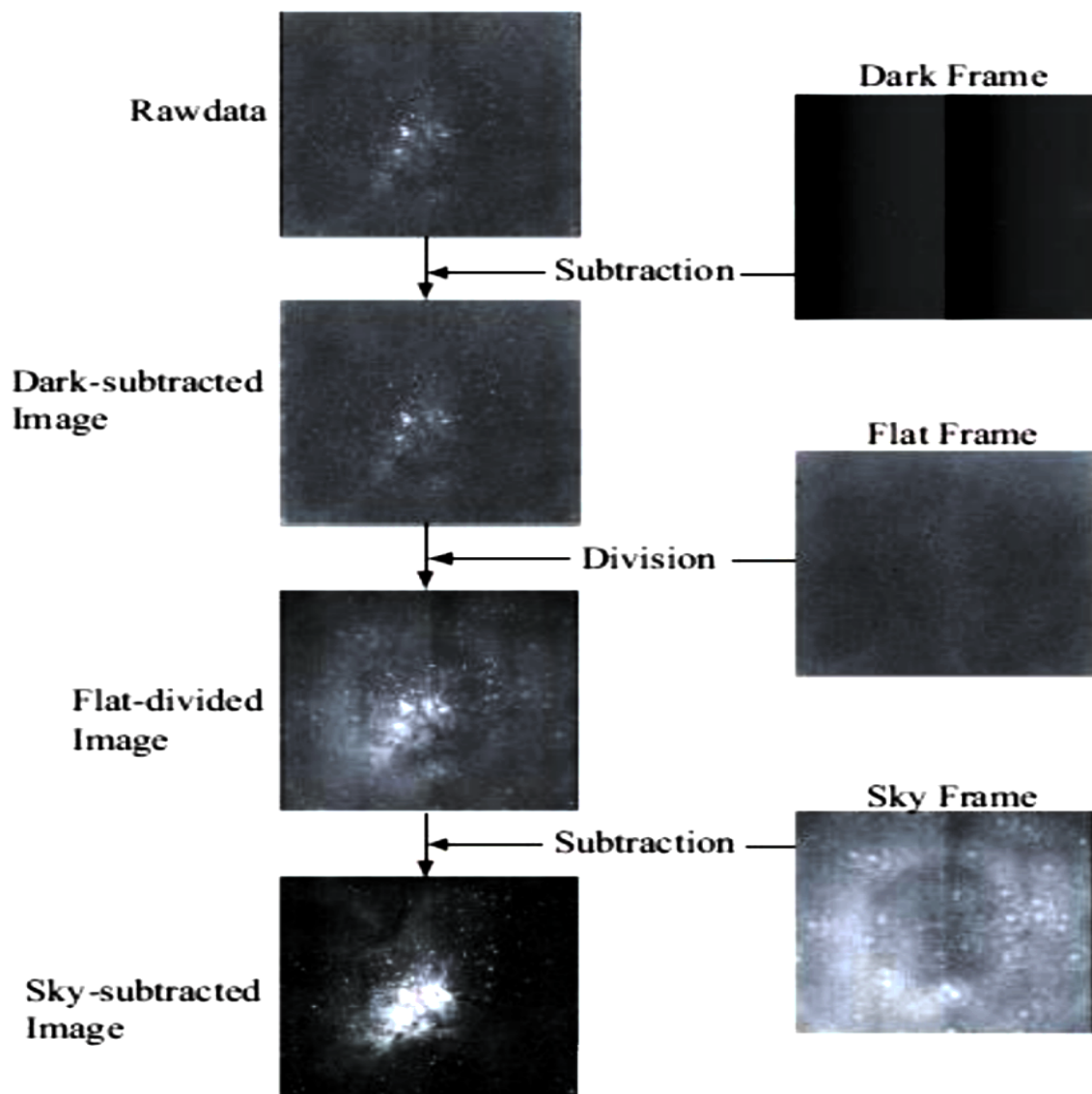


Figure 4.11: Flow chart of the near-infrared data reduction. Taken and modified from de Villiers (2009).

Chapter 5

Results

This chapter presents the results of the processed data from the instruments introduced in Chapter 3 and the observations described in Chapter 4. The results of the reduced 6.7 GHz CH₃OH maser observations and the 22 GHz H₂O maser observations with the HartRAO 26-m single-dish telescope are presented first, followed by the light curves of selected maser features and their time series analysis. The results from the estimation of variability indexes of the water masers are presented thereafter. In addition, the continuum and the spectral line images from the archival interferometric observations described in the previous chapter are presented. The masses of the continuum cores, IRS 3, IRS 1, and VLA 1, estimated from the interferometric images, are also presented. The chapter ends with the presentation of the photometry results of the near-infrared observations with the Kanata/HONIR telescope.

5.1 Results from single-dish observations

5.1.1 Non-detection of 6.7 GHz methanol masers

A total of 48 unique observations were reduced with post-processed PSS values. The PSS distribution of 3C123 from January 2019 to May 2020 is shown in Figure 5.1. The average PSS of the LCP and RCP was 5.2 Jy K⁻¹ and 4.2 Jy K⁻¹, respectively, for the post-processed data. The V_{lsr} of the reduced spectra ranged from 1.22 km s⁻¹ to 23.69 km s⁻¹. Figure 5.2 shows a sample of reduced 6.7 GHz methanol (CH₃OH) maser from an observation made with the HartRAO 26-m telescope. The spectrum from all epochs remained flat, with no visible maser features detected. A dynamic spectral plot, shown in Figure 5.3, was made from all 48 reduced spectra. There are no visible maser features over the whole time range.

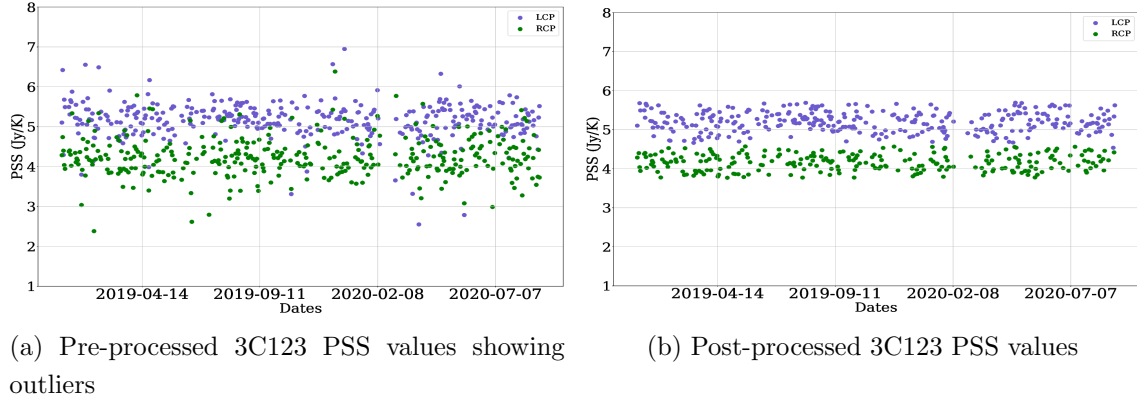
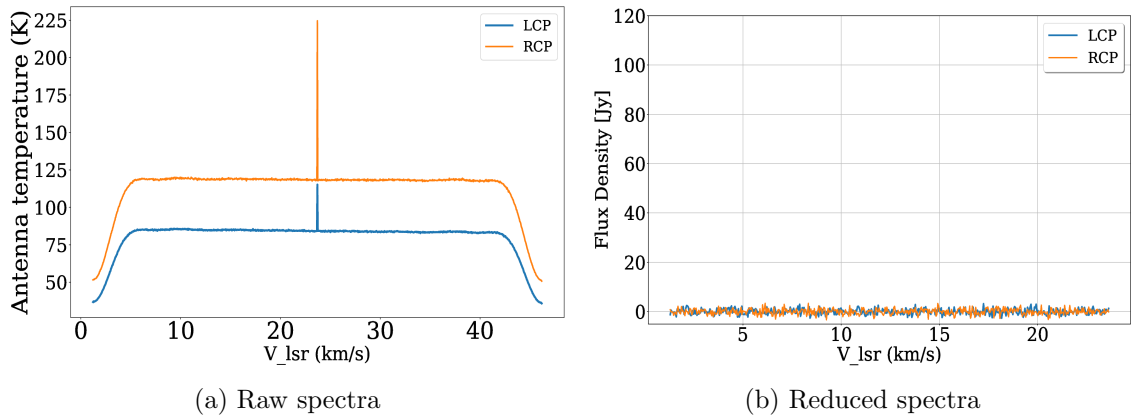
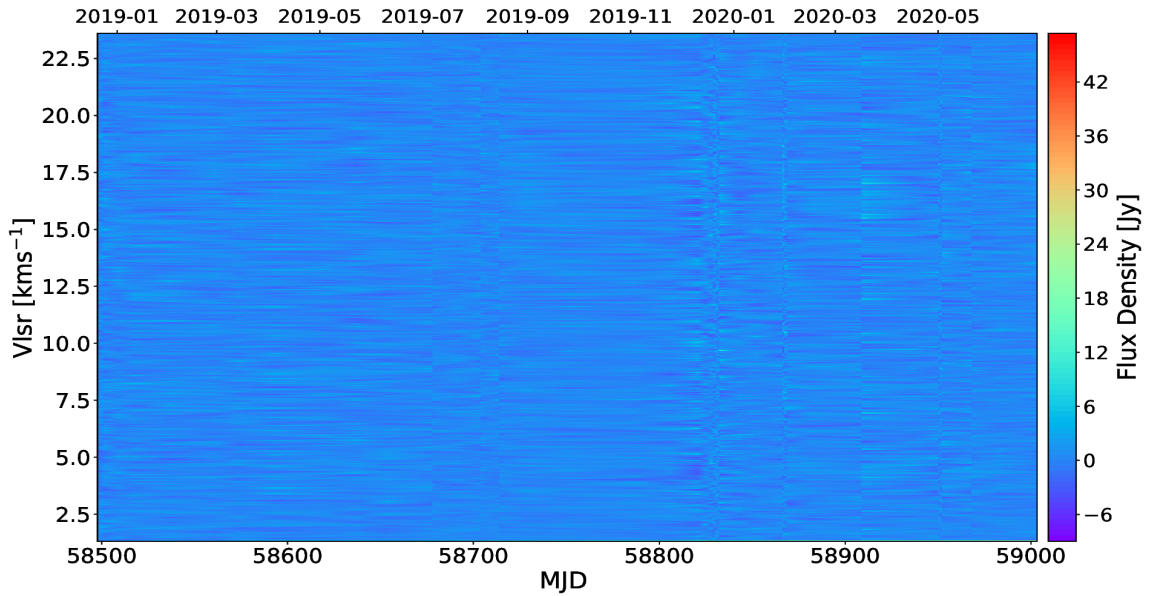


Figure 5.1: Pre-processed and post-processed 3C123 PSS values

Figure 5.2: Uncalibrated and calibrated 6.7 GHz CH_3OH spectra of NGC 2071-IR observed on 2019-01-18 (MJD 58501). No maser features were detected.Figure 5.3: Dynamic spectra of NGC 2071-IR 6.7 GHz CH_3OH maser observations from 2019 to 2020. No maser was detected over the total time range.

5.1.2 Variations in the 22 GHz water maser spectra

Reduction of the 460 water maser data revealed the detection of multiple maser features. Table 5.1 presents the dominant maser features in the spectra. The maser features appear to drift in velocity over time. The position of their peak also appears to drift. Due to a large number of maser spectra, six spectra rich with maser features are presented per calendar year. Only five are presented for the 2022 observations.

Table 5.1: Velocity of the main maser features in the H₂O maser spectra of NGC 2071-IR and their peak flux density

Peak velocity of maser feature (km s ⁻¹)	-6.35	-3.40	-3.35	-1.29	3.33	3.34	9.97	10.07	14.60	15.02
Peak flux density (Jy)	387.4	1459.9	1384.8	457.2	1609.6	1798.5	1463.5	1475.2	4417.5	2040.1
Peak flux density error +/- (Jy)	2.0	4.7	7.3	1.0	1.1	1.1	7.3	7.3	2.4	2.2
Associated core*	-	IRS 3	IRS 3	IRS 1	IRS 3	IRS 3	IRS 1	IRS 1	IRS 1	IRS 3

* Based on water maser positions from Seth et al. (2002) (see Appendix C).

Six NGC 2071-IR H₂O maser spectra, sampled from the 2019 batch of spectra, are presented in Figure 5.4. The spectra show significant variation in the size and profile of the maser features in the spectra. The maser features appear joined together from velocity channels 9.97 km s⁻¹ to 19 km s⁻¹. A feature at $V_{lsr} = -6.35$ km s⁻¹ was initially present with a peak flux value of 24 ± 2 Jy, occurring at velocity channel -6.77 km s⁻¹. By 12 February 2019 (MJD 58526), the -6.35 km s⁻¹ feature disappeared and only reappeared on 11 November 2019 (MJD 58798) and again on 13 November 2019 (MJD 58800) spectra.

A total of 232 high-cadence 22 GHz H₂O maser observations towards NGC 2071-IR, made in 2020 were reduced. Figure 5.5 shows 6 H₂O maser spectra sampled from the 2020 batch of reduced spectra. The spectra showed variation in the velocity position of the dominant features. A masing feature with peak intensity at $V_{lsr} = 5.51$ km s⁻¹ appeared on MJD 58853, and its peak drifted gradually in V_{lsr} from -5.51 km s⁻¹ to -6.56 km s⁻¹ before it disappeared on MJD 58887. The feature reached a maximum intensity of 415 ± 3 Jy on MJD 58867 with the peak intensity occurring at velocity channel -5.93 km s⁻¹. The $V_{lsr} = 14.60$ km s⁻¹ feature remained the dominant feature, which had a peak intensity of 3427 ± 4 Jy. The $V_{lsr} = 3.44$ km s⁻¹ feature appeared on MJD 59063 and increased in amplitude to become the dominant feature, peaking on MJD 59119, with an intensity of 1798 ± 1 Jy before gradually decreasing to 12 ± 1 Jy. Observations in the fourth quarter of 2020 saw an increase in H₂O maser activity towards NGC 2071-IR. Several new features appeared, particularly around the $V_{lsr} = 14.60$ km s⁻¹ and 15.02 km s⁻¹ features, but were not clearly discernible. The $V_{lsr} = -3.51$ km s⁻¹ and -3.40 km s⁻¹ features were quiescent throughout 2020.

A total of 136 unique observations made in 2021 were reduced. Similar to the 2020 observations, the dominant feature changed from the $V_{lsr} = 14$ km s⁻¹ to the 10 km s⁻¹ feature and finally to the 3.5 km s⁻¹ feature. The $V_{lsr} = -6.35$ km s⁻¹ feature remained quiescent

throughout 2021. A discernible feature appeared briefly between the $V_{lsr} = -3.5 \text{ km s}^{-1}$ and -1.2 km s^{-1} from MJD 59528 to MJD 59546, lasting only 18 days. Figure 5.6 shows six samples of reduced water maser spectra towards NGC 2071-IR.

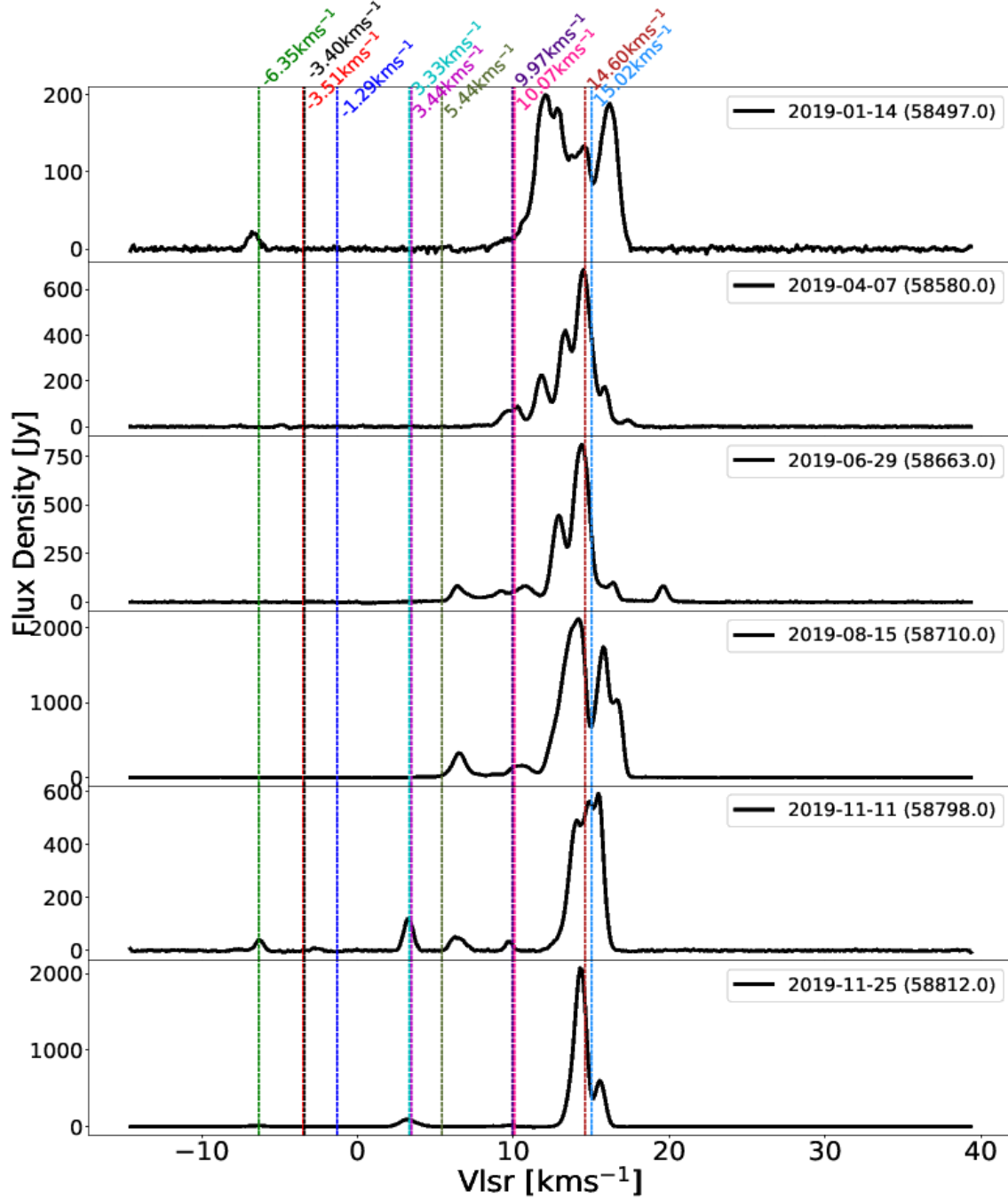


Figure 5.4: Six samples of 22 GHz H_2O maser spectra observed in 2019. Vertical coloured lines indicate the positions of the main maser features. The flux density scales vary per spectra.

Figure 5.7 shows five selected spectra from the 2022 observations. The $V_{lsr} = -3.51 \text{ km s}^{-1}$ maser feature remained the dominant feature with flux density reaching $654 \pm 4 \text{ Jy}$. The

$V_{lsr} = 14.60 \text{ km s}^{-1}$ feature, which dominated the 2021 spectra remained around 300 Jy. The $V_{lsr} = 9.97 \text{ km s}^{-1}$ feature reduced in flux over time but remained within the range of 150 to 250 ± 1 Jy. Finally, the $V_{lsr} = -1.2 \text{ km s}^{-1}$ feature, which disappeared after flaring briefly to a peak flux of 303 ± 4 Jy in 2021 on MJD 59539, reappeared in 2022 and increased in flux to 203 ± 1 Jy. The $V_{lsr} = -6.35 \text{ km s}^{-1}$ feature did not reappear in the 2022 spectra.

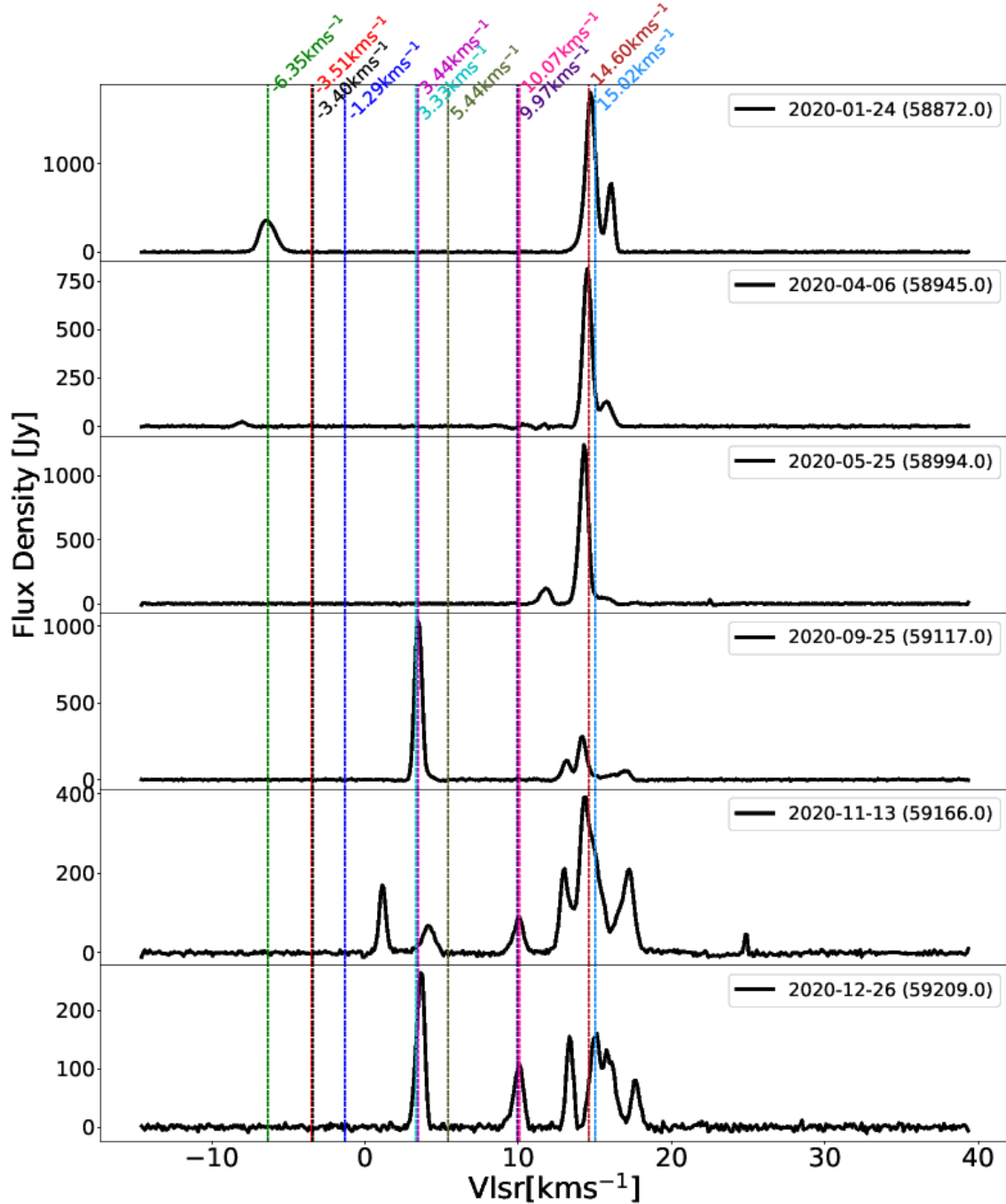


Figure 5.5: Samples of 22 GHz H₂O maser spectra observed in 2020. Multiple features appeared in the last quarter of 2020.

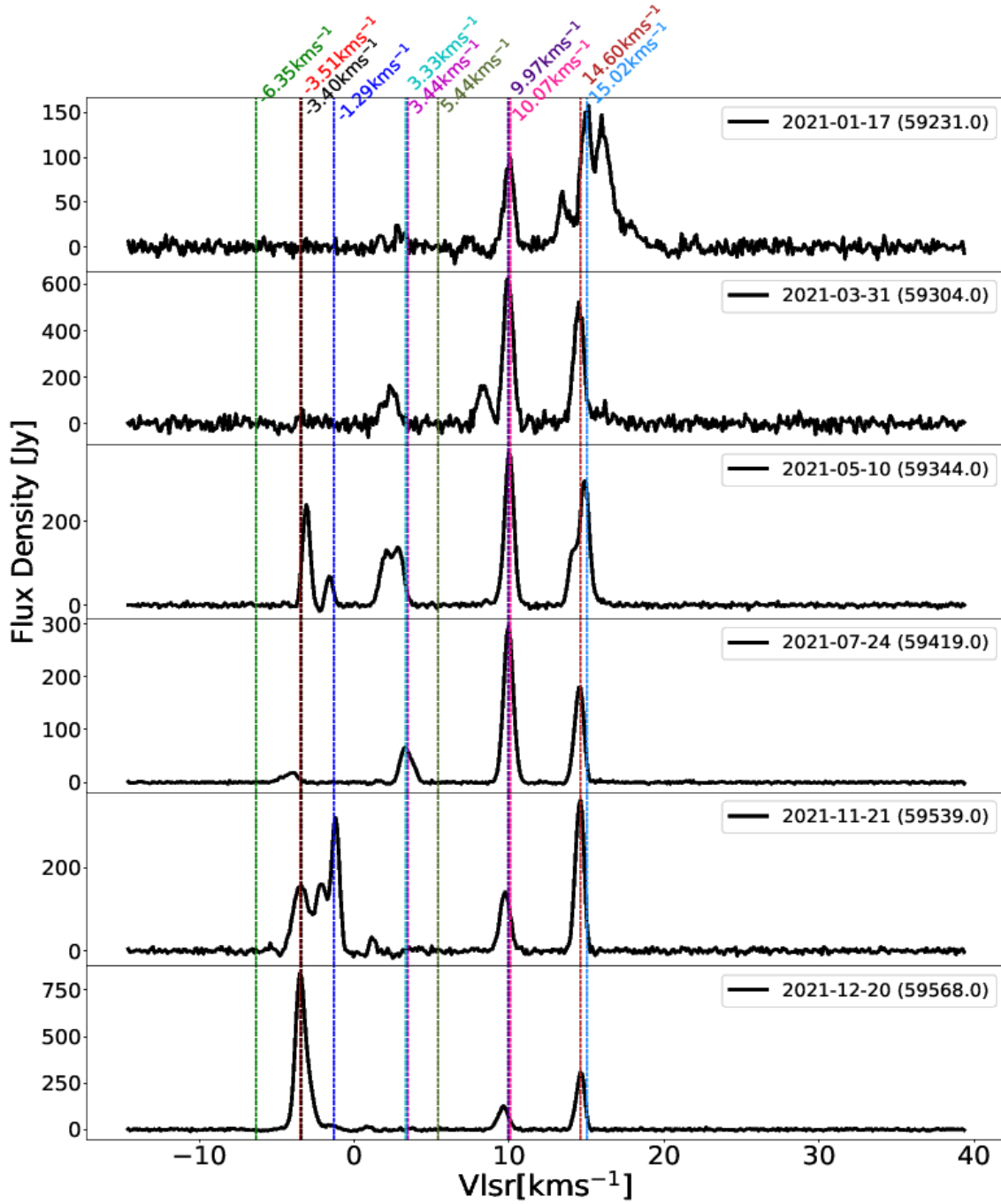


Figure 5.6: Samples of calibrated water maser spectra from the 2021 observations. Multiple features appeared and disappeared during the period.

5.1.3 Light curves of dominant 22 GHz water maser features

Light curves for the channels with the main maser features of the 22 GHz water maser spectra listed in Table 5.1 are presented in Figure 5.8. The sparsely populated observations of 2019 are clearly visible, as well as the pause in observations in 2021.

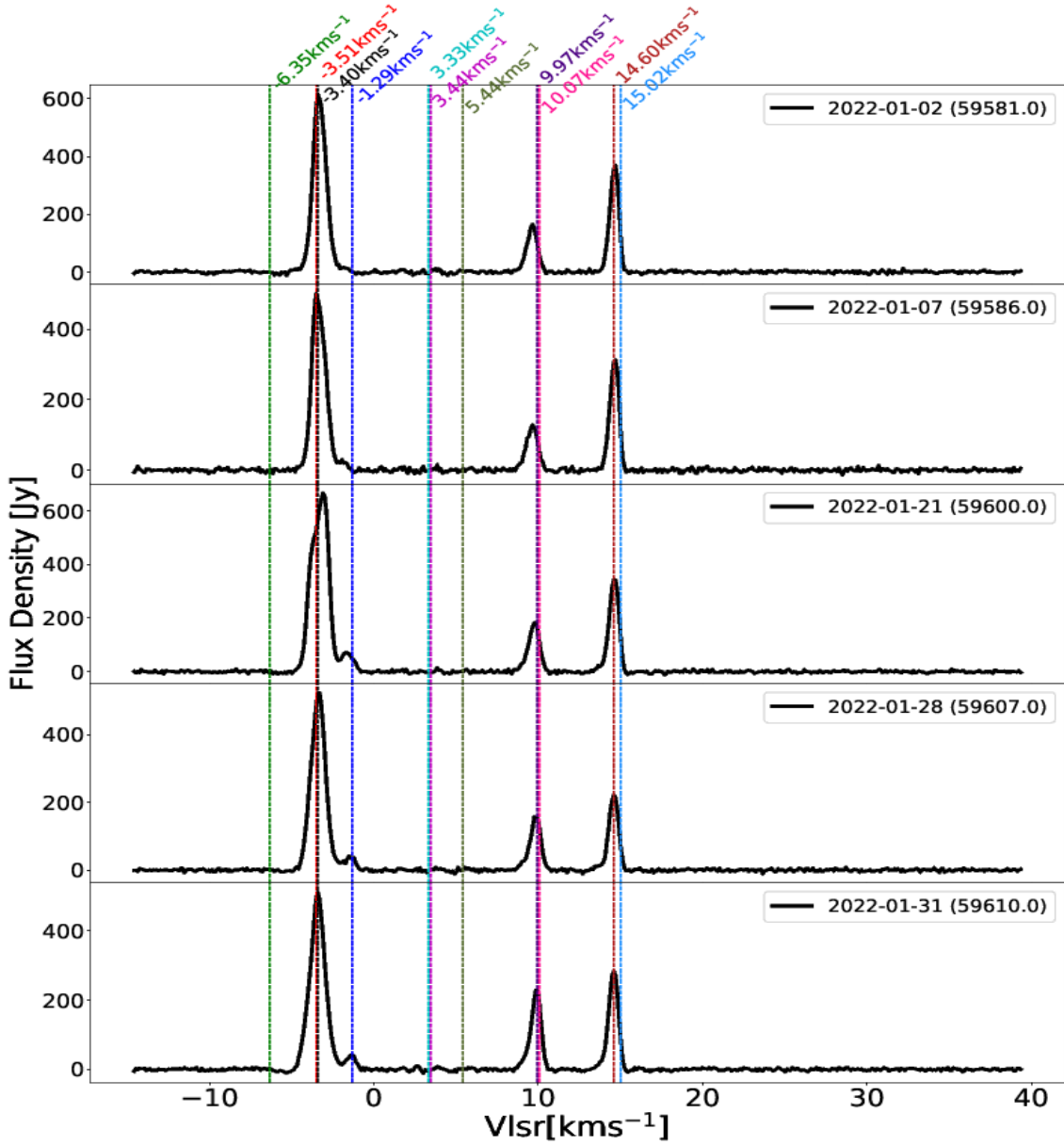


Figure 5.7: Samples of 22 GHz H_2O maser spectra observed in 2022. The $V_{lsr} = -3.51 \text{ km s}^{-1}$ feature became the dominant feature. The $V_{lsr} = -3.51 \text{ km s}^{-1}$ and the -3.40 km s^{-1} feature appear to drift into each other over time. The same is shown by the $V_{lsr} = 9.97 \text{ km s}^{-1}$ and 10.07 km s^{-1} features.

The $V_{lsr} = -6.35 \text{ km s}^{-1}$ feature emerged and peaked in amplitude approximately the same time that the $V_{lsr} = 15.02 \text{ km s}^{-1}$ was peaking in amplitude. The $V_{lsr} = 14.39 \text{ km s}^{-1}$ feature, which blended into the 14.60 km s^{-1} feature, was just decreasing after a rise in amplitude, which reached a flux density of $4722 \pm 4 \text{ Jy}$ at its peak on MJD 58837. The flux density of the flares that occurred at later MJDs did not reach the values seen at the start of the flaring activity, but rather only attained a maximum of $1798 \pm 1 \text{ Jy}$ and averaged $1400 \pm 1 \text{ Jy}$.

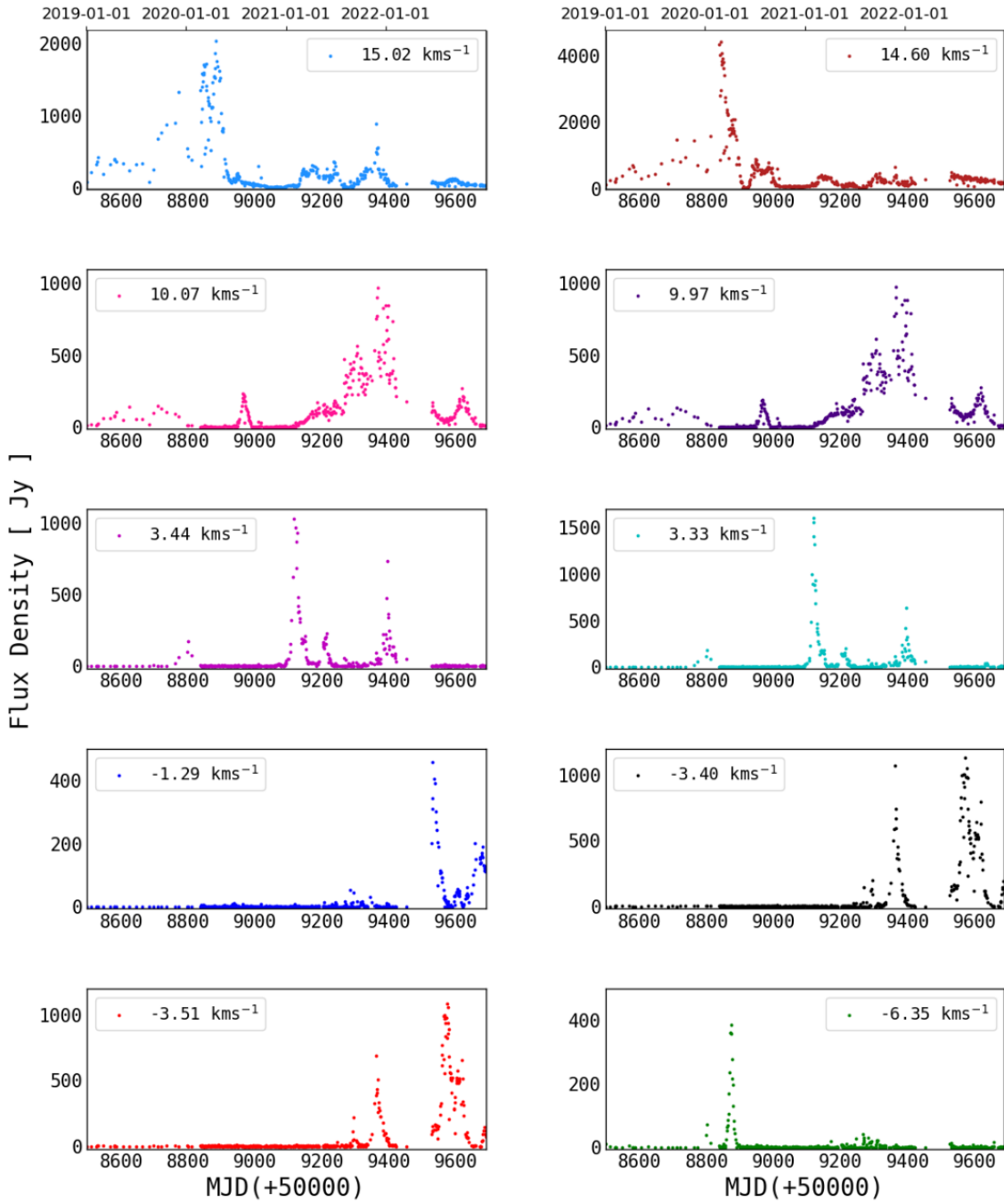


Figure 5.8: Time series of channels (in km s^{-1}) with dominant water maser features in the 22 GHz H_2O maser spectra listed in Table 5.1. The upper x-axis is Julian dates, which correspond to the modified Julian dates on the bottom x-axis.

The light curve of the brightest maser feature ($V_{lsr} = 14.4 \text{ km s}^{-1}$) in the HarTRAO data exhibits four distinct flares. The first flare km-designated as Flare 1 and depicted within the red box in Figure 5.9, exhibited a gradual rise over 341 days to reach a maximum, followed by a rapid decline to reach a minimum over 79 days on MJD 58915 (7 March 2020). The duration of the first flare was 420 days. A second flare (Flare 2), was observed

exhibiting a similar gradual rise and rapid decline after reaching a peak, with a peak value of 1459 ± 1 Jy. A third flare followed, exhibiting a gradual rise and decay for approximately 100 days. A fourth flare was also observed, which lasted 77 days. The $V_{lsr} = 14.4 \text{ km s}^{-1}$ feature was only detected towards IRS 1 and the 14.6 km s^{-1} and 15.0 km s^{-1} which were also reported towards IRS 1 all have almost the exact light curve profile as the 14.4 km s^{-1} feature. It is thus safe to assume the strong flare in 2019 originated from IRS 1.

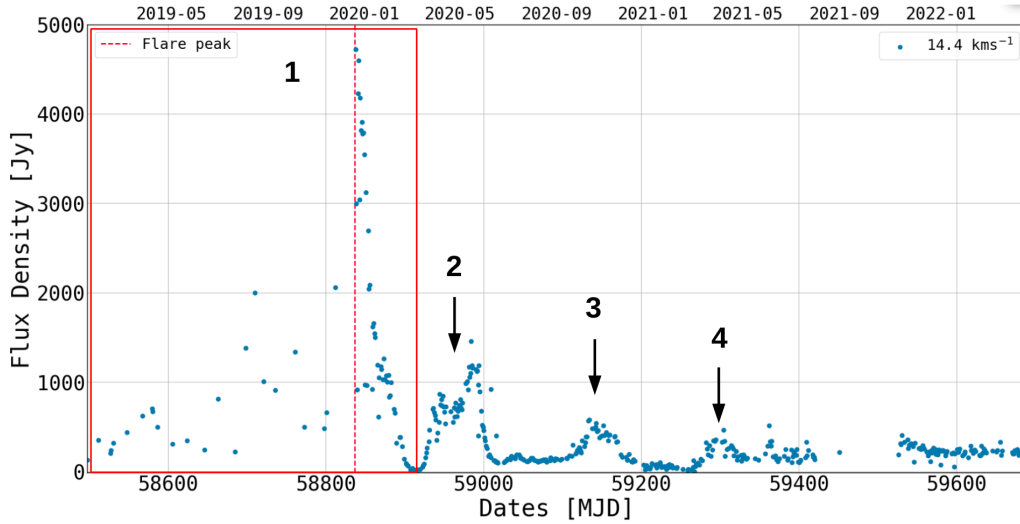


Figure 5.9: Light curve of brightest water maser feature ($V_{lsr} = 14.4 \text{ km s}^{-1}$) in the Hartrao data. The first flare is in a red box with the vertical dashed red line showing the position of the peak of the first flare. The other flares have been labelled.

The light curve profiles of the $V_{lsr} = 9.97 \text{ km s}^{-1}$ and 10 km s^{-1} features are also identical, with the 10 km s^{-1} feature detected towards IRS 3 by Torrelles et al. (1998), and towards IRS 1 by Seth et al. (2002) and Trinidad et al. (2009). The light curves of the $V_{lsr} = 3.44 \text{ km s}^{-1}$ and 3.33 km s^{-1} features, which, based on historical maser spot maps, are exclusively associated with IRS 3 (see Appendix C), also have identical profiles. Figure 5.10 presents the light curves of the dominant maser features exclusively associated with IRS 3 according to the spot maps from the literature, including the combined light curves of the 3.44 km s^{-1} and -3.51 km s^{-1} features. The light curve of the 3.44 km s^{-1} feature shows two major flares, with the strongest flare lasting 38 days and reaching a maximum of 1798.5 ± 4 Jy. The $V_{lsr} = -3.40 \text{ km s}^{-1}$ feature also flared with a similar profile, but with a narrower width and a duration of 92 days. Gaussian fits of the flares revealed the presence of two peaks in the second flare in both the $V_{lsr} = -3.40 \text{ km s}^{-1}$ and -3.51 km s^{-1} light curves, with the highest peak occurring on MJD 59570 (22 December 2021). The second strongest flare of the $V_{lsr} = 3.44 \text{ km s}^{-1}$ feature and the first flare of the -3.40 km s^{-1} feature have identical profiles, and their peaks are separated by 33 days, with the -3.40 km s^{-1} flare lasting 92 days and the 3.44 km s^{-1} flare lasting 38 days, respectively.

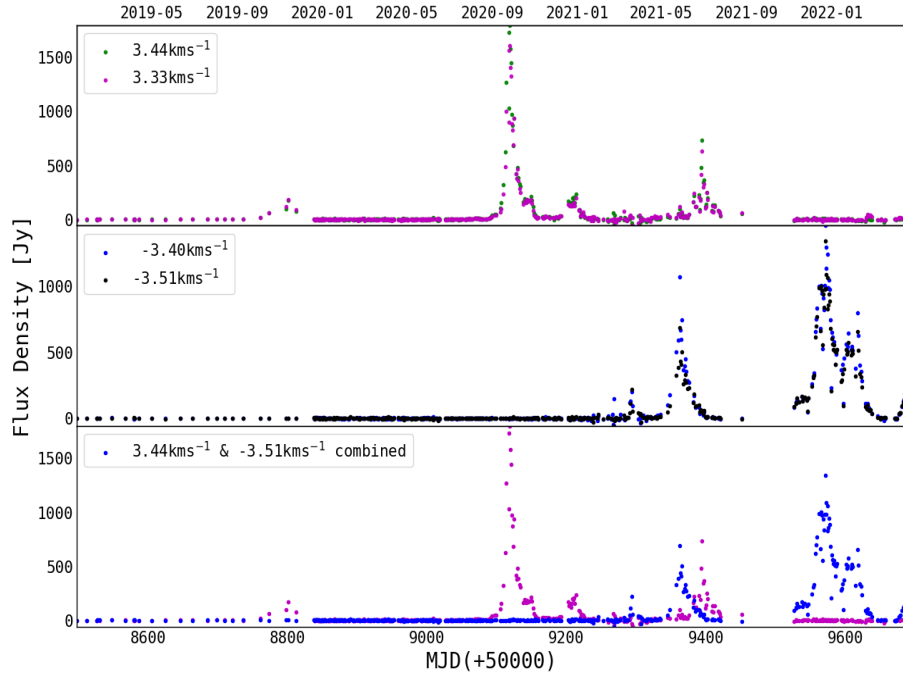


Figure 5.10: Light curve of dominant water maser features associated with IRS 3.

5.1.4 Dynamic spectra of 22 GHz water masers

The total intensity values at each velocity in all the reduced spectra of NGC 2071-IR water masers from 2019 to 2022 were utilised to produce a dynamic spectra plot utilizing python scripts. Dynamic spectra plots help in visualizing the flux density variations of the maser features over time. Figure 5.11 shows the dynamic spectra of the water masers.

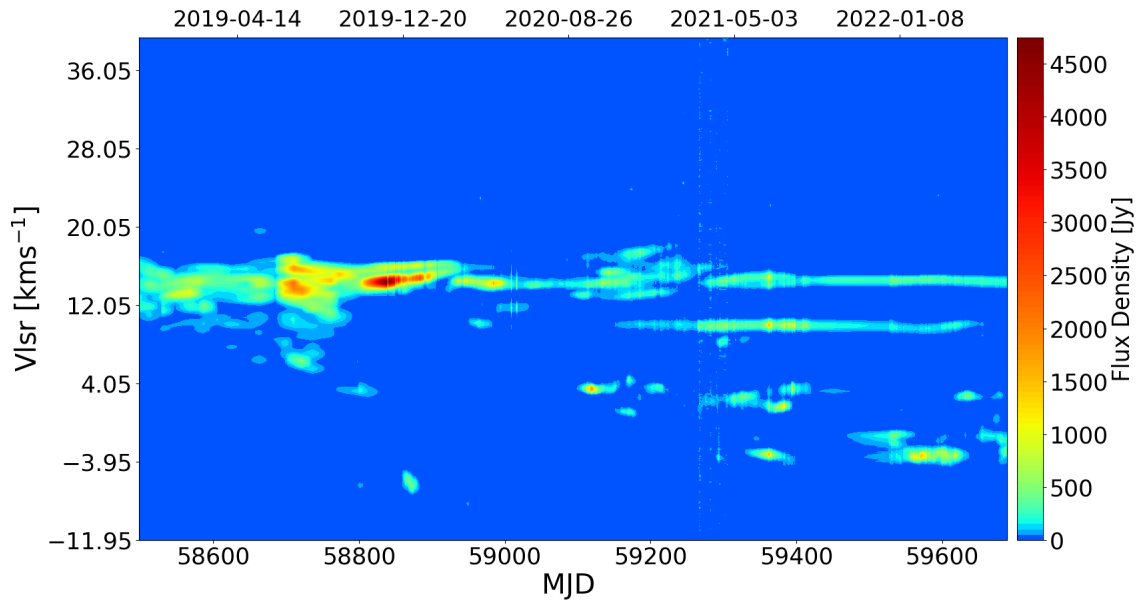


Figure 5.11: Dynamic spectra of 22 GHz H_2O maser in NGC 2071-IR.

5.2 Estimation of variability-indexes of the water masers

It is relatively easy to see the variability in the water maser spectra plot; however, visual observation is not a quantifiable method. With this limitation, a more objective method for estimating the variability was desired. The procedures of estimating variability index I for a time series of single-dish maser observations introduced by Goedhart et al. (2004) were adopted. Stetson's formula for automatic determination of lightcurve parameters such as the variability index for Cepheid variable stars (Stetson, 1996), which was adapted and modified by Goedhart et al. (2004), was used for the variability index estimation. It is given as:

$$I = \frac{\sum_{i=1}^N (F_\nu(t_i) - \bar{F}_\nu)^2 - \sum_{i=1}^N [(Fn(t_i) - \bar{F}n)]^2}{\bar{F}_\nu}, \quad (5.1)$$

where $F_\nu(t_i)$ is the observed flux density at a specified velocity channel, $Fn(t_i)$ is the flux density in a channel with no detected emission (noise channel), N is the total number of observations, $\bar{F}_\nu$ is the mean flux density in the specified velocity channel over the total time series, $\bar{F}n$ is the mean flux density in the noise channel and I is the variability index.

The variability indexes were calculated using the antenna temperature values instead of the flux density values. This was done to avoid introducing errors arising from the variability in the PSS values. The time series of the water masers were divided into 4 Julian calendar years before the variability indexes were calculated for the dominant maser features. The velocity channel $V_{lsr} = 35.35 \text{ km s}^{-1}$ was used as the noise channel since it remained feature-free in all observations. There were negative flux values present in the data, particularly in the 2021 data, which seem to be generated by system fluctuations. These values increase the variability index values when they are subtracted and squared via $[Fn(t_i) - \bar{F}n]^2$. The absolute value of the fluxes of the noise channel was thus used throughout the calculation to remove large negative flux values. Table 5.2 shows the calculated variability indexes. The highest variability indexes were in the 2020 time series, with the highest value estimated to be 21626.8 for the $V_{lsr} = 15.03 \text{ km s}^{-1}$ maser feature. The high variability index values may be partly due to the high cadence of the 2020 observations as well as the period coinciding with the post-flaring phase where the fluxes reduced significantly over a short period (see Figure 5.8). Similar to the findings by Goedhart et al. (2004), there is no correlation between the average flux densities and the degree of variability. For the 2019 variability index values, the high variability of the $V_{lsr} = 14.6 \text{ km s}^{-1}$ may be attributed to the flaring which occurred from November to December 2019. The feature with the highest flux density during the flare was in the $V_{lsr} = 14$ to 15 km s^{-1} velocity range. In the 2020 line profiles, the $V_{lsr} = 3.44$, 14.61 , and the 15.03 km s^{-1} features took turns becoming the dominant feature. Interestingly, these features all had high variability indexes in orders of 10^4 in 2020. In 2021, the water masers exhibited a relatively calmer phase, which was reflected in the variability indexes that were all on the order of

10^3 . The 2022 variability indexes had the lowest values, which may be explained by the lower number of observations.

Table 5.2: Variability indexes (I) for the dominant features in the 22 GHz water maser spectra.

V_{lsr} (km s $^{-1}$)	$\bar{F}_\nu$	$\bar{F}n$	$\sum_{i=1}^N (F_\nu(t_i) - \bar{F}_\nu)^2$	$\sum_{i=1}^N [Fn(t_i) - \bar{F}n]^2$	I
2019					
-6.35	-0.1	0.5	53.8	1.8	-623.9
-3.51	40.2	0.5	57963.2	1.8	1442.2
-3.41	41.6	0.5	61734.1	1.8	1483.3
-1.30	2.7	0.5	255.5	1.8	92.7
3.44	22.8	0.6	5188.4	2.8	227.1
10.08	15.5	0.5	6502.7	1.8	420.7
14.40	213.1	0.5	2682993.0	1.8	12592.1
14.61	215.5	0.5	2500153.5	1.8	11599.0
15.03	94.7	0.5	387988.8	1.8	4097.9
2020					
-6.35	0.8	0.6	13785.7	21.8	16299.5
-3.51	54.6	0.6	326395.7	21.8	5972.5
-3.41	56.5	0.6	348234.8	21.8	6161.6
-1.30	3.6	0.6	1521.0	21.8	411.0
3.44	2.2	0.6	47491.9	21.8	21348.1
10.08	20.3	0.6	33783.3	21.8	1665.2
14.40	46.5	0.6	664816.0	21.8	14295.2
14.61	54.1	0.6	1066915.9	21.8	19703.9
15.03	26.0	0.6	562425.6	21.8	21626.8

Table 5.3: Table 5.2 continued

V_{lsr} (km s ⁻¹)	$\bar{F}_\nu$	$\bar{F}_n$	$\sum_{i=1}^N (F_\nu(t_i) - \bar{F}_\nu)^2$	$\sum_{i=1}^N [F_n(t_i) - \bar{F}_n]^2$	I
2021					
-6.35	-0.2	0.8	168.2	172.8	21.4
-3.51	61.6	0.8	165399.4	172.8	2679.8
-3.41	65.4	0.8	188932.7	172.8	2885.3
-1.30	5.0	0.8	6843.9	172.8	1333.4
3.44	1.6	0.8	5406.6	172.8	3306.3
10.08	35.2	0.8	106244.3	172.8	3010.8
14.40	30.5	0.8	15014.1	172.8	487.0
14.61	37.7	0.8	20988.1	172.8	551.7
15.03	16.9	0.8	37417.7	172.8	2208.2
2022					
-6.35	-0.2	0.8	168.2	172.8	-13.3
-3.51	62.8	0.6	52983.6	2.8	843.6
-3.41	65.5	0.6	56044.6	2.8	855.0
-1.30	7.5	0.6	2281.0	2.8	305.0
3.44	0.0	0.6	10.1	2.8	1536.1
10.08	22.8	0.6	5188.4	2.8	227.1
14.40	30.5	0.8	15014.1	172.8	26.5
14.61	39.5	0.6	1797.7	2.8	45.4
15.03	11.7	0.6	541.4	2.8	46.2

5.3 Interferometric observations: Continuum images

The radio continuum emission from the NGC 2071-IR region was imaged from interferometric observations made by ALMA and VLA described in chapter 4. To develop a detailed multi-wavelength view of the region, additional continuum images at other wavelengths were obtained from public repositories. Multiwavelength continuum images offer insight into the morphology of the region.

ALMA (ACA) 0.8 mm band 7 continuum image

Figure 5.12 displays the intensity map of the 0.88 mm continuum produced from the observation of the NGC 2071-IR (HOPS 361) region using the ALMA Compact Array (ACA). The image size is 400×400 pixels and the beam size is $5.71'' \times 2.87''$, with a beam position angle of -74° . Two distinct continuum cores joined together can be visually identified with a lobe structure at the northeast side of the first core. The centre of the two cores coincides with the positions of NGC 2071 IRS3 and NGC 2071 IRS1, respectively. The peak flux density was 1.58 ± 0.14 Jy/Beam, located at the centre of IRS 3.

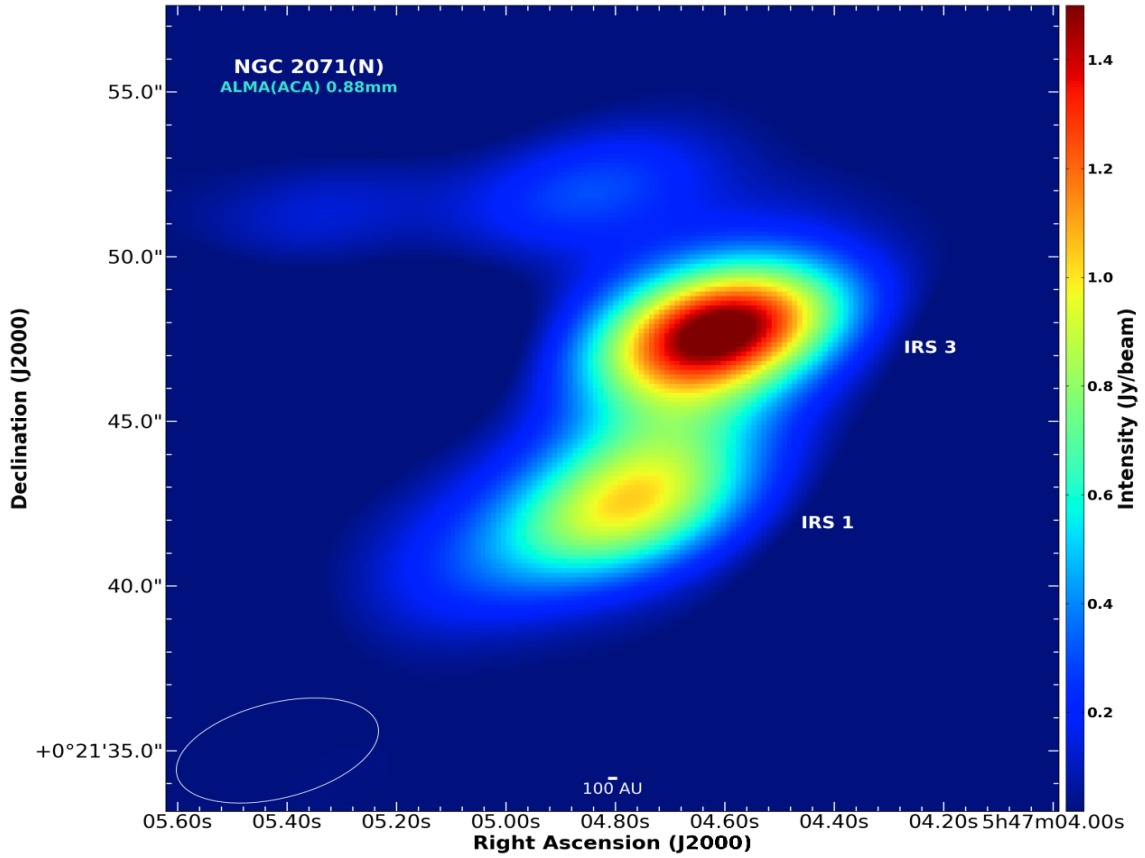


Figure 5.12: ALMA Compact Array (ACA) band 7 continuum map of NGC 2071-IR region as observed on 12 October 2018. IRS 3 and IRS 1 cores are prominent.

ALMA 1.3 mm continuum image

The 1.3 mm continuum emission distribution of NGC 2071-IR, observed by ALMA in band 6, was imaged and is shown in Figure 5.14. Five measurement sets were obtained and combined to increase the sensitivity. The image size, cell size, and synthesized beam were 1008×1008 pixels, 0.044 arcseconds, and $0.31'' \times 0.28''$ (BPA= -60°), respectively. The stokes plane was ‘I’, and the phase centre was ICRS 05:47:04.634000 +00.21.47.80000. Seven unique spectral windows were combined to produce the continuum image using multi-frequency synthesis (mfs). Using Högbom’s deconvolver, a standard gridded was employed with Briggs weighting, which provides a good compromise between sensitivity and resolution. The peak flux density was 149 ± 3.5 mJy and the signal-to-noise ratio was 418. Eight continuum cores were resolved. The recently discovered embedded YSO named VLA 1 (Trinidad et al., 2009), was resolved and is located between IRS 3 and IRS 1. Calibration processes and imaging were done with CASA version 5.4.0-68.

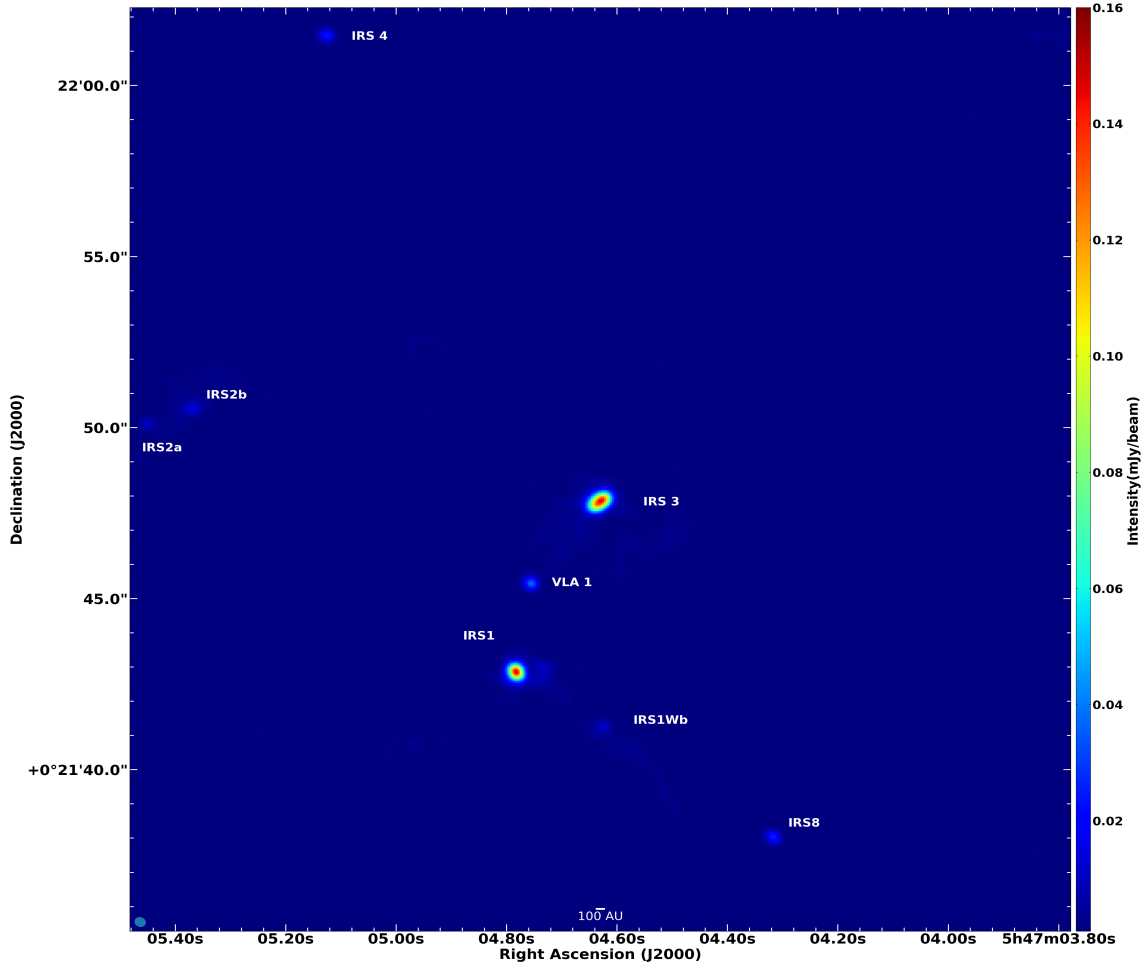


Figure 5.13: The 1.3 mm ALMA band 6 continuum image of NGC 2071-IR. The labelled cores; IRS 1, IRS 1Wb, IRS 2, IRS 3, IRS 4, IRS 8, and VLA 1 were resolved.

ALMA 0.8 mm band 7 extended configuration continuum image

Figure 5.14 presents the 0.88 mm ALMA continuum map of NGC 2071 (HOPS-361) obtained from the VANDAM database (Tobin et al., 2020b). Deconvolution and imaging were done using CASA 4.7.2 using multi-frequency synthesis (mfs). The image size, synthesized beam size, and position angle were 2450×2450 pixels, $0.12'' \times 0.10''$, and -67.0 degrees, respectively. The root mean square (rms) noise level of the image was 2.67 mJy. The peak flux is 148 ± 6.9 mJy/beam. Three continuum cores were resolved, with two coinciding with the positions of infrared counterparts NGC 2071-IRS3 and NGC 2071 IRS1. VLA 1 was also resolved and located offset to the left from the centre of the image. NGC 2071-IRS3 appears elongated in the south-west direction, whilst IRS 1 appears to be oval, with two protrusions appearing at the top and bottom pointing in opposite directions.

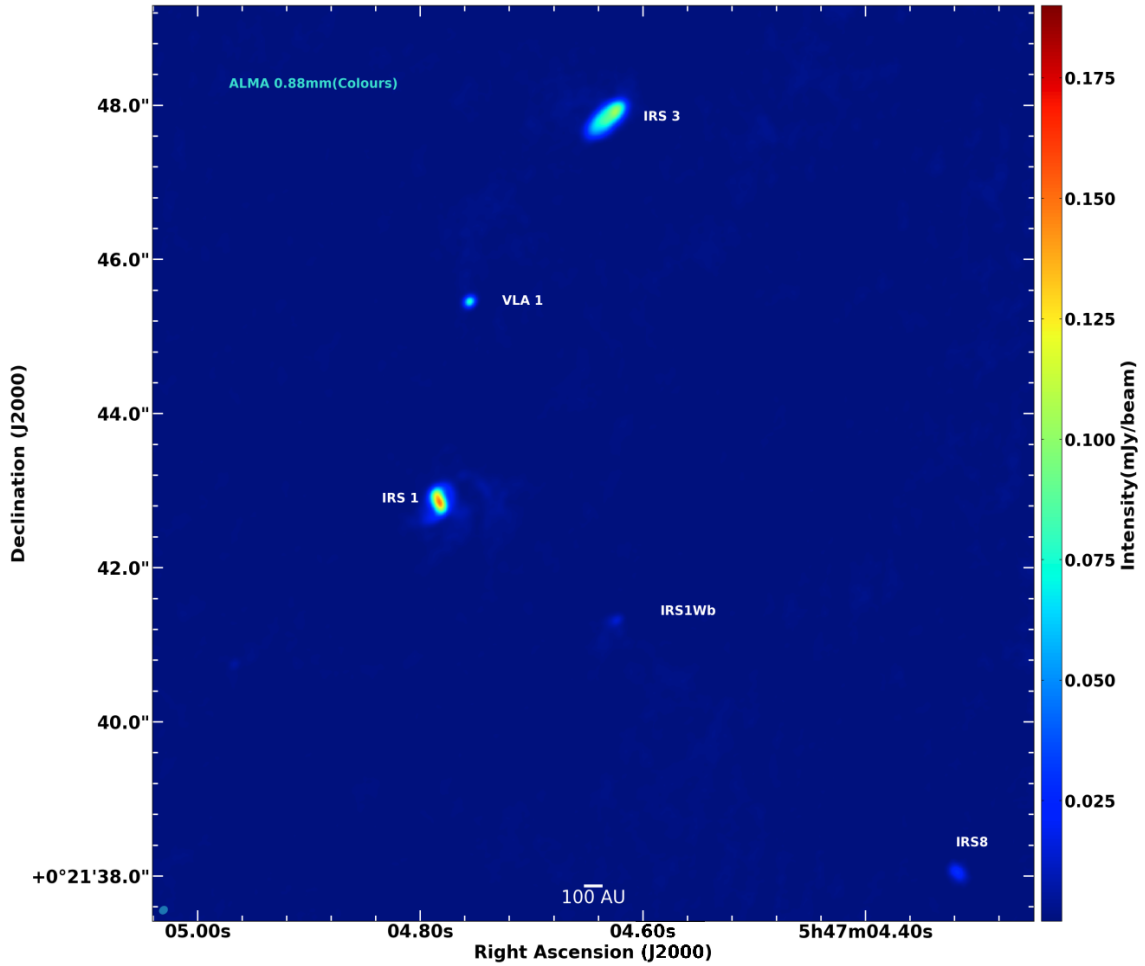


Figure 5.14: ALMA band 7 continuum image of NGC 2071-IR region observed on 3 September 2016. Three sub-millimetre continuum cores were detected with the positions of two coinciding with infrared counterparts IRS 3, IRS 1, IRS 8, and VLA 1, which does not have an infrared counterpart.

5.3.1 VLA continuum images

VLA 3.6 cm continuum image

Figure 5.15 shows the VLA 3.6 cm continuum image obtained from Carrasco-González et al. (2012). The image was made using natural weighting with multi-frequency synthesis (mfs), producing an rms of $19 \mu\text{Jy beam}^{-1}$. Continuum cores IRS 3 and IRS 1 were both resolved to show elongated continuum emission from the core. VLA 1 was also resolved and visible in the centre of the image. Visually, IRS 1 shows an extended, arm-like protrusion extending towards the northwest direction. The peak emission was 2.65 mJy/beam , located at the centre of IRS 1 and the SNR was 170. The image size is 2048×2048 pixels and the synthesized beam size was $0.34'' \times 0.252''$ (BPA= -13.64°). Additional details of the image can be found in Carrasco-González et al. (2012).

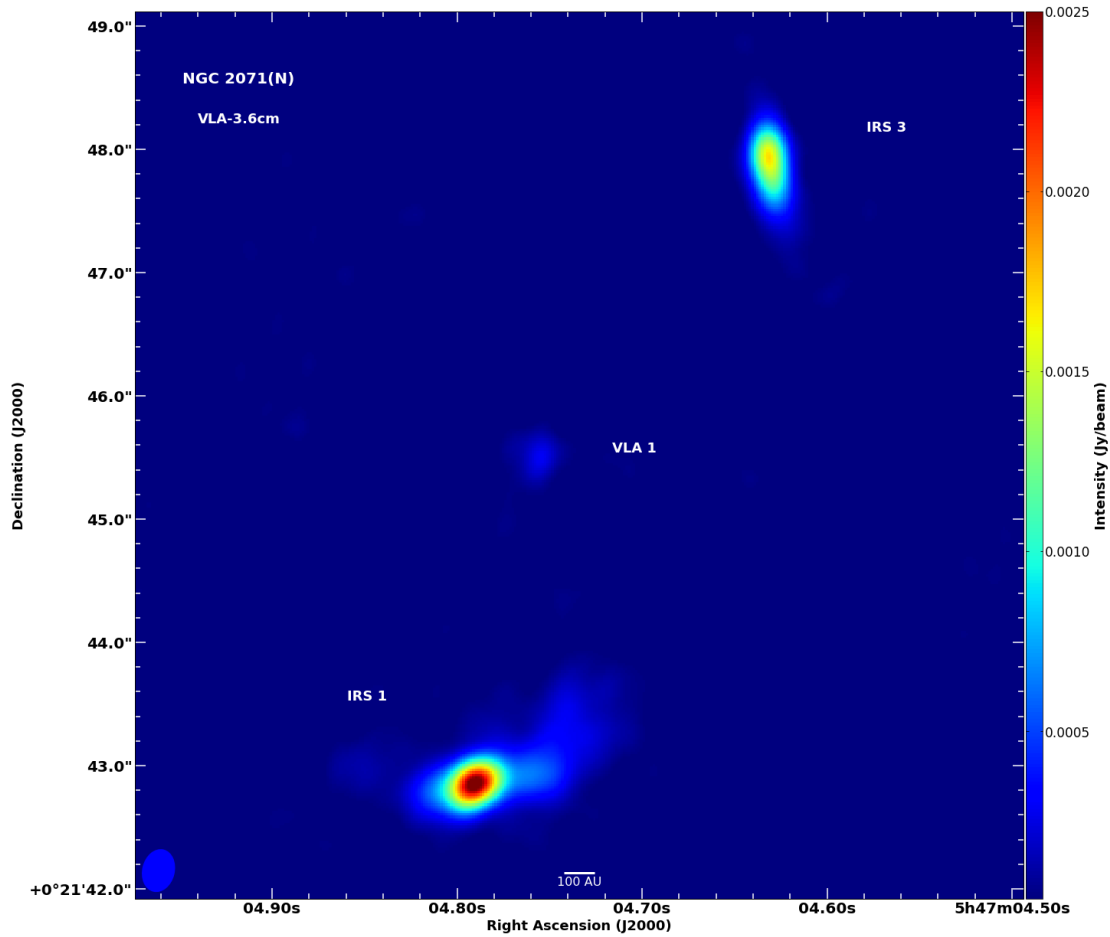


Figure 5.15: 3.6 cm VLA continuum image of NGC 2071-IR obtained from Carrasco-González et al. (2012).

VLA 9 mm continuum image

Figure 5.16 shows a 9 mm continuum map of NGC 2071-IR, obtained from the VANDAM database (Tobin et al., 2020b). The observation was conducted on 9 December 2016, with the VLA in A configuration, and the observation frequency was centered at 32.94 GHz. The image size is 8192×8192 pixels. The image was produced using the *CLEAN* task of CASA (version 4.5.1) using natural weighting and multi-frequency synthesis (mfs) with *nterms* set to 2 across both basebands. The resulting rms noise level of the final image was $8 \mu\text{Jy beam}^{-1}$, and the synthesized beam was $0.11'' \times 0''.8$. Solely phase-only self-calibration was performed on HOPS-361, due to the field having a high signal-to-noise ratio (> 100) and not being limited by dynamic range (Tobin et al., 2020b).

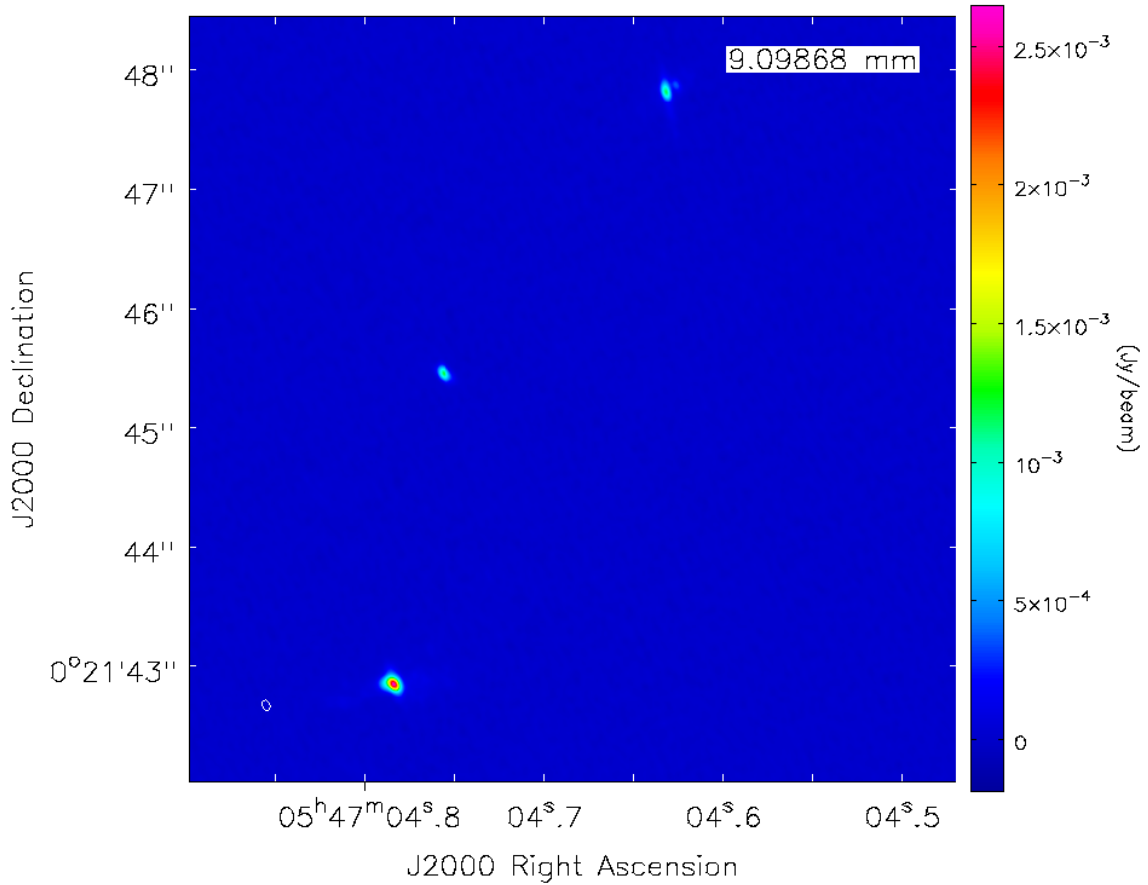


Figure 5.16: The 9 mm VLA continuum image of NGC 2071-IR from Tobin et al. (2020b). The three cores are resolved. IRS 3 is resolved into a binary system.

5.4 Method of protostellar mass estimation

The total enclosed masses (dust+gas) $M_{\odot}$ of protostellar cores can be estimated from the integrated flux density of the dust continuum emission. The mass estimation procedure adopted and utilized for this study is outlined in Hildebrand (1983). The integrated flux density is related to the dust mass of a core by:

$$F_{\nu} = \frac{K_{\nu} B_{\nu}(T_{dust} \lambda) M_d}{D^2}, \quad (5.2)$$

where K_{ν} is the extinction coefficient of absorption cross section per mass of dust in cm^2/g for the observation frequency, which can be obtained from Weingartner and Draine (2001), F_{ν} is the integrated flux density in Jansky, D is the distance to the source in meters, T_{dust} is the dust temperature in Kelvin, λ is the wavelength of the observation in meters. B_{ν} is the brightness temperature which is a function of T_{dust} and λ .

Re-writing equation 5.2, the dust mass is then:

$$M_d = \frac{F_{\nu} D^2}{K_{\nu} B_{\nu}(T_{dust} \lambda)}. \quad (5.3)$$

Substituting brightness temperature $B_{\nu}(T_{dust} \lambda) = \frac{2K_b T_{dust}}{\lambda^2}$, where K_b is Boltzmann's constant $= 1.380649 \times 10^{-23} \text{ J K}^{-1}$, the dust mass can be rewritten as:

$$M_d = \frac{F_{\nu} D^2 \lambda^2}{2K_{\nu} K_b T_{dust}}. \quad (5.4)$$

Finally, the total mass of the core is given by:

$$M_c = M_d \times 100. \quad (5.5)$$

5.4.1 Estimated masses

The total enclosed masses (dust+gas) $M_{\odot}$ of the three cores, NGC 2071-IRS3, NGC 2071-IRS1, and NGC 2071 VLA-1, were estimated from the ALMA 0.88 mm and 1.3 mm continuum images following the procedure for mass estimation outlined earlier. To obtain the integrated flux density ' F_{ν} ', a two-dimensional Gaussian was fitted to the cores interactively with CASA in the primary beam-corrected images. The integrated fluxes from the fitting were then obtained from the Gaussian fits. A value of 400 pc was used as distance to the source, based on measurements by Kounkel et al. (2017). The dust temperature was assumed to be 20 K, based on estimates from Lekht et al. (2011). K_{ν} values for 0.88 mm and 1.3 mm wavelengths from Weingartner and Draine (2001) were $5.718 \times 10^{-1} \text{ cm}^2/\text{g}$ and $3.298 \times 10^{-1} \text{ cm}^2/\text{g}$, respectively. Table 5.4 presents the results of the masses estimated for the three ALMA datasets.

Table 5.4: Summary of estimated masses of NGC 2071-IR cores from the ALMA continuum images.

ALMA Data	IRS 3 Mass $\pm$ Error ($M_{\odot}$)	IRS 1 Mass $\pm$ Error ($M_{\odot}$)	VLA 1 Mass $\pm$ Error ($M_{\odot}$)
ALMA Band 7 (ACA)	4.3 ± 0.5	3.2 ± 0.3	Unresolved
ALMA Band 7	4.7 ± 0.3	1.0 ± 0.1	0.2 ± 0.00
ALMA Band 6	2.9 ± 0.1	1.6 ± 0.03	0.3 ± 0.005

5.5 Interferometric observations: Spectral lines

Carbon monoxide transition lines $^{12}\text{CO } J=3-2$ and $^{13}\text{CO } J=3-2$ were detected towards the NGC 2071-IR region with ALMA observing in band 7. Figure 5.17 shows 12 selected channels of the $^{12}\text{CO } J=3-2$ distribution. The 0.8 mm dust continuum is overlaid in white contours. CO is suitable for the detection of warm gas (20 K - 100 K) and interaction between jets and their environment (Chernin and Masson, 1992). In a bid to understand the gas outflow orientations and jet dynamics in the NGC 2071-IR region, the CO emission maps produced were studied. These outflows and jets may play a role in the observed variability of the water masers presented earlier. The channel map of $^{12}\text{CO } J=3-2$ and $^{13}\text{CO } J=3-2$ is presented with a descriptive overview and will be discussed in detail in Chapter 6.

5.5.1 The $^{12}\text{CO } J=3-2$ line emission

Figure 5.17 shows selected channel maps of the $^{12}\text{CO } J=3-2$ line emission of NGC 2071-IR. The velocity range covered -100 to 99 km s^{-1} , spaced at 1 km s^{-1} intervals with the systemic velocity at 9.7 km s^{-1} . The colour scale is located on the right side of the bottom right panel. The 0.8 mm dust continuum contours are plotted in white over all the channel maps to indicate the locations of the continuum peaks. Each image panel has a size of $1'.26'' \times 13''$, with the centre of each image set to (J2000) $05^h47^m04^s.80, +00^\circ21'43''.34$. A 500 Kilo Lambda taper was applied to enhance sensitivity and aid the resolution of faint emission. The self-absorption feature in CO is visible in the velocity channel centred on 10.0 km s^{-1} (Panel V). The self-absorption extends from velocity channel 7.0 km s^{-1} to 10.0 km s^{-1} .

There are several striking features in the channel maps. First is the well-collimated blue-shifted outflow in the -28.0 km s^{-1} velocity channel (panel I), which appears to be associated with IRS 3. A hollow heart-shaped shell appears from velocity channel -24.0 km s^{-1} to -1.0 km s^{-1} . The source of this structure is unclear, although it appears to be associated with IRS 1. From velocity channel -4 km s^{-1} to 0 km s^{-1} , an arc-like structure

appears on the east side of the heart-shaped structure which can be seen in the -1 km s^{-1} velocity channel (panel III).

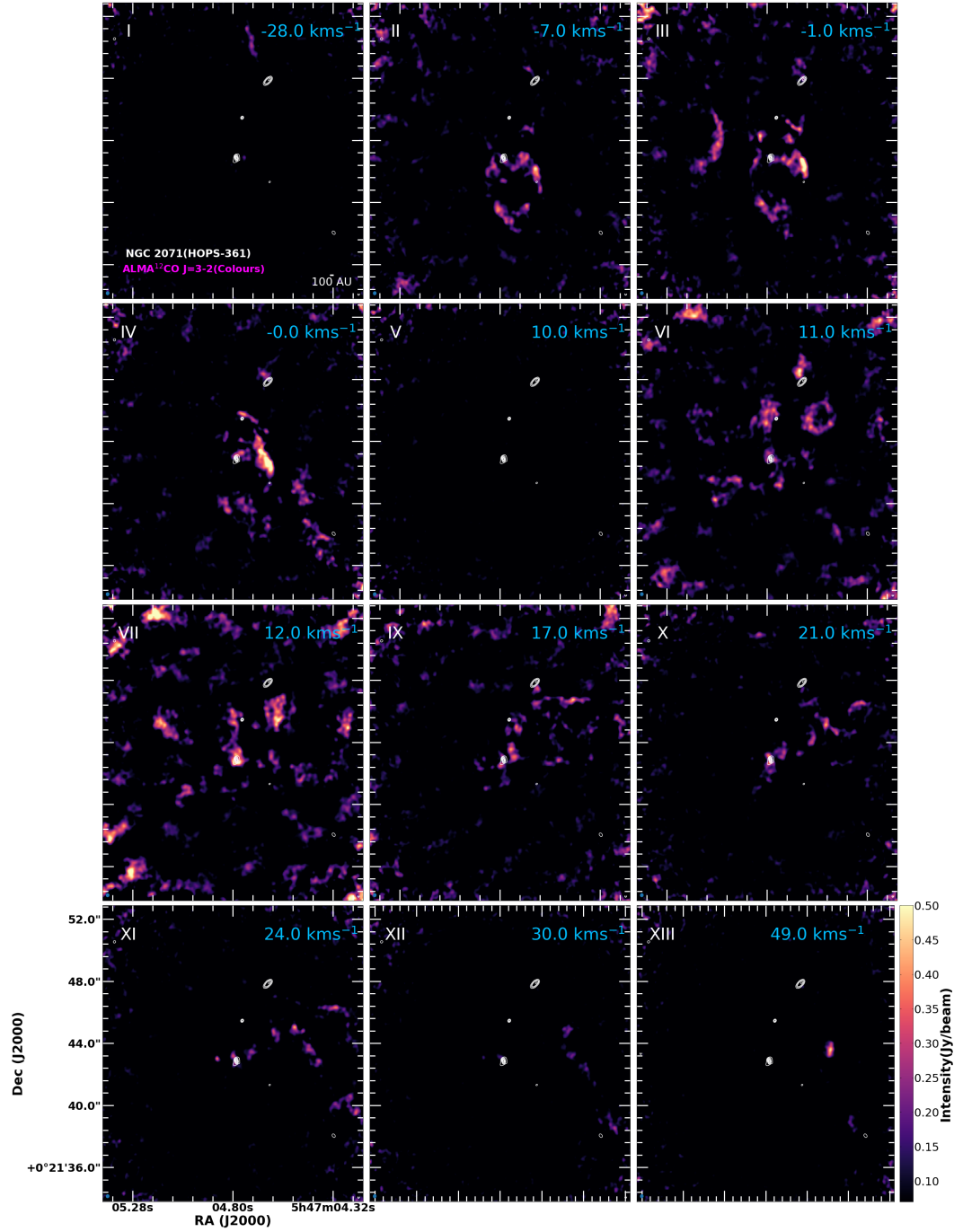


Figure 5.17: ALMA band 7 maps of $^{12}\text{CO } J=3-2$ line emission distribution in the NGC 2071-IR region. The 0.8 mm dust continuum map from ALMA (band 7) is superimposed on all the channel maps in white contours. The central velocities are labelled on the top right corner of each panel, and the colour scale is on the right side of the bottom panel.

In panel VI, a ring-like structure appears and becomes diffused in panel VII (12 km s^{-1}), but with a strong peak ($\sim 0.5 \text{ mJy/beam}$). The last three panels show the red-shifted lobe side of outflows from IRS 3 and IRS 1 which appear to be interacting. The last panel shows a compact bright emission on the western side. The full channel maps are provided in Appendix B.

5.5.2 The $^{13}\text{CO } J=3-2$ line emission

Figure 5.18 presents selected velocity channel maps of $^{13}\text{CO } J=3-2$ line emission observed with ALMA. The selection is based on channels with significant emissions relative to the other channels. All the velocity channels are provided in Appendix B. The channels cover a velocity range of 4.32 km s^{-1} to 16.60 km s^{-1} . Similar to the $^{12}\text{CO } J=3-2$ maps, each image panel has a size of $1'.26'' \times 13''$ with the colour scale located at the right side of the right bottom panel. A 500 Kilo Lambda taper was also applied in the imaging process. The systemic velocity is $9 - 10.0 \text{ km s}^{-1}$, hence velocities before and after are blue-shifted and red-shifted, respectively. The $^{13}\text{CO } J=3-2$ maps also display interesting features. One interesting observation is the little, or lack thereof, of $^{13}\text{CO } J=3-2$ emission around IRS 3. Panel (d) shows the self-absorption feature of CO at systemic velocities. Absorption detection present in $^{13}\text{CO } J=3-2$ spectra at 8 km s^{-1} has been proposed by van Kempen et al. (2016) to be associated with large-scale cold material in the outer envelope. In the blue-shifted panels (a - c), emission appears to be concentrated around IRS 1, peaking at a centre position $0.1''$ eastward of IRS 1. In the red-shifted panels, 'e' to 'i', the concentration of emission appears to be around IRS 1 with diffused emission spread northwest of IRS 1. The emission also appears to be concentrated around VLA-1. In panel 'k' and 'i', similar compact bright features seen in panels X and XIII of the $^{12}\text{CO } J=3-2$ also manifest. Although the bright feature in panel XIII of $^{12}\text{CO } J=3-2$ maps have wide separation in velocity from the bright feature in panel 'k' and 'i', they have a spatial separation of only $0.6'' \pm 0.2''$.

Figure 5.19 shows the integrated intensity distribution of the $^{13}\text{CO } J=3-2$ emission in the NGC 2071-IR region. The channels were divided into blue-shifted and red-shifted channels, taking 9.5 km s^{-1} as the systemic velocity. The first panel shows the integrated blue-shifted emissions covering velocity ranges 4.17 km s^{-1} to 9 km s^{-1} , and the second panel shows the red-shifted emission covering velocity ranges 10.0 km s^{-1} to 17.82 km s^{-1} . The 0.8 mm continuum contours are plotted over the maps to indicate the positions of the continuum cores. The blue-shifted map shows a northwest oriented distribution with respect to IRS 1. The emission covers a region of $\sim 7'$ long and $5'$ wide. A concentration of red-shifted emission can be seen around the IRS 1. The blue-shifted distribution is extended in the southeast direction from IRS 1. The red-shifted emission extended $11'$ long and $6'$ wide. It narrows with increasing distance from IRS 1. Together, the integrated $^{13}\text{CO } J=3-2$ emission maps appear to trace a bipolar outflow oriented in the northwest-

southeast direction centred around IRS 1. There appears to be little to no emission around IRS 3, particularly blue-shifted ^{13}CO $J=3-2$ emission.

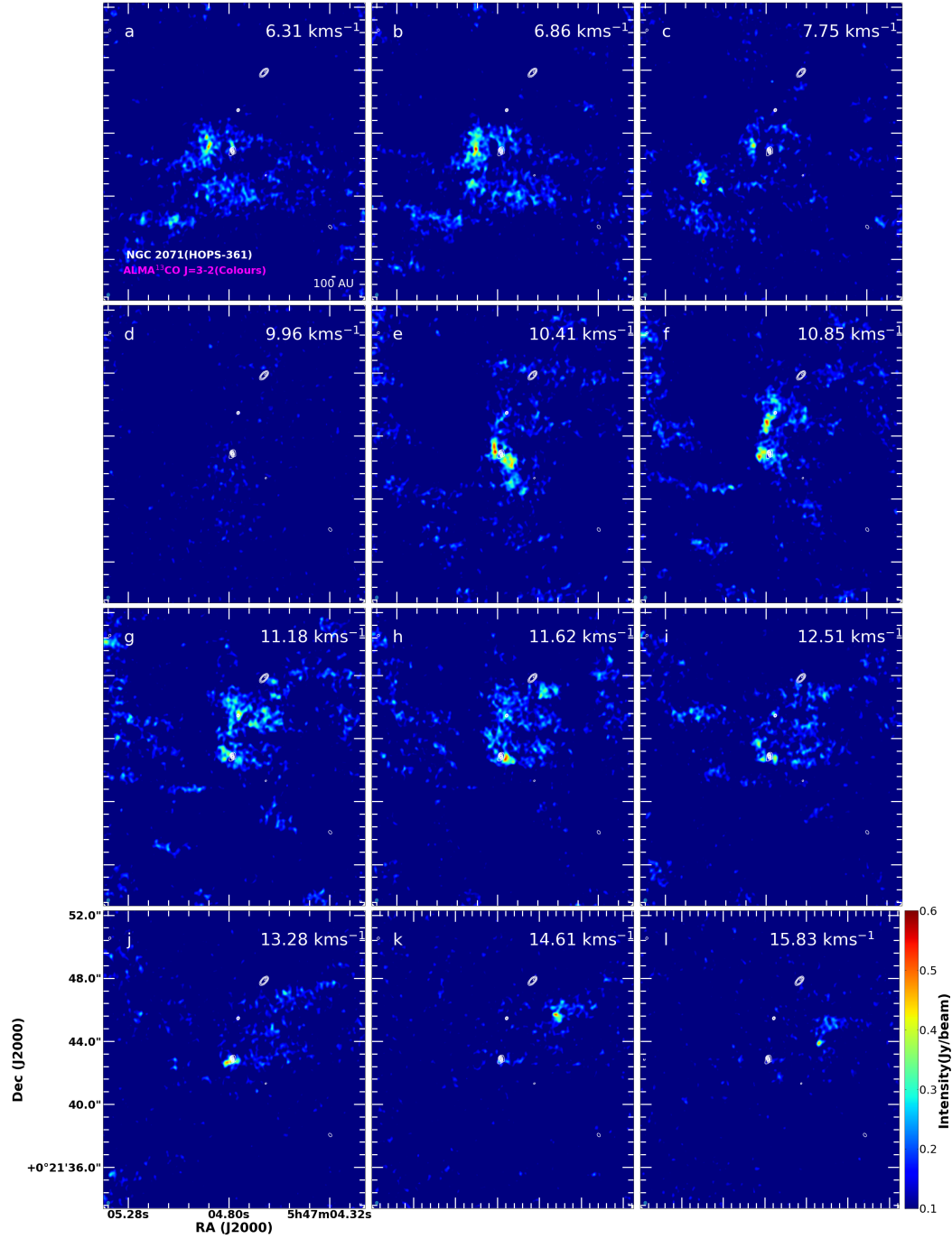


Figure 5.18: ALMA 0.8 mm map of ^{13}CO $J=3-2$ distribution towards the NGC 2071-IR region. ALMA 0.8 mm dust continuum map contours (white) superimposed to show the position of the continuum cores IRS 3, IRS 1, VLA 1, and IRS 8.

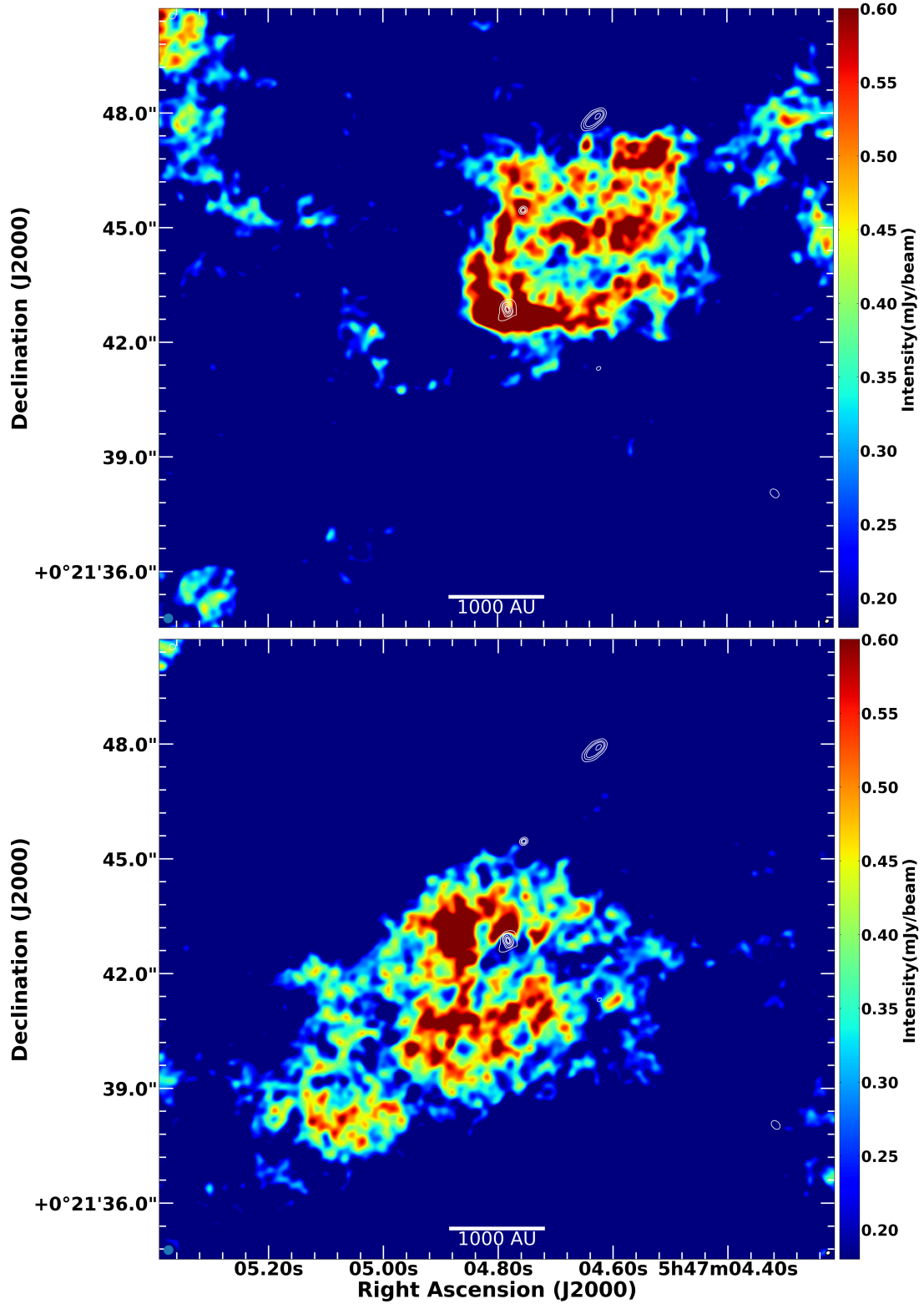


Figure 5.19: Integrated intensity maps of $^{13}\text{CO } J=3-2$ emission in the NGC 2071-IR region. The first panel shows the distribution of blue-shifted emission ($4.17 \text{ km s}^{-1} - 9 \text{ km s}^{-1}$), and the second panel the red-shifted emission ($10.0 \text{ km s}^{-1} - 17.82 \text{ km s}^{-1}$). The map appears to trace a bipolar outflow. The ALMA 0.8 mm continuum contours have been superimposed on the maps in white contours. The beam size of the $^{13}\text{CO } J=3-2$ image is indicated in the bottom left corner in blue and that of the 0.8 mm continuum in the bottom right corner in white.

5.6 Results of Kanata/HONIR observations

Figures 5.20 and 5.21 show the calibrated image of the 28 December 2019 and 3 January 2020 observations of NGC 2071-IR with the Kanata/HONIR telescope, respectively. The images were calibrated to the point where photometry could be performed. The instrumental magnitudes were derived using IRAF task “phot” from the “noao.digiphot.apphot” software package for both the 2019 and the 2020 images. Table 5.5 presents the values from the photometry carried out on the HONIR images. The Ks-band magnitude increased by 0.2 mag for the 2019 observations when compared to the 2MASS magnitude.

Table 5.5: Photometric values from the NGC 2071-IR Ks-band observation, made on 28 December 2019 and 3 January 2020 with the Kanata/HONIR telescope. The positions of the reference stars used are indicated in Figure 5.20 and Figure 5.21, respectively.

Obs. date: 28-12-2019					
Target	Ins. Mag.	Ins. Mag. er.	2MASS mag.	2MASS mag. er.	Ins. Mag.-2MASS mag.
IRS 1	13.015	0.007	11.212	0.052	
Ref. 1	14.209	0.011	12.140	0.027	2.069
Ref. 2	14.643	0.015	12.503	0.029	2.140
Ref. 3	13.004	0.005	11.012	0.024	1.992
Ref. 4	12.586	0.004	10.641	0.023	1.945
Ref. 5	14.482	0.013	12.398	0.023	2.084
Ref. 6	14.379	0.012	12.488	0.030	1.891
				Average (Avg)	2.020
				Ins. Mag. (IRS 1)	13.015
				Ins. Mag. - Avg.	10.995
				2MASS Ks mag.	11.212
				Mag. Difference	-0.217
Obs. date: 03-01-2020					
Target	Ins. Mag.	Ins. Mag. er.	2MASS mag.	2MASS mag. er.	Ins. Mag.-2MASS mag.
IRS 1	13.302	0.006	11.212	0.052	
Ref. 1	14.380	0.013	12.488	0.030	1.892
Ref. 2	14.473	0.014	12.398	0.023	2.075
Ref. 3	13.115	0.006	11.012	0.024	2.103
Ref. 4	12.552	0.004	10.641	0.023	1.911
				Average (Avg)	1.995
				Ins. Mag. (IRS 1)	13.302
				Ins. Mag. - Avg.	11.307
				2MASS Ks mag.	11.212
				Mag. Difference	0.095

The 2MASS magnitudes from observations made on 10 October 1999 were obtained from <https://aladin.u-strasbg.fr/AladinLite/>, with search the target as [PGS81]IRS1.

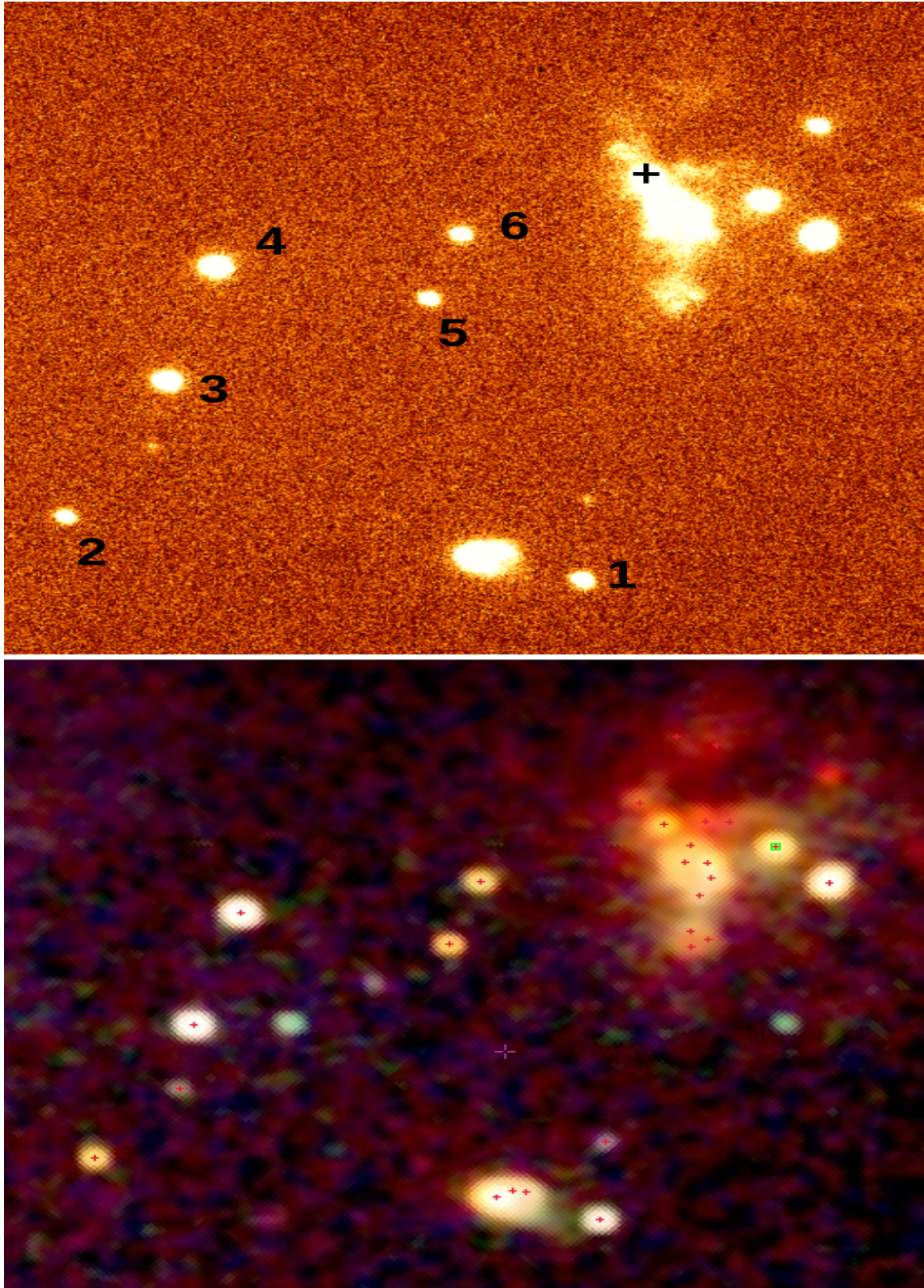


Figure 5.20: Top: Pseudo-colour NIR image of the NGC 2071-IR region made on 28 December 2019. The image is background and sky subtracted. The reference stars used for photometry are labelled, and the black cross indicates the position of NGC 2071-IRS 1. Bottom: The 2MASS image of the NGC 2071-IR. The green square indicates the position of IRS 1. The 2MASS image has been flipped and inverted to reorient it similarly to the HONIR image.

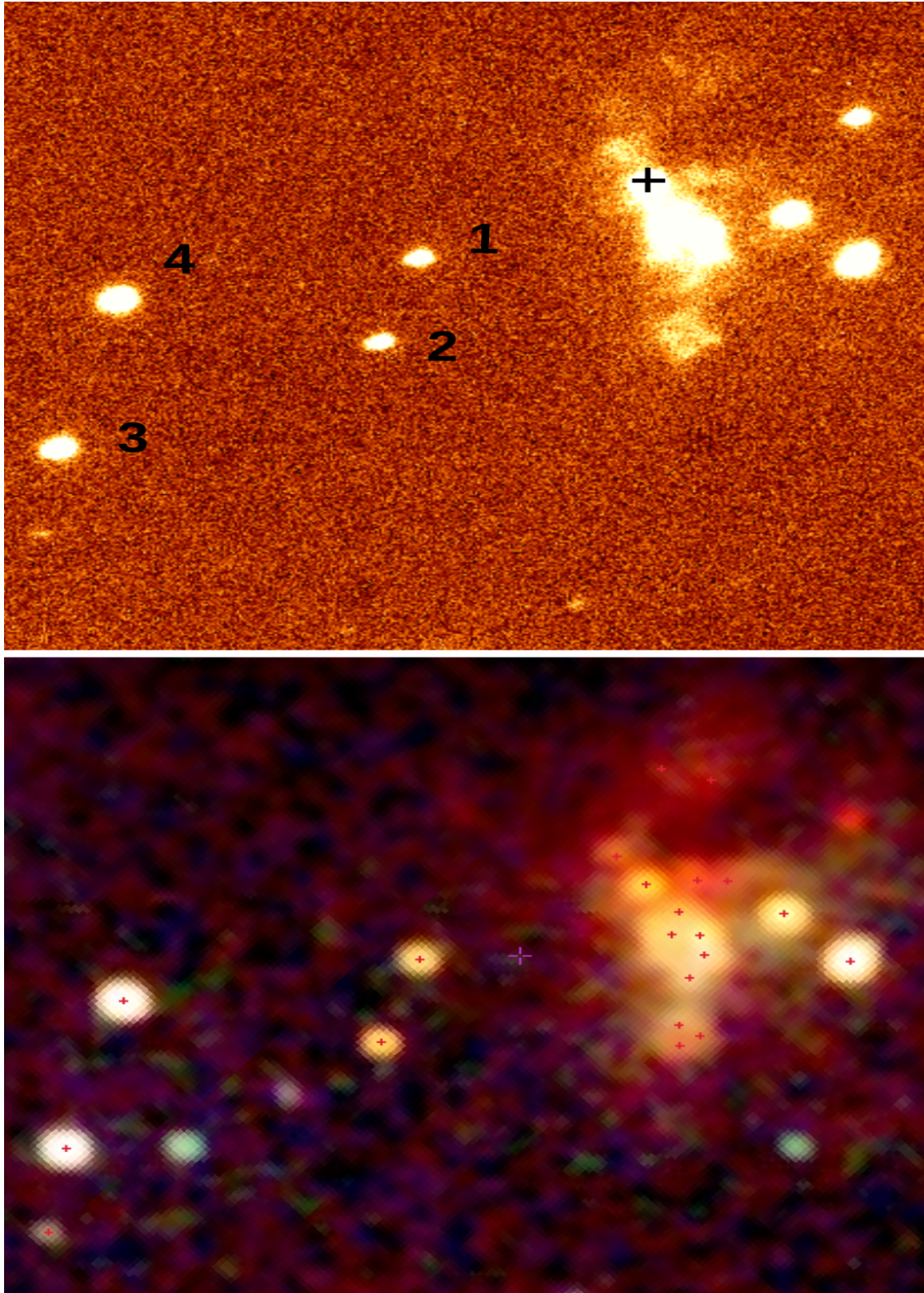


Figure 5.21: Same as Figure 5.20 but with observations made on 03 January 2020.

Chapter 6

Discussions

In this chapter the results and analysis are discussed and interpreted. The chapter begins with an analysis of the maser spectra from the single-dish results, covering the variability of water masers in NGC 2071-IR and the non-detection of 6.7 GHz methanol masers. The evolution of water masers in the HartRAO observations is explored, along with a water maser feature of interest located at $V_{lsr} = -6.35 \text{ km s}^{-1}$. Next, the water maser distributions in the region obtained from literature are discussed, followed by a description of the morphology of the NGC 2071-IR region based on the results from the high-resolution continuum images presented in chapter 5. The chapter concludes with a discussion of the water maser flare in the context of the occurrence of an accretion burst in the region. Throughout the discussions, the terms ‘water maser’ or ‘H₂O masers’ refer to 22 GHz (1.3 cm line) water masers.

6.1 Variability of 22 GHz water masers in NGC 2071-IR

The HartRAO single-dish maser spectra of the H₂O masers towards NGC 2071-IR exhibit high variability on short timescales. Strong variability in the H₂O maser lines from star-forming regions have been reported since 1977 (Pankonin et al., 1977). The water masers in NGC 2071-IR have been reported by Lekht and Krasnov (2000) and Ashimbaeva et al. (2020) to exhibit variability on scales of weeks to months. The HartRAO data also showed variability on weekly and monthly scales, in addition to variations in profiles of the maser features. Variability indexes calculated for the dominant features presented in chapter 5 showed high variability indexes.

As presented in Chapter 5, the spectra were divided into four groups based on the calendar year of observation before the variability indexes were calculated for the dominant features. The variability index values for 2021 were the highest, whilst those for 2022 were the

lowest. The highest variability indexes were found, in the $V_{lsr} = 14\text{--}16\text{ km s}^{-1}$ range, with the highest index of 21,626.8 coming from the $V_{lsr} = 15.03\text{ km s}^{-1}$ feature in 2020. The lowest variability index was -623.9 and came from the $V_{lsr} = -6.35\text{ km s}^{-1}$ in 2019. Only the -6.35 km s^{-1} feature yielded negative variability indexes. A negative variability index implies a flux density decrease throughout the observing period.

Water masers are collisionally pumped (Elitzur et al., 1989), and the observed variability may likely be due to turbulence and energetic kinematic processes occurring in the region, such as the impact of shock waves or the collision of masing clouds with dense ejecta expelled from the protostar. Shocks may result from violent internal interactions in a fast jet; or from the jet with the ambient cloud, and may excite the masing medium (Eisloffel and Mundt, 1997). Lekht et al. (1982) suggested that the variability observed in water masers may be due to changes in the power of the pumping source, the internal physical conditions in the maser, and the geometry of the masing cloud. The variations are uncorrelated across the different features, and it is unlikely that one driving source is responsible for the variations. Detailed studies of the morphology and orientations of disks and outflows in the region would give insight into the processes triggering the variability. For masers tracing a disk, the alignment of masing clouds along the line of sight may increase the path length, thereby increasing the observed intensity. The measured intensities may be integrated since the beam of the HartRAO 26-m telescope at 1.3 cm receiver is relatively large (HPBW = 0.036°). For example, the maser feature at $V_{lsr} = 5.4\text{ km s}^{-1}$ has been detected by Torrelles et al. (1998) towards both IRS 1 and IRS 3. Trinidad et al. (2009) later discovered a maser feature at $V_{lsr} = 5.4\text{ km s}^{-1}$ and reported it to be associated with the young protostellar core VLA 1. The three features with a common velocity are all located within a radius of $\sim 5''$ when taking VLA 1 as the centre. This implies that the beam of the HartRAO telescope (HPBW = $0.036^\circ = 129''.6$) will integrate the emission from the three maser features at $V_{lsr} = 5.4\text{ km s}^{-1}$ although they are associated with separate objects. The intensity recorded will thus be a contribution from the three features. The $V_{lsr} = 14.4\text{ km s}^{-1}$ feature appears to have undergone a strong outburst where the flux density increased by a factor of 10 compared to its quiescent phase flux density. Such changes in masing media may be caused by strong winds, outflows, or external or internally generated shock waves; accretion bursts are also a possible explanation.

6.2 Non-detection of 6.7 GHz methanol masers in NGC 2071-IR

Methanol masers (6.7 GHz) are extensively distributed in the Milky Way Galaxy, and more than 1000 sources have been documented so far (Nguyen et al., 2022). Studies by Breen et al. (2007) concluded that there is no spatial relation between 6.7 GHz methanol masers and water masers, however regular detection of both maser species in the same

SFRs suggest that the masing phases of both species are coeval (Codella and Moscadelli, 2000). The 6.7 GHz methanol observations conducted with the HartRAO 26-m telescope towards the NGC 207-IR region for this study showed no detection. The rms noise level of the spectra ranged between 1.0 Jy $\sim$ 2.3 Jy. For a 3σ detection, a maser feature(s) would have to possess a minimum amplitude of 3 Jy to be considered a detection, taking the lowest rms as the lower limit. To rule out attribution of the non-detection to the telescope, previous observations of 6.7 GHz methanol masers towards the region were checked for reported detections. The most sensitive 6.7 GHz methanol line observations towards NGC 2071-IR were conducted by Xu et al. (2003) by means of a high sensitivity 6.7 GHz methanol maser survey towards H₂O maser positions using the Effelsberg 100-m telescope (Wielebinski et al., 2011) at rest frequency of 6668.519 MHz. The mean rms noise level of their observations was $\sim$ 0.1 to 0.2 Jy. This is a factor of 10 more sensitive than the HartRAO observations. Xu et al. (2003), as part of their survey, pointed the telescope towards the H₂O maser ‘05445+0020’ located in the NGC 2071 region and despite the high sensitivity of their instruments, they also reported a lack of 6.7 GHz methanol masers towards NGC 2071-IR. There have been no reported detections of 6.7 GHz methanol masers towards the region as of the time of writing this work.

Methanol masers often trace the systemic velocities of the ambient clouds within which they reside, and 6.7 GHz methanol masers particularly, have velocities within 3 km s⁻¹ to 5 km s⁻¹ of the systemic velocity of their associated clouds (Breen et al., 2013), therefore the detection of 6.7 GHz masers towards NGC 2071-IR with a systemic velocity of 9.5 km s⁻¹ should be within the velocity range of 4.5 km s⁻¹ and 14.5 km s⁻¹, which was not present in the dynamic spectra plot (see Figure 5.3). The estimated masses of the dominant protostars in the NGC 2071-IR region, specifically IRS 3 and IRS 1, suggest that they are not massive enough to produce the requisite quantities of UV photons, as well as the physical conditions required to produce class II methanol maser emissions, such as temperature and methanol column densities. According to the Sobolev-Deguchi model introduced in subsection 2.12.3, the average dust temperature required for yielding 6.7 GHz masers is 90 K. The thermal emission of the central star would have to be strong enough to adequately populate the excitation levels of the methanol molecules. The most recent average dust temperature of the NGC 2071-IR region was estimated by Cheng et al. (2022) as 43 K, a factor of 2 less than that required by the model. The 6.7 GHz methanol maser line is suggested to be exclusively associated with high-mass protostars and are yet to be detected nearby low to intermediate-mass stars (Minier et al., 2002; Xu et al., 2008; Breen et al., 2013; Paulson and Pandian, 2022). This further supports the conclusion that the active star-forming region of NGC 2071-IR is populated by low and intermediate-mass protostars rather than high-mass protostars.

6.3 The evolution of water masers in NGC 2071-IR from 2019 to 2022

Figure 6.1 shows the dynamic plot of the water masers with horizontal dotted lines tracing the positions of the dominant maser features. The dynamic spectra cover the period from January 2019 to April 2022. Two major periods of activity can be seen separated by a brief quiescent period. The first period of activity is a continuation of the period of increased activity which began around February 2019. In July 2019, the maser features in the $V_{lsr} = 10 - 17 \text{ km s}^{-1}$ range saw a rise in amplitude which was preceded by strong flaring of the maser features in the V_{lsr} range of $14 - 15 \text{ km s}^{-1}$, with the flux value reaching a peak of 4417 Jy . The second period of activity started around September 2020. This period was characterised by the simultaneous flaring of multiple features. Features centred on $V_{lsr} = 14.6$, 10 , and 3.44 km s^{-1} flared on 26 May 2021.

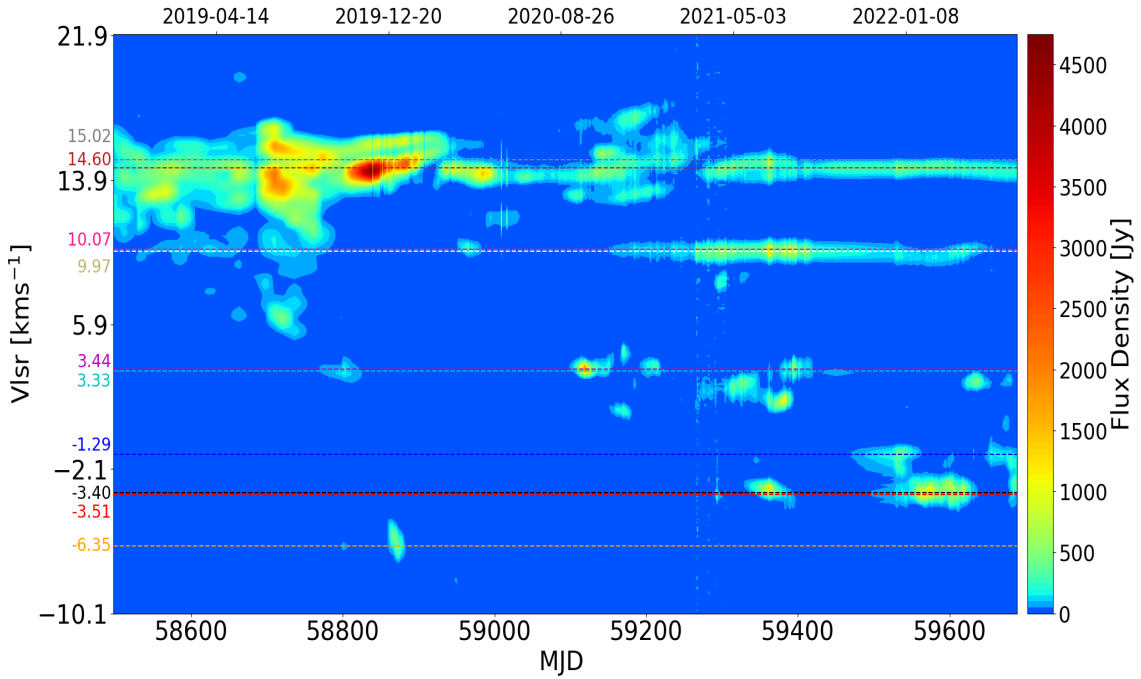


Figure 6.1: Dynamic spectra of NGC 2071-IR H_2O maser with horizontal dashed lines showing the V_{lsr} of the main maser features listed in Table 5.1.

6.3.1 The -6.3 km s^{-1} water maser feature

A water maser feature centred at $V_{lsr} = -6.3 \text{ km s}^{-1}$ is of particular interest due to its unusual behaviour. This feature has not been detected in any high-resolution maser maps at the time of writing this work. It is strongly blue-shifted with respect to the ambient cloud's systemic velocity of 9.5 km s^{-1} . The positions of water masers towards NGC 2071-IR have been observed using the Very Long Baseline Array (VLBA) by Seth et al. (2002)

and by Torrelles et al. (1998) and Trinidad et al. (2009) with the VLA. The VLBA water maser maps of the NGC 2071-IR region from Seth et al. (2002) with an angular resolution of $\text{HPBW} \sim 0.5 \text{ mas}$ (0.39 AU) are the highest angular resolution maser maps available. None of the observations detected the -6.3 km s^{-1} feature. A possible explanation is the feature being dormant at the time the observations were conducted. From Seth et al. (2002)'s maser positions, the most blue-shifted feature was at $V_{lsr} = -7.9 \text{ km s}^{-1}$ and it is suggested to be associated with IRS 3 as per Seth et al. (2002) (see Appendix C). The most blue-shifted maser feature associated with IRS 1 was at a radial velocity of -1.12 km s^{-1} and was detected in the first three of the four epochs observed. It is tempting to speculate that the -6.3 km s^{-1} feature may be associated with IRS 3 since the strongest blue-shifted features detected were associated with it. The velocity extents of the features found around IRS 3 were $V_{lsr} = 18.86 \pm 0.55$ to $-7.90 \pm 0.21 \text{ km s}^{-1}$. The velocity extents found for IRS 1 were $V_{lsr} = 27.48 \pm 0.21$ to $-1.33 \pm 0.01 \text{ km s}^{-1}$. Nonetheless, it is still possible that the $V_{lsr} = -6.35 \text{ km s}^{-1}$ feature is associated with IRS 1.

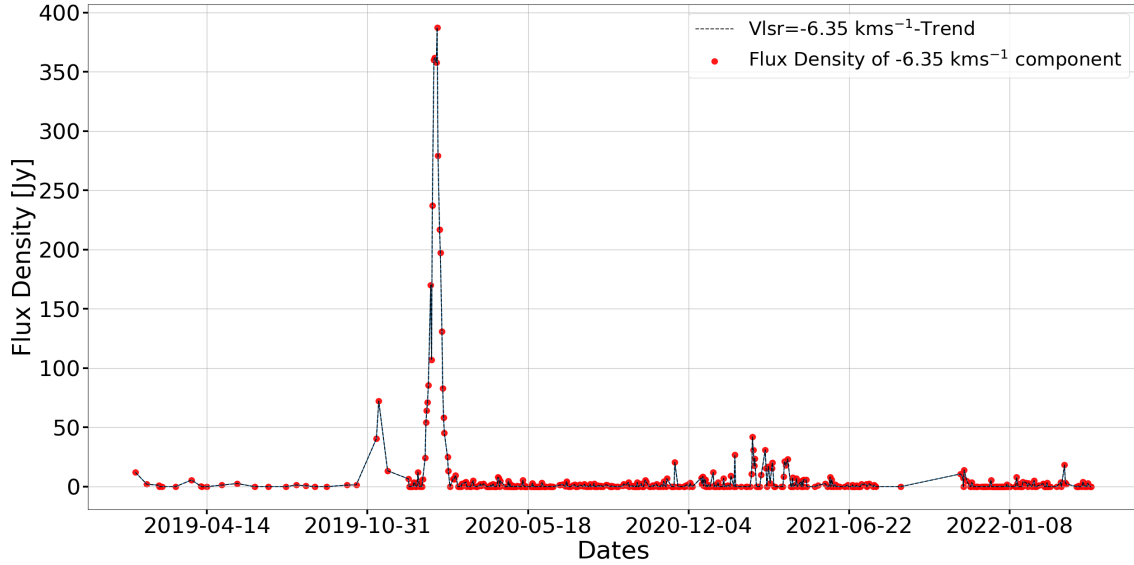


Figure 6.2: Light curve of the $V_{lsr} = -6.3 \text{ km s}^{-1}$ maser feature. The feature appeared around January 2020 in the HartRAO spectra, reaching a peak flux density of 387.5 Jy . The fluctuations between December 2020 and April 2021 are due to increased noise levels and should be disregarded.

The appearance of the $V_{lsr} = -6.3 \text{ km s}^{-1}$ feature in the HartRAO spectra coincided with the flaring of the 14.6 km s^{-1} feature (see Figure 6.3). The -6.3 km s^{-1} feature appeared during the flaring of the 14.6 km s^{-1} feature and increased in amplitude post-peak phase of the flare of the 14.6 km s^{-1} feature. The peak of both features is separated by 32 days, suggesting that the same exciting mechanism is responsible for the excitation of both maser features. Revisiting the Seth et al. (2002) VLBA maser positions, the closest velocity component reported associated with IRS 3 in the 13 km s^{-1} to 15 km s^{-1} range is 14.86 km s^{-1} , which corresponds to 14.81 km s^{-1} in the HartRAO single-dish velocities.

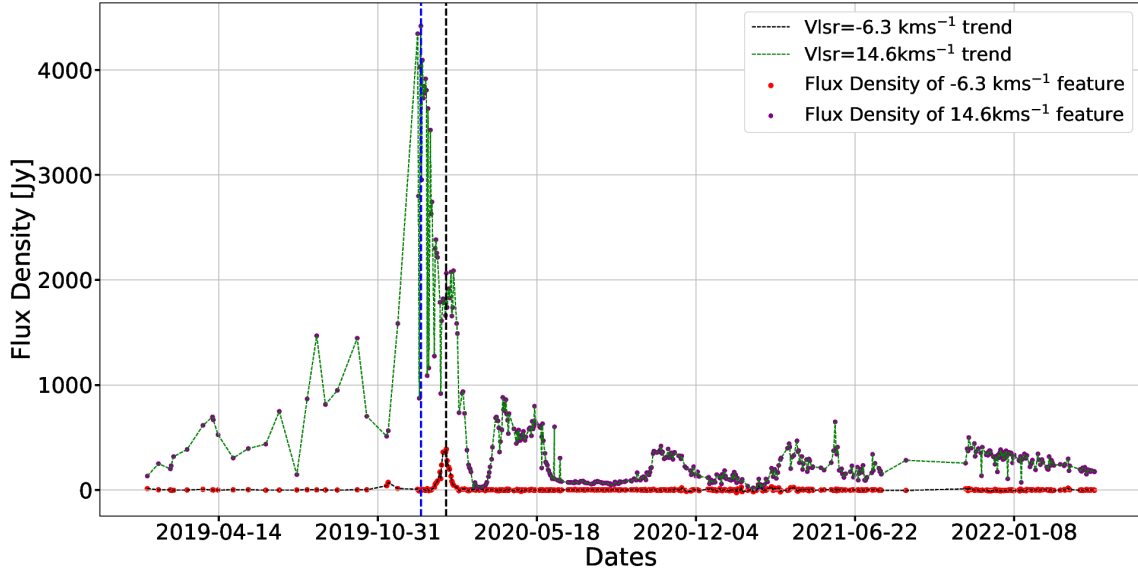


Figure 6.3: Lightcurve of the $V_{lsr} = -6.3 \text{ km s}^{-1}$ maser feature superimposed with the lightcurve of the 14.6 km s^{-1} feature. The vertical blue and black dashed lines indicate the peaks of the 14.6 and -6.3 km s^{-1} flares, respectively. The time lag between both peaks is 32 days. The -6.3 km s^{-1} only appeared during the flaring phase of the 14.6 km s^{-1} feature.

The 14.6 km s^{-1} thus appears to be associated with IRS 1, due to IRS 1 having the closest radial velocity feature from the Seth et al. (2002) positions to 14.6 km s^{-1} , which is 14.46 km s^{-1} and corresponds to 14.5 km s^{-1} in the HartRAO single-dish velocities. It must, however, be noted that water masers do drift in velocity so this interpretation may be inaccurate and thus the 14.86 km s^{-1} feature associated with IRS 3 may be the 14.6 km s^{-1} feature seen in the Seth et al. (2002) maps.

To verify if the -6.3 km s^{-1} feature made earlier appearances, the historical spectra were examined. The feature can first be seen in the 13 February, 12 June and 22 June 1981 spectra published by Lekht et al. (1982). It had a peak antenna temperature of $\sim 5 \text{ K}$ on June 22. There appears to be two other manifestations of the -6.3 km s^{-1} feature in Felli et al. (2007)'s dynamic spectra (See Figure 6.4). The -6.3 km s^{-1} feature appeared during the flaring of another feature. From around day 500 (1 August 1988), several red-shifted masers flared, which lasted until day 2500 (22 January 1994). During the start of the flares, the -6.3 km s^{-1} feature appeared, albeit centred around a shifted velocity of -7 km s^{-1} (see red box 1 in Figure 6.4). It must be noted that the maser feature that flared the strongest during the appearance of the -6.3 km s^{-1} feature was not at 14.6 km s^{-1} as in the case of the HartRAO spectra but rather a feature centred around 16.5 km s^{-1} . The -6.3 km s^{-1} feature can be seen again in Figure 6.4 at about 6000 days (3 August 2003) from 20 March 1987. The second appearance also coincided with the flare of a red-shifted feature centred at 11 km s^{-1} . Similarly, the -6.3 km s^{-1} feature appeared again on 19 December 2018 with a peak flux density of 82 Jy during the flare of a red-shifted feature

in the spectra published by Ashimbaeva et al. (2020).

The appearance of the -6.3 km s^{-1} maser feature during the flaring of red-shifted features is interesting due to the relatively strong blue-shifted nature. If the -6.3 km s^{-1} maser feature is tracing a circumstellar disk and gravitationally bound to it, thus experiencing Keplerian rotation, it would have to be fairly distant from the centre of the disk to be able to exhibit the strong blue shift. High angular resolution VLBI observations will provide robust constraints to the actual position of the -6.3 km s^{-1} .

6.4 Distribution of water masers in NGC 2071-IR

The coordinates of the water maser positions from published high angular resolution interferometric observations were obtained. The positions utilised are those published by (from oldest to most recent), Seth et al. (2002) from 4 epoch observations with the VLBA array, Torrelles et al. (1998) from observations with the VLA, Trinidad et al. (2009) also from observations with the VLA, and finally, Shchurov et al. (2021) from observations made with the ground-space radio interferometer RadioAstron in tandem with the Medicina, Torun, and RT-64 telescope. Table 6.1 presents an overview of the observations from which the water maser positions were obtained.

Table 6.1: Summary of observations from which the water maser positions were obtained.

Observer	Obs. Date	Instrument	Beam size (Arcsec)	P. A. ($^{\circ}$)	Features Detected	Spectral Resolution (km s^{-1})	Max. Baseline (km)
Seth et al.	24-03-1996	VLBA	0.9×0.51	-9	74	0.42	8611
Seth et al.	02-06-1996	VLBA	1.08×0.59	-1	67	0.42	8611
Seth et al.	05-07-1996	VLBA	1.03×0.57	8	81	0.42	8611
Seth et al.	3-08-1996	VLBA	1.36×1.26	24	47	0.42	8611
Torrelles et al.	15-12-1996	VLA	0.10×0.09	-20	35	1.3	36
Trinidad et al.	30-12-2000	VLA	0.12×0.09		28	0.64	36
Shchurov et al.	11-01-2014	SRT-Mc-Tr-Kz	0.006×0.0006	-23	13	0.11	40000

Figure 6.5 shows the maser spots from the observations listed in Table 6.1, superimposed on the 0.8 mm continuum map from ALMA. The water masers show two clustered distributions with the clusters coinciding with dust continuum cores IRS 3 in the northwest, and IRS 1 in the southeast, respectively. There are also maser spots detected by Trinidad et al. (2009), which are not directly associated with both cores. There is one blue-shifted maser which was coincident with the peak of the continuum core VLA 1, two red-shifted maser spots northeast of IRS 3, and one blue-shifted maser located northeast of IRS 1. The masers are colour coded as blue and red according to their velocity in the rest frame of the cloud (9.5 km s^{-1}) to represent blue-shifted and red-shifted masers, respectively.

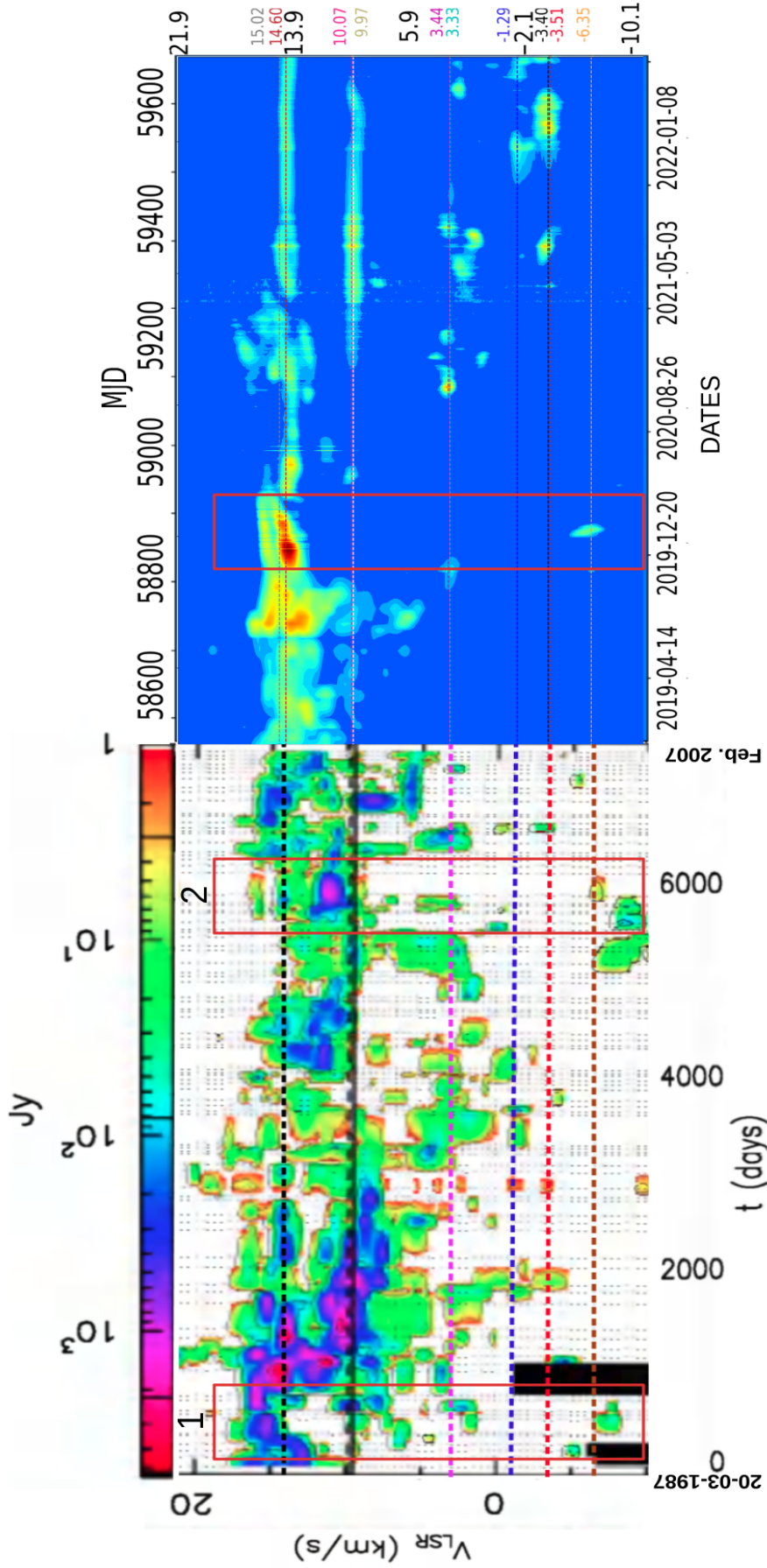


Figure 6.4: Felli et al. (2007)'s dynamic spectra of NGC 2071-IR water masers juxtapositioned with the HartRAO dynamic spectra. Red boxes labelled 1, 2, and 3 show the appearances of the $V_{LSR} = -6.3 \text{ km s}^{-1}$ feature, which appear to always coincide with the flaring of another maser feature in the 10 - 14 km s^{-1} range.

The results revealed clustering of the masers. The red-shifted masers associated with IRS 3, were located southward, and the blue-shifted masers were clustered northward. The masers associated with IRS 1 are distributed over 130 AU in the east-west direction. A pattern of alternation between the blue-shifted and red-shifted masers along the east-west distribution across the minor axis of the IRS 1 is observed (see Figure 6.8). The water maser distributions around the three dust cores, namely IRS 1, VLA 1, and IRS 3, will now be discussed in detail.

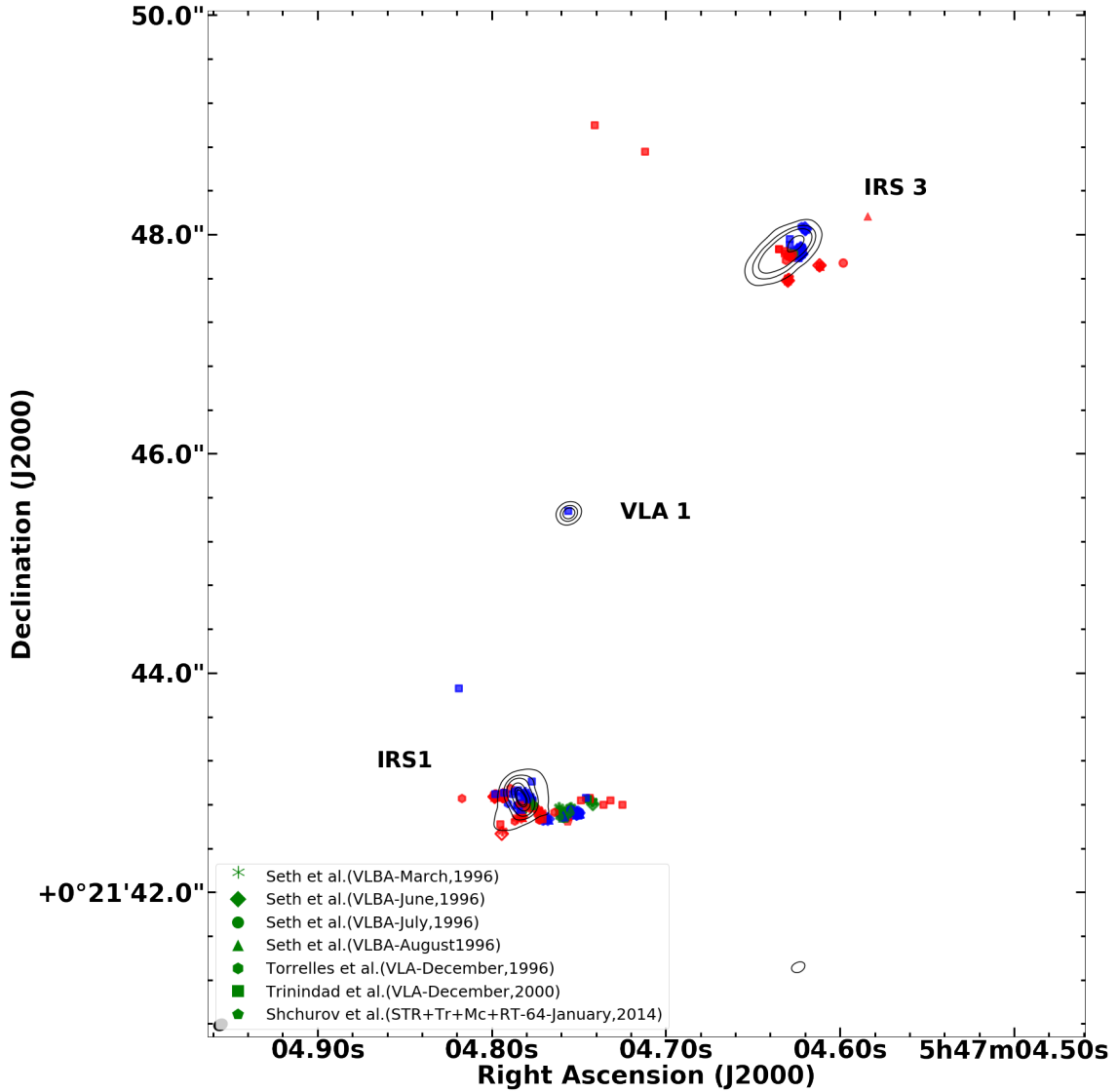


Figure 6.5: Distribution of water masers in the NGC 2071-IR region overlaid on the 0.8 mm continuum map from ALMA. The water maser positions were obtained from past observations outlined in Table 6.1. Using a similar scheme as Carrasco-González et al. (2012), the masers have been colour coded as either red ($V_{lsr} > 11.8 \text{ km s}^{-1}$), blue ($V_{lsr} < 7.8 \text{ km s}^{-1}$), or green ($7.8 \text{ km s}^{-1} < V_{lsr} < 11.8 \text{ km s}^{-1}$) to indicate their Doppler radial velocities. The legend details the masers detected by each observation.

6.4.1 Water maser associated with NGC 2071 VLA 1

Trinidad et al. (2009) detected one water maser towards VLA 1 which is the only water maser observed towards VLA 1 in all the seven observations of water maser positions towards the NGC 2071-IR region. This maser was blue-shifted at $V_{lsr} = 5.4 \text{ km s}^{-1}$ with respect to the cloud velocity (9.5 km s^{-1}). It had a peak flux density of 1.68 Jy . The detection of a water maser towards this core may indicate the presence of a disk and/or an outflow. The nature of VLA 1 remains unclear.

6.4.2 Water masers associated with NGC 2071-IRS3

Figure 6.6 presents a multi-epoch maser map of NGC 2071-IRS 3 plotted over the ALMA 0.8 mm continuum emission contours. Similarly, the water masers in IRS 3 are colour-coded according to their Doppler velocities in reference to the ambient cloud velocity. Red-shifted maser features are in red, and the blue-shifted features are in blue. The observations by Shchurov et al. (2021) did not cover the IRS 3 region. The overall distribution of water masers appears to be concentrated around a region extending about 40 AU . The masers are distributed in two groups. The blue-shifted features are concentrated in the northwest and the red-shifted masers more towards the southeast. The water masers associated with IRS 3 appear to be tracing a disk. Water masers are known to trace disks and the edges of outflows (Trinidad et al., 2009). Seth et al. (2002) detected cluster of masers concentrated at the edge of the 0.8 mm continuum peak and suggested they are tracing the edge of an edge-on disk of size $\sim 9 \times 2 \text{ AU}$ at a position angle of -55° . A similar conclusion was deduced by Carrasco-González et al. (2012), who mapped the water maser positions by Torrelles et al. (1998) onto 3.6 and 3 mm continuum emission maps from VLA. The clusters detected by Seth et al. (2002) were undetected by Torrelles et al. (1998), whose observations were made four months after Seth et al. (2002)’s observation. However, they also show a similar velocity gradient leading to the conclusion by Carrasco-González et al. (2012). There are also blue-shifted and red-shifted peripheral masers located on the northwestern and southeastern sides of the putative disk.

IRS 3 is suggested by many studies to be driving a large-scale bipolar outflow oriented in the northeast to southwest direction (Eisloffel, 2000; Seth et al., 2002). What role could this outflow play in the observed high variability in the water masers in NGC 2071-IR? The single-dish beam size of 0.31° is too large to distinguish the masers associated with IRS 3 apart from those associated with IRS 1 and VLA 1; hence the observed high variability could be a contribution from the masers associated with the three YSOs.

Seth et al. (2002) suggested a simple model for the spatial distribution of water masers associated with the IRS 3. The model proposes the water masers trace a conical shape with an opening angle of $\sim 110^\circ$ centred on the minor axis of the circumstellar disk, whose

edge is traced by the clump of masers. Figure 6.7 shows the simplified model.

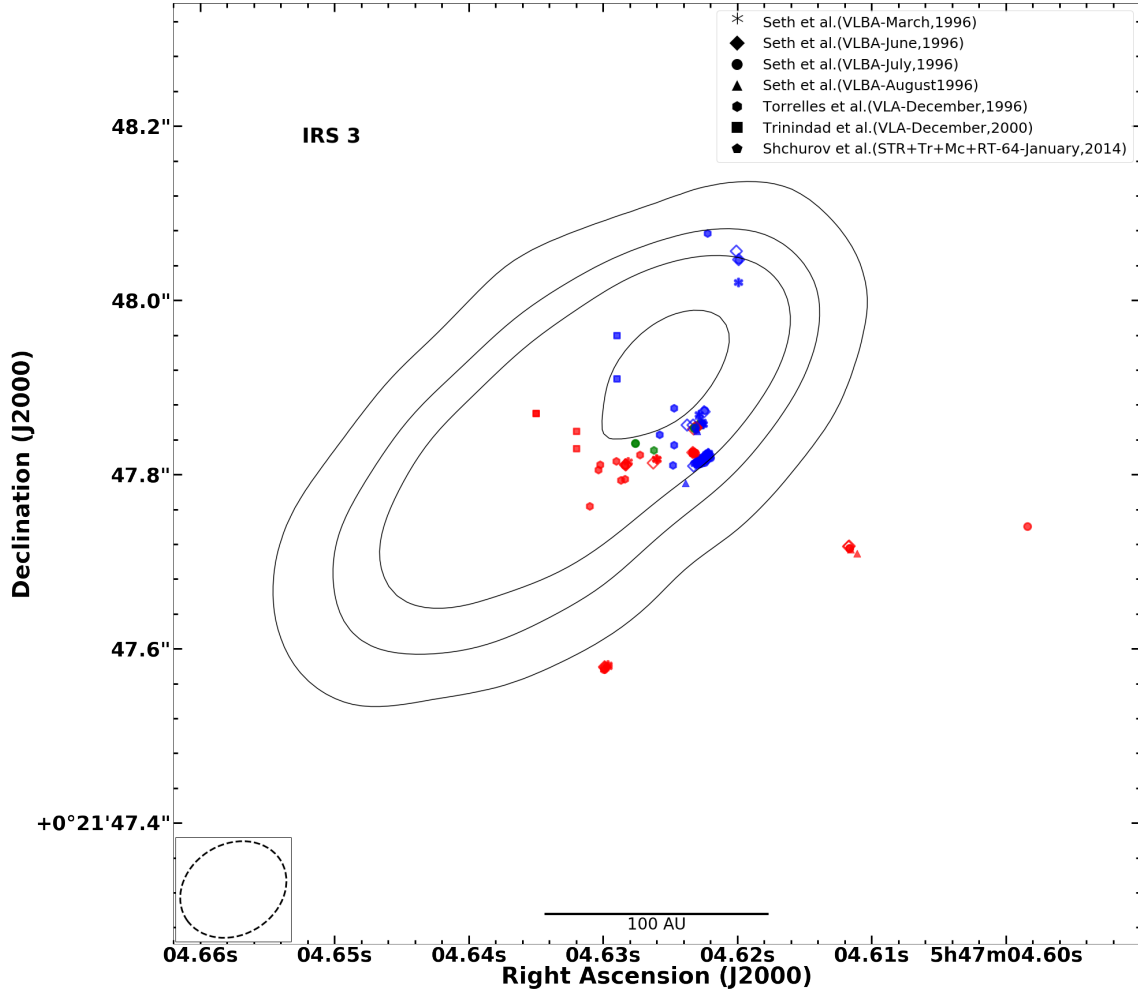


Figure 6.6: Distribution of water masers associated with NGC 2071-IRS3 overlaid on the 0.8mm continuum map of the region from ALMA. The masers have been colour coded as either red ($V_{lsr} > 11.8 \text{ km s}^{-1}$), blue ($V_{lsr} < 7.8 \text{ km s}^{-1}$), or green ($7.8 \text{ km s}^{-1} < V_{lsr} < 11.8 \text{ km s}^{-1}$) to indicate their Doppler radial velocities. The legend details the masers detected by each observation.

Trinidad et al. (2009) further suggest the disk may be tracing the interface between infalling and outflowing material, thus a natural site of maser formation due to the prevalence of shocks. Furthermore, a collimated jet is suggested to be present within the outflow cone. The model did not take into consideration the red-shifted masers on the reverse side of the putative disk since they are sparsely populated and thus difficult to determine their morphology with certainty.

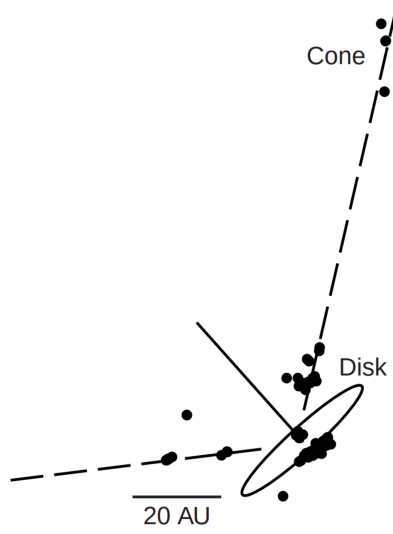


Figure 6.7: Simplified model of the distribution water maser around IRS 3 based on four epochs observations (see Table 6.1). The masers are suggested to trace a conical outflow with a collimated outflow in the centre of the cone (Seth et al., 2002).

6.4.3 Water masers associated with NGC 2071-IRS1

The maser spots around IRS 1 are distributed within a radius of ~ 259 AU from the centre of Figure 6.8. There are two locations where the water masers are clustered. This is an indication that the masers at those locations were detected in several epochs and are thus persistent. One clump is largely dominated by red-shifted masers about 32 AU from the peak of the 0.8 mm dust continuum in the southwest direction. Trinidad et al. (2009) proposed this clump traces the top side of a disk which is ~ 17 AU in length and ~ 2 AU wide. The position angle of the disk was estimated to be $\sim 11^\circ$. According to Trinidad et al. (2009), the velocity gradient in the clump with red-shifted masers lying south and blue-shifted masers lying north in the clump would thus be tracing infalling and outflowing material, respectively, if the masers in the clump are indeed tracing the disk. Seth et al. (2002)'s estimation of the mean velocity of the disk was 13 km s^{-1} .

The other clump is located at 100 AU further from the first clump in the eastward direction. A pattern of alternation can be seen in the blue-shifted and red-shifted masers which appear to alternate in a sequence starting from the east to the west. Seth et al. (2002) suggested the masers are tracing a compact circumstellar disk, with the first clump located at the edge of the disk. Seth et al. (2002) also suggested that the second clump of masers that extends ~ 8 AU in length in the north-south direction, are tracing a bow shock created by a high speed outflow. Another explanation suggested by Seth et al. (2002) is that the second clump which was referred to as 'The Arc', may be tracing a shock which is located near the wall of a wind-blown cavity.

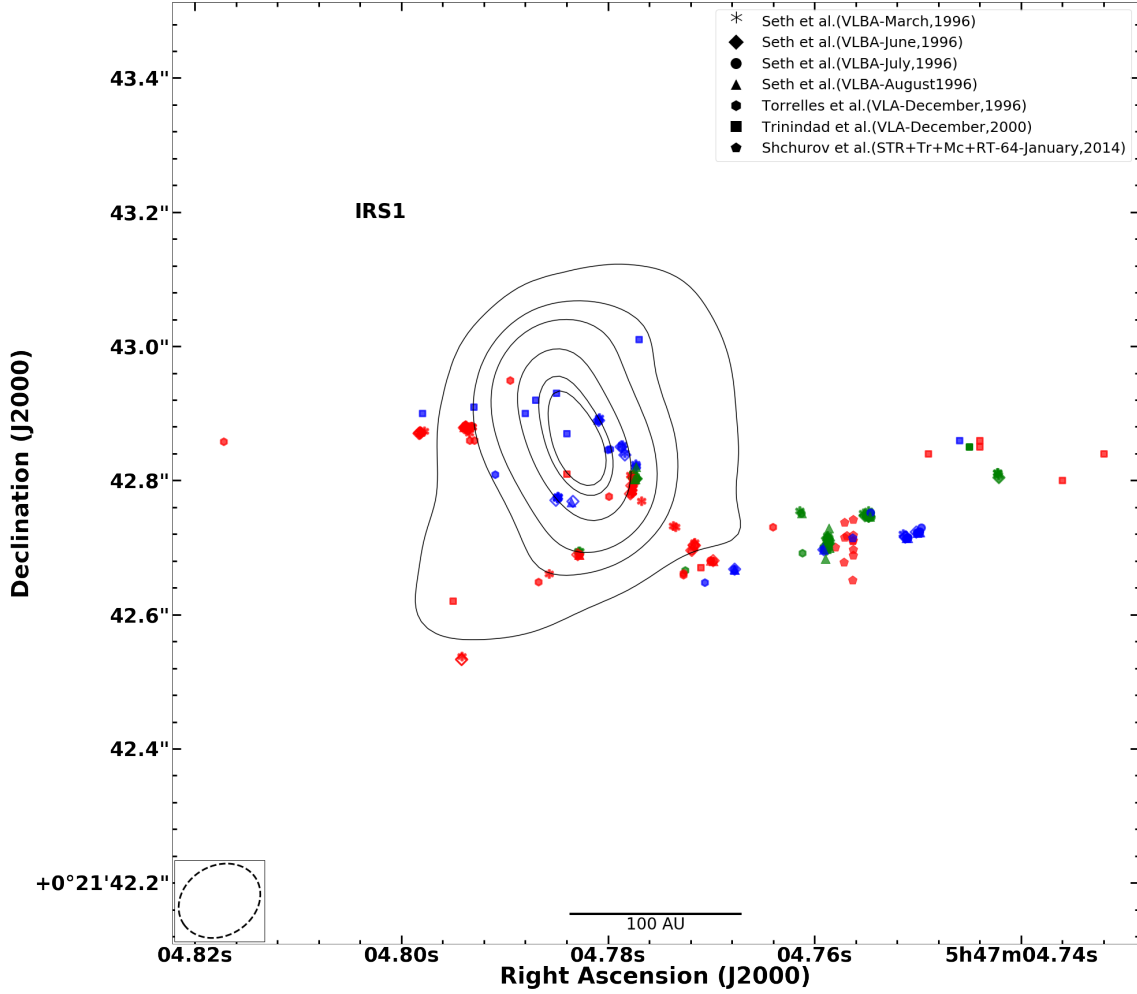


Figure 6.8: Distribution of water masers associated with NGC 2071-IRS1 overlaid on the 0.8mm continuum map of the region from ALMA. The masers have been colour coded as either red ($V_{lsr} > 11.8 \text{ km s}^{-1}$), blue ($V_{lsr} < 7.8 \text{ km s}^{-1}$), or green ($7.8 \text{ km s}^{-1} < V_{lsr} < 11.8 \text{ km s}^{-1}$) to indicate their Doppler radial velocities.

Seth et al. (2002) proposed a third explanation for an observed arc, which could be a second protostellar disk with a mass of $2 M_{\odot}$ located 120 AU away from the first disk. The maser spots in the arc were found to be 15 % larger on average than those in the entire IRS 1 region, and this could be due to maser emission extending over the shock front.

Torrelles et al. (1998) proposed that the water masers associated with IRS 1 lie in a cylindrical radially expanding shell, distributed along the direction of the strongest H_2 emission. Shchurov et al. (2021) observed a north-south distribution of masers, which appear to trace a ring-like structure, located $\sim 14 \text{ AU}$ from the arc structure observed by Seth et al. (2002). The masers in the arc and Shchurov et al. (2021)'s masers show clustering of blue, red, and green masers based on their velocities, with only one of Shchurov

et al. (2021)’s masers being blue-shifted. This may support Shchurov et al. (2021)’s third hypothesis that the arc may be tracing a second protostellar disk.

6.4.4 Model of water maser distribution in NGC 2071-IRS 1

The superposition of the water maser positions from all the seven past observations reveals a peculiar structure. The distribution of the masers appears to trace a rotating helical structure which would be in agreement with Torrelles et al. (1998)’s postulation that the masers lie in a shell around the jet. Seth et al. (2002) also indicated the presence of rotation. A similar configuration has been observed and reported towards S235 AB-MIR by Burns et al. (2015), which they referred to as a ‘water spout’. In the case of S235 AB-MIR, the water masers trace an outflow of a diameter of 15 AU and exhibit a radial velocity gradient perpendicular to the jet’s axis. This agrees with the simplified model proposed by Seth et al. (2002) as a possible explanation of the observed water maser distributions towards NGC 2071-IRS 1.

Figure 6.9 shows Figure 6.8, but with the simplified wide outflow model of Seth et al. (2002) and the rotating cylindrical outflow shell model from Burns et al. (2015) oriented along both outflow directions. The Seth et al. (2002) model suggests that the first cluster of masers (clump 1) traces a disk from which four arms extend which traces the limb-brightened edges of two funnel-shaped cavity facing outward. In this bipolar funnel-shaped cavities is a narrow high-speed bipolar outflow which has its axis oriented perpendicular to the elongation of the disk, with the arc (clump 2) tracing a bow shock. Burns et al. (2015)’s rotating cylinder model of masers in S235 AB-MIR water masers shows a colour coding indicating the line of sight velocity. The grey lines show the trajectory of a test particle in the outflow. The black arrows indicate the direction and magnitude of its proper motions. The trajectory of the test particle may be along magnetic field lines present in the cylindrical shell as illustrated in the disk-scale kinematic by Frank et al. (2014) in Figure 2.3. The peripheral masers in the NGC 2071-IRS 1 region may thus be tracing the outer shell of the narrow outflow.

The superimposed models also show that the arc is largely blue-shifted, and Shchurov et al. (2021)’s masers may be on the opposite sides of the cylindrical shell. The distribution of the Shchurov et al. (2021) masers shows no influence of the shock front which created the arc. The impact of the jet on the ambient gas may create a shock front on the boundary between the jet and the ambient cloud material. This shock front will change in intensity as this cylindrical surface shell rotates. The water masers pumped by the shock front will change in intensity as they are impacted tangentially by the momentum carried by the rotating material. This will further be amplified should two maser spots align along the line of sight. This may be a possible explanation for the slow long-term variability; however, it does not explain the strong maser flares observed in the NGC 2071-IR spectra.

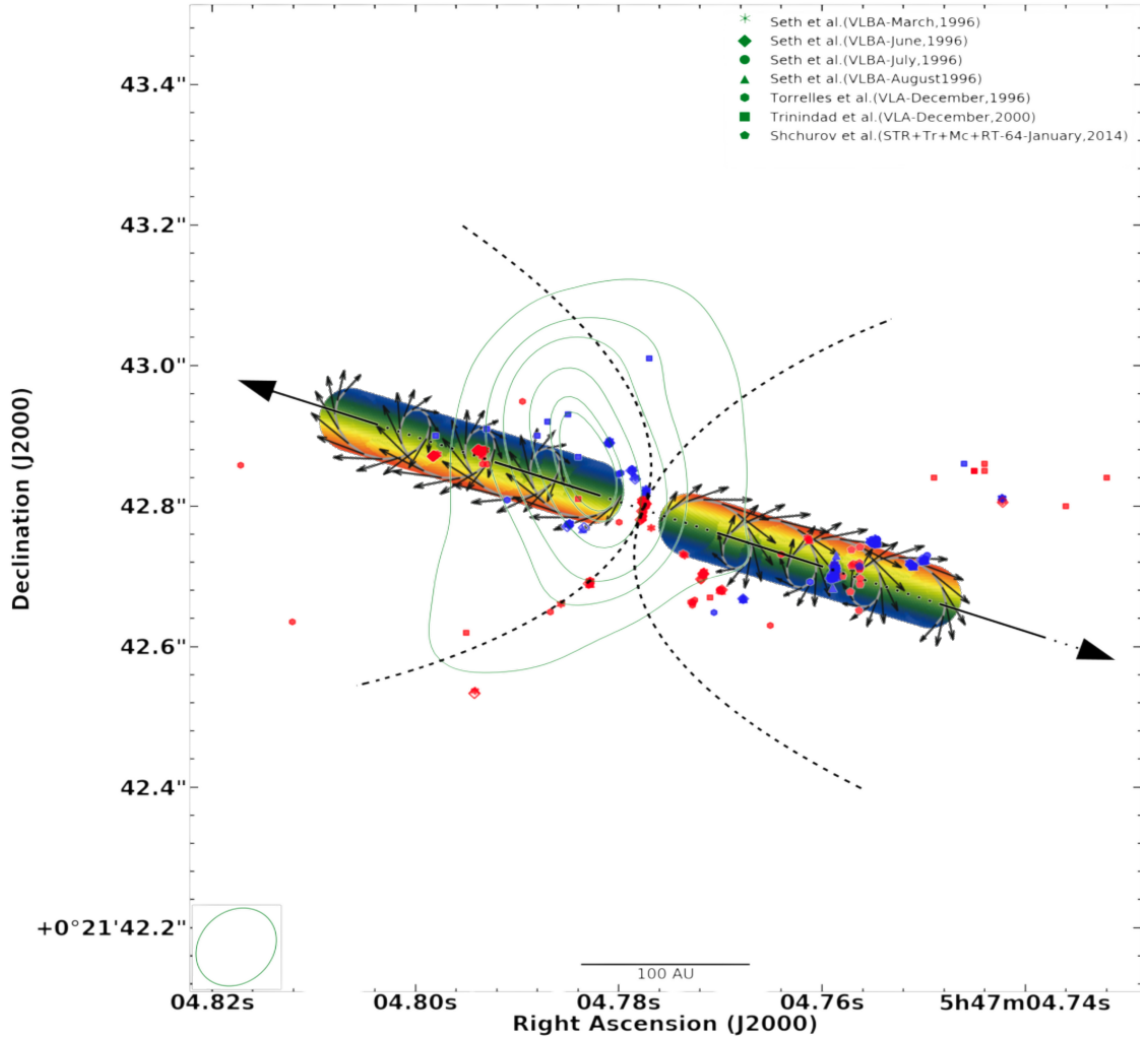


Figure 6.9: Simplified model of the configuration of water masers associated with IRS 1 derived from overlaying the masers on the models from Seth et al. (2002) and Burns et al. (2015). In this model, the water masers are tracing the cylindrical shell of the north-east south-west outflow from IRS 1.

6.5 Morphology of the NGC 2071-IR region

To obtain insight from the variability of water masers in the NGC 2071-IR region, there is a need to have a good overview of the morphology of the region. The multi-wavelength continuum images will provide the needed overview of the region in tandem with the literature. Figure 6.10 presents the superposition of the continuum emission maps presented in chapter 5, namely the 0.8 mm observed by ACA in black contours, the 0.8 mm continuum emission map from ALMA in an extended configuration in red contours, the 3.6 cm continuum map from Carrasco-González et al. (2012) in gold, and lastly, the 1.3 mm continuum emission from ALMA in green contours. In addition, the positions and directions of out-

flows reported in the region from past studies have been indicated with coloured straight lines. ACA's compact configuration and relatively shorter baselines (maximum = 32 m) allow it to be sensitive to low brightness and weak extended sources. This is evident in the continuum emission mapped by ACA towards NGC 2071-IR. It shows a diffused dust emission extending ~ 7000 AU from north to south and ~ 4000 AU from east to west. An extended lobe structure is seen on the northern portion of the structure stretching ~ 3000 AU in the eastern direction from the main structure. There are two dust continuum peaks located within the lobe.

Out of the eight protostars reported in the region (Cheng et al., 2022), designated IRS 1 to IRS 8, seven of them appear in Figure 6.10. IRS 1 and IRS 3 is located centrally, with a separation of ~ 2000 AU. VLA 1 is located at the centre. The presence of VLA 1 was previously unknown in the region due to a lack of associated infrared emission. High-resolution interferometric observations at millimetre and centimetre wavelengths by Trinidad et al. (2009) with JVLA were the first to resolve VLA 1. It must be also noted that the ACA observations did not resolve VLA 1 into a distinct core. IRS 4 and IRS 8 are located in the far northernmost and southernmost parts of Figure 6.10, respectively. IRS 2 which has been resolved into a binary system (Cheng et al., 2022), is located in the far east and is encompassed by the extended lobe emission detected by ACA. Intermediate-mass stars are known to form in clusters via fragmentation of the molecular clouds within which they form (Kun et al., 2004), resulting in the formation of multiple cores with small spatial separations referred to as multiplicity. Emission at 0.8 mm traces heated dust, thus suggesting IRS 1, IRS 2, IRS 3, VLA 1 and IRS 8 were all formed from the same dust cloud. The region NGC 2071-IR appears to exemplify multiplicity (Carrasco-González et al., 2012). The 3.6 cm continuum emission map shows free-free emission from IRS 3, IRS 2b, IRS 1 and VLA 1, with IRS 3 and IRS 1 showing elongation in the north-south and east-west directions, respectively. The free-free emission is thermal and is suggested to be emanating from ionized jets as well as from thermal dust (Carrasco-González et al., 2012). The absence of high-mass protostars that are in the region rule out the possibility of the free-free emission emanating from a photo-ionized HII region.

The masses of the dominant hot cores in the region IRS 3, IRS 1 and VLA 1, with which water masers are spatially associated, were estimated from the ALMA ACA 0.88 mm continuum image as $4.3 M_{\odot}$, $3.2 M_{\odot}$ for IRS 3 and IRS 1, respectively. The mass of VLA 1 is estimated to be $\sim 0.3 M_{\odot}$ from the 0.8 mm continuum from ALMA in an extended configuration. The estimated mass shows that IRS 1 and IRS 3 are both low-intermediate mass protostars, which is consistent with past studies such as Seth et al. (2002), Carrasco-González et al. (2012), and Trinidad et al. (2009).

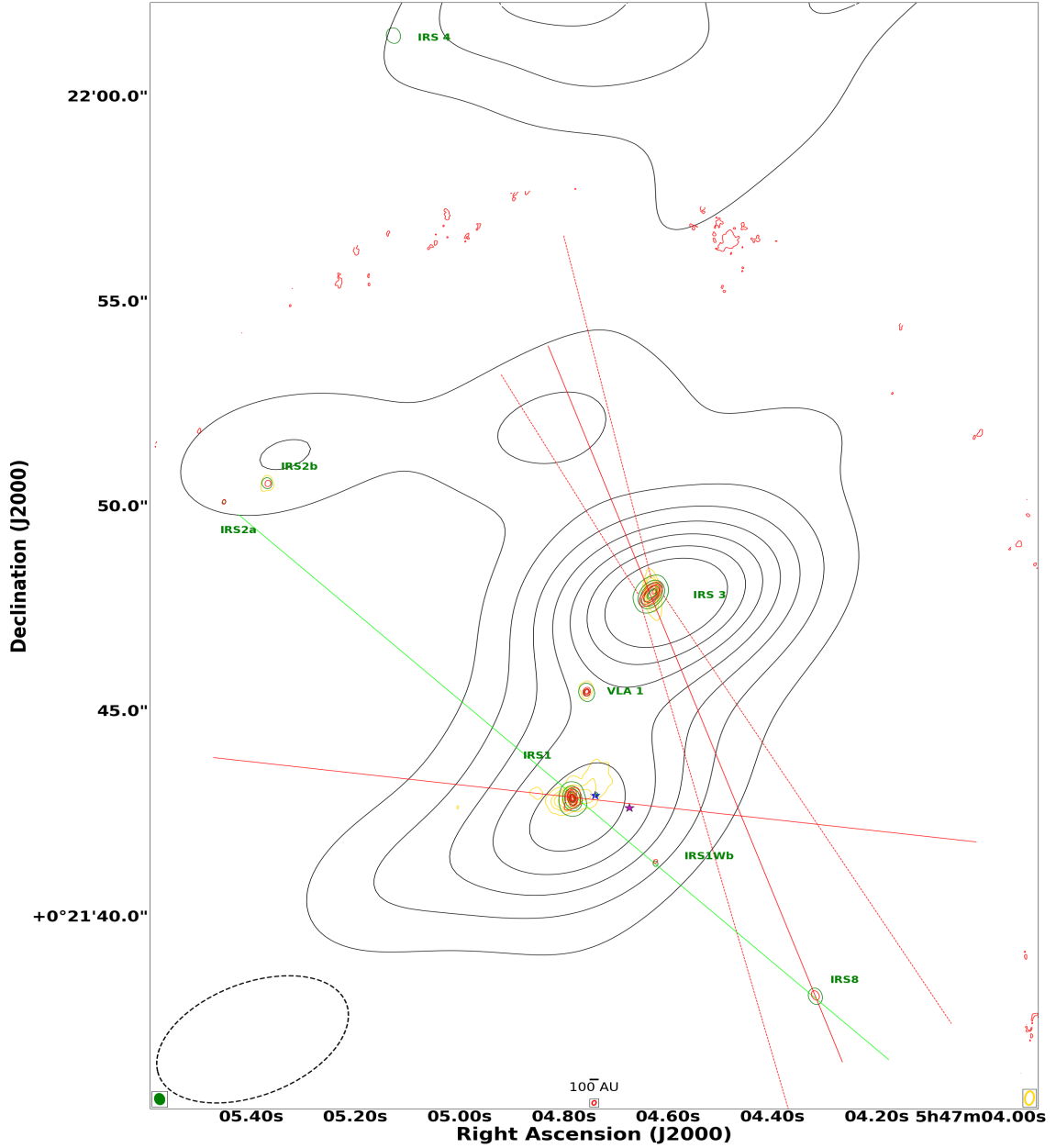


Figure 6.10: Layout of the NGC 2071-IR region. The 0.88 mm continuum from ALMA-ACA (black contours) is superimposed with a 1.3 mm continuum from ALMA (green contours), the 3.6 cm continuum (gold contours), and 0.88 mm continuum from ALMA extended array (red contours). The beam sizes of the respective emission maps are shown at the bottom of the figure. The solid red lines represent high-velocity outflows, the dashed red lines show low-velocity outflows, and the green line is a radio jet. A total of seven protostars were resolved and labelled. The blue and magenta stars indicate the positions of 1.3 cm continuum peaks resolved by Trinidad et al. (2009). The spotty red emissions in the north are artefacts from the edges of the field observed with ALMA’s extended array.

6.6 Outflows in NGC 2071-IR

Outflows emanating from YSOs are well-established as a common phenomenon in star formation. In this section, the outflows in the NGC 2071-IR region are examined to establish a link between them and the water masers. The outflows in NGC 2071-IR were mapped with dense ($n_{H_2} \sim 10^{4-6} \text{ cm}^{-3}$) gas tracers such as CS, HCO^+ , and HCN by Kitamura et al. (1990). High-velocity components were detected in the CS covering the 14 km s^{-1} to 20 km s^{-1} range. High-velocity components (15 to 23 km s^{-1}) were detected in the HCO^+ $J=1-0$ as well. Kitamura et al. (1990) observed two clumpy expanding dense bubbles which they suggested are shock-compressed layers which are swept up by the high-velocity stellar wind from the YSO. CO is easily excited even at low temperatures (Elitzur, 1992a), and ^{12}CO is one of the most abundant molecules found in star-forming regions (Ward-Thompson and Whitworth, 2011). For this reason, ^{12}CO ($J=3-2$ transition) emission maps were used to investigate the outflows in the NGC 2071-IR region. ^{12}CO $J=3-2$ emission can be optically thick (Stahler and Palla, 2004), thus it needs to be supplemented with optically thinner CO lines such as ^{13}CO . In this regard, ^{13}CO $J=3-2$ maps will also be utilised for probing the outflows in the NGC 2071-IR region.

Figures 6.11 and 6.12 present selected channels of the ^{12}CO $J=3-2$ transition distribution maps from the ALMA band 7 observations introduced in section 5.5.1. The full channel maps are presented in Appendix B. The velocity labels are colour-coded blue, for the blue-shifted velocities, and red for red-shifted velocities, with respect to the systemic velocity (9.5 km s^{-1}). A narrow collimated outflow can be observed in the first four rows of Figure 6.11, and it appears to be associated with IRS 3, its axis is perpendicular to the putative IRS 3 disk traced by the water masers. The jet appears to be composed of knots and clumps with varied directions suggestive of precession. The second four rows show a faint emission extending from the northeast to the southwest across IRS 1.

An extended bubble-shaped structure begins to appear from the 18 km s^{-1} about 5 arcseconds southward of IRS 1. This lobe becomes very prominent in the channels from -6.0 km s^{-1} to -1.0 km s^{-1} . The emission from the northeast-southwest outflow becomes brightened. An arc structure is also seen in an offset of approximately 5 arcseconds in the east from IRS 1. This structure does not seem to be spatially associated with IRS 1. The bow part of the arc is oriented towards the east suggesting it is likely an outflow from another protostar in the vicinity. The last row of Figure 6.11 shows extended emission in the southwest. The origin of this emission is unclear.

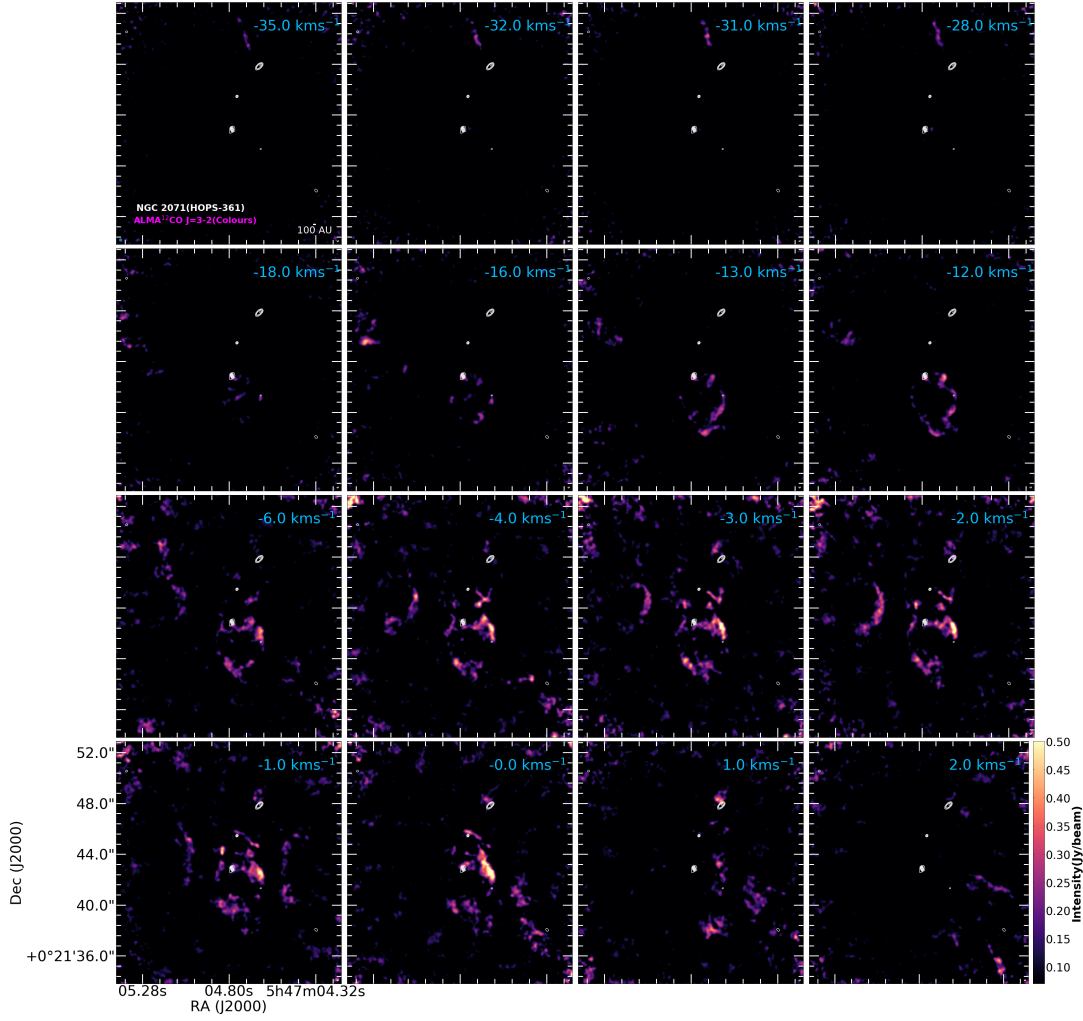


Figure 6.11: Selected $^{12}\text{CO } J=3-2$ intensity distribution maps of the NGC 2071-IR region in pseudo colour scale. The colour scale is on the right of the bottom right panel. The centre velocities of each channel are shown in each panel on the top right corner with blue labels indicating blue-shifted velocities and red-labelled velocities indicating red-shifted velocities with respect to the cloud velocity (9 km s^{-1} to 10 km s^{-1}). The 0.8 mm dust continuum is overlaid in white contours in each panel. The rms noise level is $9.33 \mu\text{Jy}$. Contour levels of ALMA 0.8 mm continuum are 0.01, 0.03, 0.05, 0.09, 0.12, 0.13, $0.16 \times 2.67 \text{ mJy rms}$.

The 5.0 km s^{-1} panel in Figure 6.12 shows a bright emission in the east of IRS 1 just offset from eastward from the position of the arc seen in panels with velocity -4 km s^{-1} to -1 km s^{-1} . The channel maps for the velocities from 6 km s^{-1} to 10 km s^{-1} show self-absorption as expected for CO emission around the systemic velocity of the cloud. The first red-shifted channel shows widespread emission with a bright ring-like bubble emerging at about 5 arcseconds westward of VLA 1. This bubble collapses into a shapeless cloud-like structure in the 12 km s^{-1} panel. There is bright emission coincident with the location of the continuum peak of IRS 1 in the 12 km s^{-1} panel.

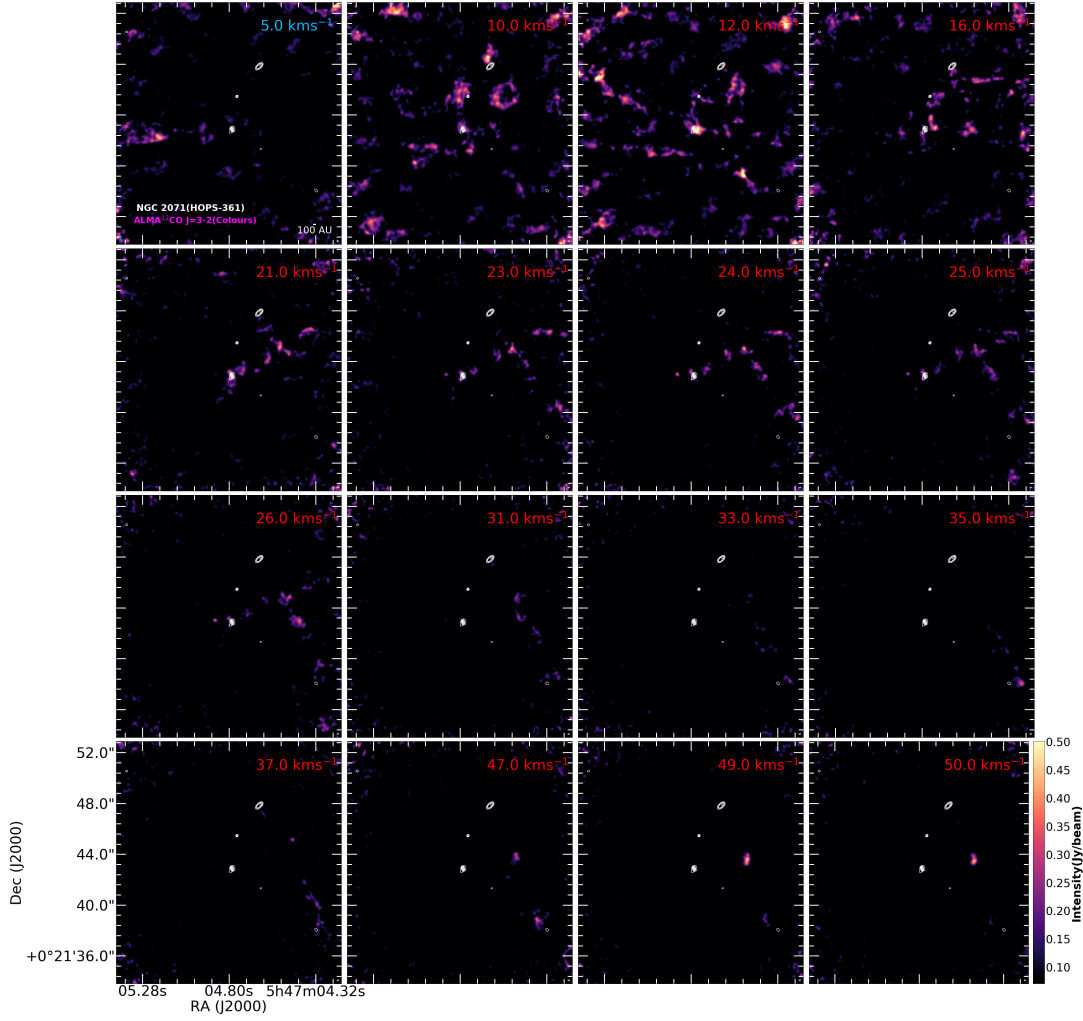


Figure 6.12: Continuation of selected $^{12}\text{CO } J=3-2$ intensity maps (Figure 6.11). Interesting to note is the bright spot which appears in the 47.0 km s^{-1} velocity channel and brightens in the remaining panels.

A chain of clumps of faint emission elongated in the southwest direction of IRS 3 begins to appear in the 16 km s^{-1} channel map and extends over about 8 arcseconds. This appears to be the red-shifted lobe of the outflow from IRS 3. The second row (21 to 25 km s^{-1} panels) of Figure 6.12 shows a chain of clumps with weak emission in the a northwesterly direction emanating from the position of the continuum peak IRS 1. The presence of clusters in four different channels indicates it is real emission and not arteficial. This would then be an outflow from IRS 1 or from the direction of IRS 7, which is not in the field of view of the ALMA observations. In the H_2 map by Eislöffel (2000), an outflow extending in northwesterly direction (marked with a purple line in Figure 6.13). The second lobe of this outflow is not visible in the H_2 maps. The north-west south-east oriented outflow visible in the 21 to 25 km s^{-1} panels may be tracing the second lobe of the IRS 7 outflow.

6.6.1 Established outflows in NGC 2071-IR

In Figure 6.15, the confirmed directions of outflows in the NGC 2071-IR region are shown using the directions from the ^{12}CO $J=3-2$ channel maps and literature comparison. Persson et al. (1981) first identified the high-velocity (100 km s^{-1}) outflows driven by intense winds from an embedded infrared source and postulated that the emission was from shock-heated gas from the flow and the surrounding cloud medium. Eislöffel (2000) also mapped the region using H_2 at $2.2\text{ }\mu\text{m}$. Figure 6.13 displays an H_2 emission map from Eislöffel (2000). Coloured lines indicate Eislöffel's stipulated outflow directions. The red line represents the northeast to southwesterly outflow from IRS 3, extended $\sim 5'$. Stojimirović et al. (2008) found that this outflow extends a total length of 1.7 parsecs, which implies the outflow extends beyond the field of view of the ALMA observations. The yellow line shows the east-west outflow from IRS 1, which is shorter at $\sim 4''$. The purple line shows an outflow from IRS 7, extending from northwest to southeast.

Comparing the ^{12}CO $J=3-2$ line maps and the outflow detections by Eislöffel (2000), the large-scale outflow running north-east to south-west through IRS 3 in the ^{12}CO map matches the red line outflow indicated by Eislöffel. The red line outflow through IRS 1 running east-west aligns with the outflow indicated with a yellow line. The purple line outflow marked by Eislöffel is not seen in the ^{12}CO maps as it falls outside the field of view of the ALMA observations. Girart et al. (1999) also mapped the northeast-to-southwest oriented outflow associated with IRS 1 using the HCO^+ ($J=3-2$) line. The outflow was found to extend $3'.5''$ long with a P.A. of 40° and clumpy in structure. Furthermore, Chernin and Masson (1992) also searched for outflows in the region with the ^{12}CO $J=3-2$ transition and found a well-collimated, symmetric and high-velocity bipolar outflow within $1.5'$ of IRS 1. The gas temperature was estimated to be 80 K, presumed to be from re-accelerated molecules behind a fast travelling shock.

Figure 6.14 shows an integrated intensity map of ^{13}CO $J=3-2$ emission, colour-coded to show blue-shifted and red-shifted emission. The emission was integrated over a velocity range of $V_{lsr} = 4.13\text{ km s}^{-1}$ to 17.82 km s^{-1} with respect to the cloud velocity (9.5 km s^{-1}). A distinctive wide-angle bipolar outflow with blue-shifted and red-shifted lobes is visible, and the intersection of the lobes coincides with the location of IRS 1, suggesting IRS 1 is driving the outflow. The outflow extends $\sim 12''$ long and has a ring-like red-shifted lobe. Moriarty-Schieven et al. (1989) suggested such ring-like morphology may be limb-brightened edges of a shell generated by an expanding molecular shell driven by a stellar wind. This shell can also be seen in the red-shifted lobe in Figure 6.14. A ring-like structure is not clearly defined in the blue-shifted lobe, possibly due to orientation effects or destruction of the ring shape by other kinematic processes such as outflows from nearby protostars.

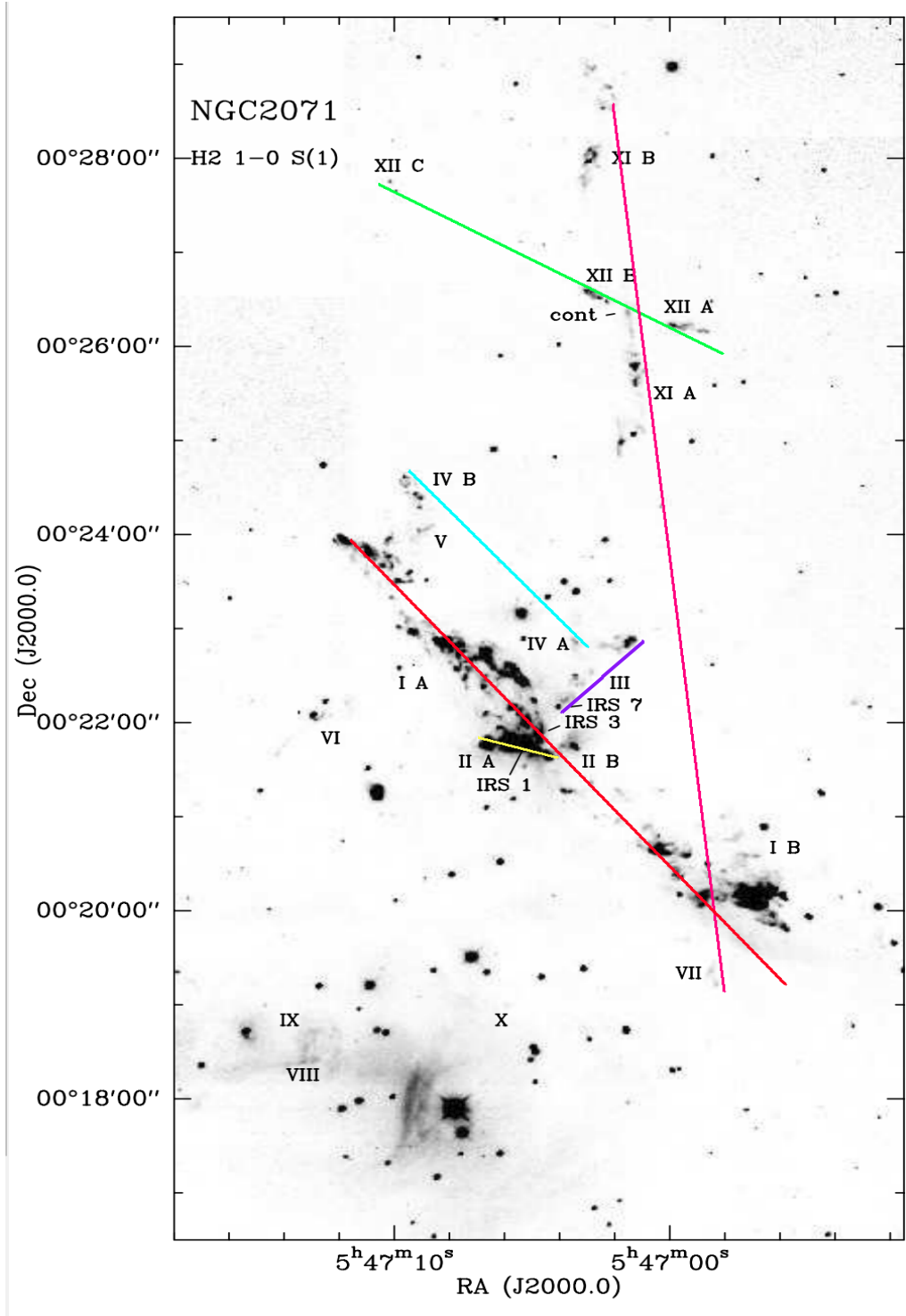


Figure 6.13: The H_2 at $2.2\,\mu\text{m}$ map of collisionally excited outflows in the NGC 2071-IR region from Eislöffel (2000). The direction of outflows and their extents have been indicated with solid coloured lines. The red (Eislöffel's flow II) and yellow line (Eislöffel's flow I) represent outflows from IRS 3 and IRS 1, respectively. These outflows are also seen in the ALMA $^{12}\text{CO } J=3-2$ maps. Outflow III appears to be coming from IRS 7. The full extent of this outflow is not visible and appears to have only one lobe in the northwest direction.

Moriarty-Schieven et al. (1989) suggested alternative explanations for the origin of the shell-structured outflow, proposing that it could be either a leftover “fossil” outflow or an entirely unrelated outflow from another region. The confirmation of this wide-angle outflow raises the question of whether it impacts the variability of water masers in the region. As per Figure 6.14, there is a concentration of CO emission in the east-to-west direction of the IRS 1 dust continuum core. For weak water masers, the movement of dense clumps of CO gas through the line of sight may temporarily obscure the masers or cause a reduction in measured flux, thus contributing to the observed variability in spectra of the water masers. The presence of fragments from ejected circumstellar material that might be entrained in the outflow could also contribute to the variability of the water masers, especially when they collide with the cold walls of the ambient cavity.

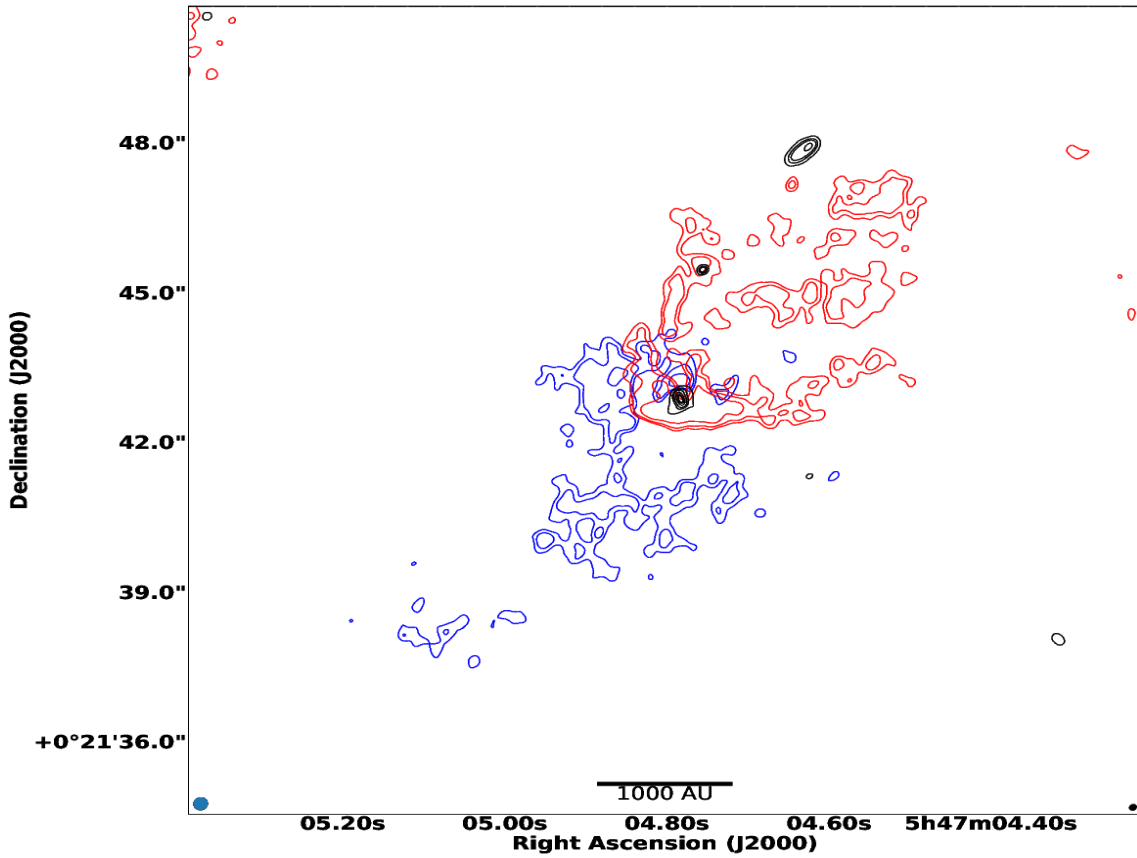


Figure 6.14: The ^{13}CO $J=3-2$ integrated intensity channel maps of the NGC 2071-IR region, integrated over 4.13 km s^{-1} to 17.82 km s^{-1} . The blue and red colours represent blue-shifted and red-shifted emissions regarding the systemic velocity 9.5 km s^{-1} . The emission reveals a $12''$ bi-polar outflow, with a ring-like shell in the red-shifted lobe and an undefined structure in the blue-shifted lobe. Notably, there is no emission spatially associated with IRS 3, and it appears that IRS 1 is the driving source of the outflow. The contour levels are set at $0.5, 0.6, \text{ and } 0.8 \times 6.67\text{ }\mu\text{Jy rms}$. The ALMA 0.8 mm dust continuum emission, with contour levels of $0.01, 0.03, 0.05, 0.09, 0.12, 0.13, \text{ and } 0.16 \times 2.67\text{ mJy rms}$, has been superimposed on the map.

The NGC 2071-IR system is similar to the Z CMa YSO system (Whelan et al., 2010; Benisty et al., 2010). Both systems have large-scale outflows, and the driver of the outflows is uncertain. An intermediate-mass protostar is suggested to be the driver of the outflow in the Z CMa YSO system, which shows wiggling close to the protostar (Whelan et al., 2010). Wiggling is seen in NGC 2071-IR in both the IRS 3 and IRS 1 jets from the $^{12}\text{CO } J=3-2$ channel maps. The wiggling of the jets in both systems may be due to precession arising from the misalignment of the disk with the orbital plane leading to tidal interactions and disk precession, which then causes the jet to precess.

Another explanation for the precession of the jet is if the driving source of the jet is orbiting around a companion YSO (Whelan et al., 2010). Nonetheless, precession in jets can indicate the presence of a binary system. The 9 mm VLA continuum map of NGC 2071-IR presented in Figure 5.16 resolves IRS 3 into a binary system, with the components having a separation of ~ 0.3 arcseconds, providing a possible explanation for the precession of the IRS 3 jet. Precessing jets may impact the cavities of the shell formed by the low-velocity outflow material at different locations of the shell, causing collisions and pumping different masers at different times. Proper motion studies such as those from Seth et al. (2002) will go a long way in explaining the role outflows play in the variability of the masers. Further examination of the $^{12}\text{CO } J=3-2$ image cubes has revealed previously unreported outflows which will be presented next.

6.6.2 Putative outflows in NGC 2071-IR

Examination of the $^{12}\text{CO } J=3-2$ channel maps in Figures 6.11 and 6.12 reveal two additional possible outflows in the NGC 2071-IR region. There is one narrowly collimated red-shifted emission oriented in the southwest direction that appears to be emanating from VLA 1. Its direction is indicated with an orange line in Figure 6.15. The blue-shifted lobe of this outflow is not seen in the $^{12}\text{CO } J=3-2$ channel maps. The absence of the second lobe of a jet/outflow is, however, common and could be due to orientation effects or the presence of high-density material just behind the east side of VLA 1, obscuring the emission or obstructing the outward propagation of the jet and thus spreading it into a nebulous structure. In both the 10 km s^{-1} and 11 km s^{-1} panels, broad diffuse emission can be seen on the east of the VLA 1 dust continuum position. The full extent of this putative outflow from VLA 1 is seen in the 12 km s^{-1} panel with the outflow extending southwest as a chain of clumps.

Another support for the likely existence of the outflow from VLA 1 is the compact emission spot which appears in the 43 km s^{-1} panel, which brightens and peaks in the 49 km s^{-1} and 50 km s^{-1} panels before disappearing in the 60 km s^{-1} panel. This spot of bright emission (position shown by a black cross in Figure 6.15) may be the intersection of the high velocity narrow collimated jet from IRS 3 and the narrow jet from VLA 1. An interesting

observation is that the lines tracing the outflows, which were derived from the $^{12}\text{CO } J=3-2$ channel maps, although not very accurate, intersect at the position of the cross, further supporting the idea that it is a point of intersection or overlap of two jets.

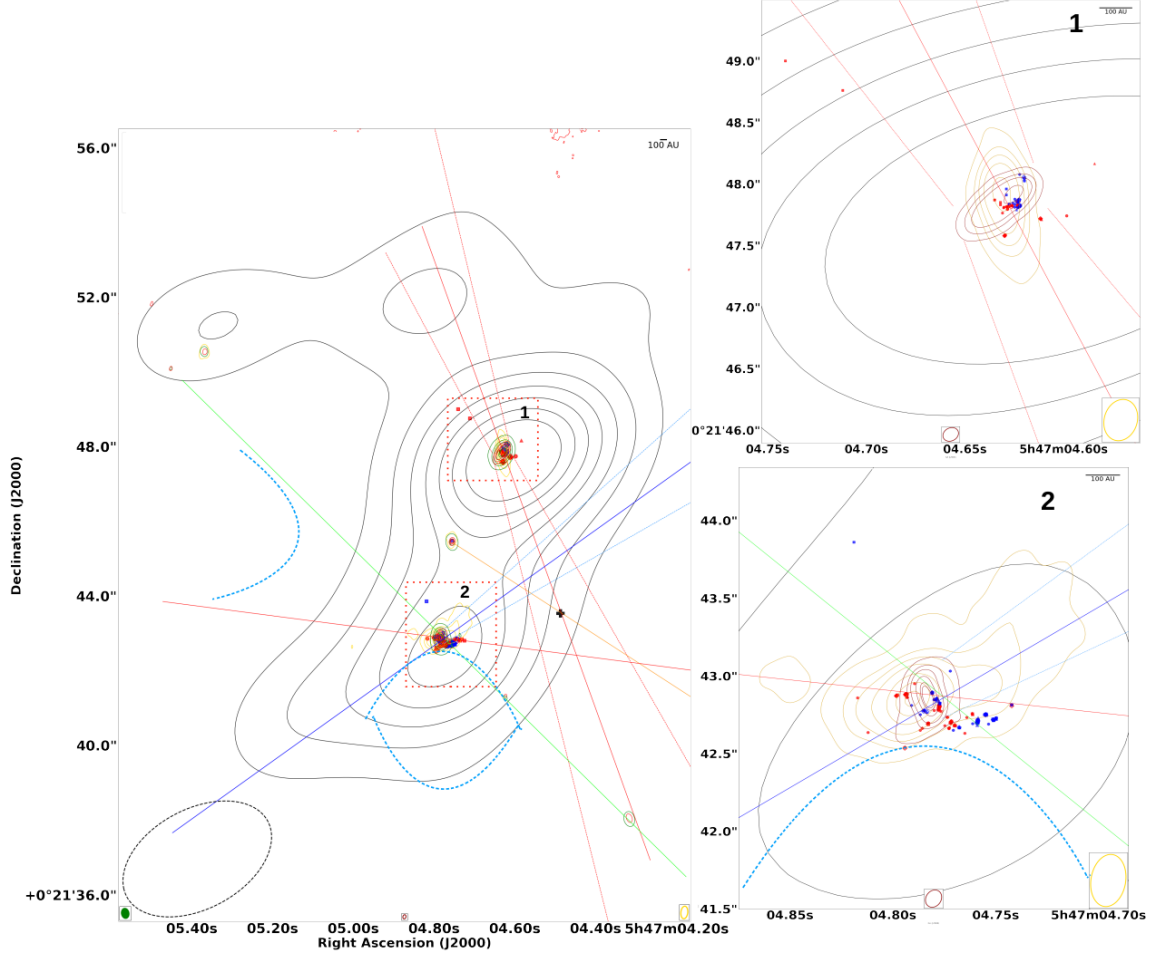


Figure 6.15: Same as Figure 6.10 but with positions of suggested outflows based on the ALMA $^{12}\text{CO } J=3-2$ channel maps. The northwest outflow from IRS 1 (orange line) and the suggested NW-SE outflow from IRS 1 are indicated (solid blue line). The black cross shows the position of the bright emission, which appears to be strongly red-shifted velocities (43 to 60 km s^{-1}), suggested to be the intersection point of the IRS 3 and VLA 1 outflows. The closed bubble, shown with blue dotted lines indicates the blue-shifted outflow appearing at -25 to 0 km s^{-1} . The arc on the east traced with blue dotted lines, is the prominent arc appearing at -4 to -1 km s^{-1} . Panels labelled 1 and 2 are zoomed-in regions around IRS 3 and IRS 1, respectively. The 1.3 mm continuum contours were not plotted on the zoomed-in panels.

Finally, the absence of infrared emission from VLA 1, the detection of sub-millimetre continuum from VLA 1, and the presence of a water maser spatially associated with VLA 1 suggests that it is likely a class 0 protostar with a disk-outflow system. Walther and

Geballe (2019) indicated that VLA 1 is ejecting material. High-resolution continuum and spectral line observations will reveal the true nature and confirm or dispute the existence of an outflow from VLA 1.

Another outflow which appears to be driven by IRS 1 in the northwest direction is seen in the 21 to 26 km s^{-1} panels in Figure 6.15. The deep blue line indicates the outflow direction, and the blue dotted lines trace its possible boundaries of low-velocity gas. Similar to the outflow from VLA 1, this outflow does not appear to have a blue-shifted lobe in the channel maps. The north-east elongation of the IRS 1 core seen in the 3.6 cm VLA continuum map, which is plotted in gold contours in Figure 6.15, was suggested by Carrasco-González et al. (2012) to be likely produced by an outflow from a deeply embedded object in the IRS 1 system.

The direction of this elongation coincides well with the direction of the presumed outflow traced by the blue lines. Multiplicity has been reported in IRS 1 by Trinidad et al. (2009). Multiple embedded YSOs may thus produce outflows in other directions based on the orientation of their circumstellar disks. Lastly, CS $J=2-1$ observations by Zhou et al. (1991) found a symmetric high velocity bipolar outflow oriented at an angle of 110° to the horizontal axis of IRS 1 (see Smith and Beck (1994)). This coincides well with the direction of this putative outflow from IRS 1, further offering support for the existence of this outflow.

6.7 Possible accretion burst in NGC 2071-IR?

According to observational and theoretical evidence, episodic accretion is common among young stellar objects (Stamatellos et al., 2011). Episodic accretions explain the discrepancy between the final mass of the protostar produced from steady-state accretion, versus the final mass of the protostars when they reach their zero-age main sequence (ZAMS) phase (Stamatellos et al., 2011).

In principle, the flaring of maser species and an increase in NIR luminosity are common indicators of the occurrence of an accretion burst event (Bayandina et al., 2022). The observation of the flaring of masers in three massive star-forming regions by the maser monitoring organization (M2O), which has led to the confirmation of accretion burst events in the associated protostars, has triggered a strong interest in conducting follow-up observations on any detected flaring.

Although both IRS 1 and IRS 3 are in active phases of accretion and/or driving outflows (Walther and Geballe, 2019), there is currently insufficient evidence that either of them underwent an accretion burst. The results from the HONIR observations; which were made during the flare (see Figure 6.16), showed a 0.2 increase in the Ks-band magnitude of NGC

2071-IRS 1 when compared to the 2MASS Ks-band magnitude. However, Walther and Geballe (2019) also reported a K-band magnitude value of 10.99 mag, from observations made on 26 December 2017. This implies that the increase in K-band magnitude had already occurred before the 2019 flare. The 2MASS observations of the NGC 2071-IR region were made in 1999, totalling a 20 yr gap. The magnitude change over 20 years will depend on the characteristics of IRS 1, along with any environmental factors that may impact its luminosity. There is also the possibility of deeply embedded unresolved binary systems present in IRS 1. Outflows from both components in a binary system have been reported (Whelan et al., 2010; Benisty et al., 2010).

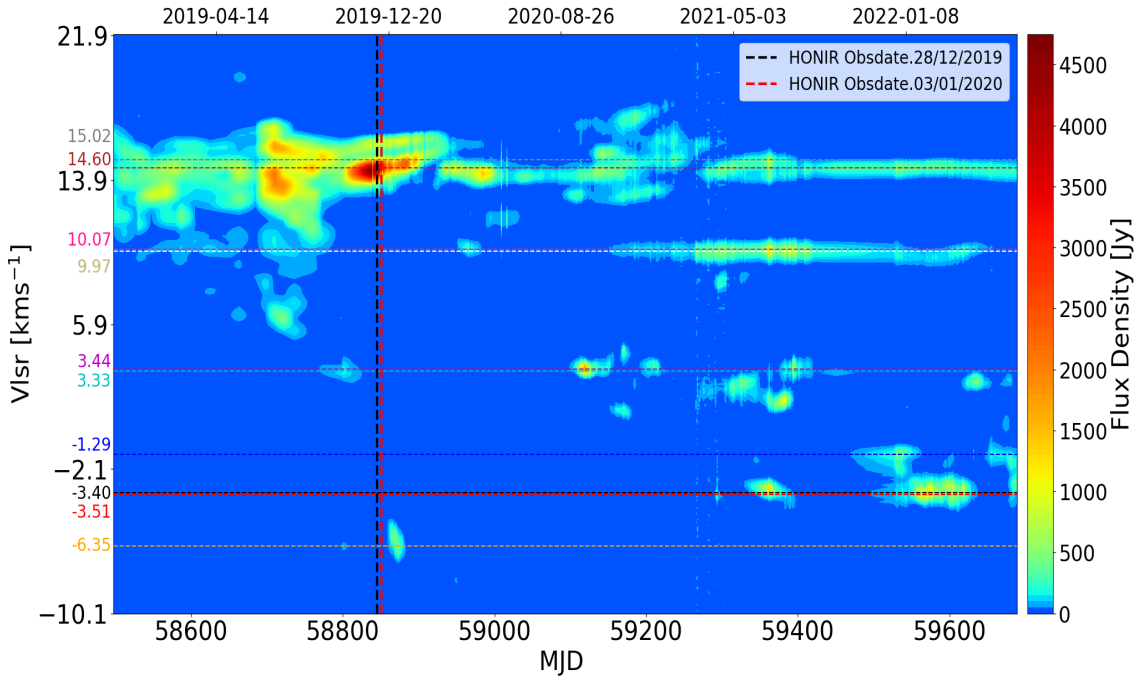


Figure 6.16: Dynamic plot of water masers in NGC 2071-IR from January 2019 to April 2022. The black and red vertical lines indicate the dates of the NIR observations with the Kanata/HONIR telescope. The 2019 NIR observation (black vertical dashed line) were made during the peak of the water maser flare.

It is unlikely that an accretion burst occurred in NGC 2071 region, specifically IRS 1 for several reasons. Firstly, the levels reached by the strongest flare (4000+Jy) and the increase in luminosity (0.2 mag, compared with 2MASS magnitude) are not significant enough in the context of accretion burst increments. The $V_{lsr} = 14.4 \text{ km s}^{-1}$ feature had the highest flux density value at $4722 \pm 4 \text{ Jy}$. The flare followed a gradual rise and steep fall profile (See Figure 5.9). From the matching of velocities in the HartRAO data to velocities in the interferometric water maser maps (see Appendix C), the $V_{lsr} = 14.4 \text{ km s}^{-1}$ feature is only detected towards IRS 1, suggesting that IRS 1 is the protostar associated with the strong flare. The only feature detected in the $V_{lsr} = 14\text{-}15 \text{ km s}^{-1}$ velocity range towards IRS 3 is the $V_{lsr} = 14.86 \text{ km s}^{-1}$. This corresponds with a 14.81 km s^{-1} velocity in the

HartRAO spectra. With a velocity resolution of 0.1 km s^{-1} HartRAO spectra, it is safe to say the $V_{lsr} = 14.4 \text{ km s}^{-1}$ and the 14.86 km s^{-1} are not the same feature.

Water masers have been known to flare up to levels above 20,000 Jy without the occurrence of a burst (Volvach et al., 2022). Alternative explanations, such as strong stellar winds and shocks from ejections within the region, can better explain the observed maser flares. These mechanisms could also result in an increase in luminosity, although the causes may differ from those seen in an accretion burst.

Furthermore, a careful analysis of the historical water maser data on the region has revealed a pattern of alternation between flares of blue-shifted masers, and red-shifted masers. This could be explained by the variations in luminosity due to the presence of binaries; in both the IRS 1 and IRS 3 cores. Carrasco-González et al. (2012) also suggested that IRS 1 hosts a binary system, based on complex morphologies seen at centimetre wavelengths. IRS 3 has also been resolved into a binary in the 9 mm image presented in Figure 5.16. It is thus plausible that shocks produced by the orbital motion of the binaries contribute to the variability seen in the water masers. Parfenov and Sobolev’s model of modulation of maser emission by binary systems (Parfenov and Sobolev, 2014) is considered, albeit based on massive binaries as well as the methanol masers instead of water masers. Nonetheless, the prevalence of shocks due to orbital motions in non-massive binary systems is also plausible. Outflows from binary systems will experience some level of precession due to the motion of the protostellar binaries producing the outflows. Indeed, the northeast-southwest outflow from IRS 3 is seen to precess, as well as the outflow from IRS 1 (Carrasco-González et al., 2012; Cheng et al., 2022). The collimated high-velocity component of outflows may impact the walls of the outflow cavity; along the axis of the jets where the water masers trace (see Figure 6.8) as they precess, thereby pumping different masers at different times.

In conclusion, whilst the observed flare in water masers; and the accompanying increase in luminosity are indicators of a possible accretion burst, there is not enough evidence to suggest a burst occurred in NCG 2071-IR. The levels attained by the flare (orders of 10^3 Jy) is insufficient in the context of accretion bursts. It also appears that the luminosity did not increase, as Walther and Geballe (2019) had reported the same Ks-band magnitude in an observation made two years prior to the HONIR observation. Increase in luminosity during an accretion burst is suggested to be by a factor of 5 - 10 compared to initial levels (Audard et al., 2014). Alternative explanations of the flare, such as stellar winds; gas interactions; or shocks, should rather be considered.

Chapter 7

Summary and Conclusions

7.1 Summary

This study aimed to investigate the behavior of water masers towards NGC 2071-IR, which is considered an intermediate star-forming region. NGC 2071-IR is situated approximately $4''$ north of the NGC 2071 reflection nebula in the Orion constellation. Two maser species, namely 6.7 GHz methanol masers and 22 GHz water masers, were observed regularly with the HartRAO 26-m telescope. The methanol maser observations, however, were discontinued due to consistent non-detection. The water maser observations were conducted from 2019 until the middle of 2022. Water masers, detected at 3σ , exhibited strong variability in their spectra. To further investigate the variability, high-resolution archival data from ALMA and VLA, was analysed to derive insight into the morphology of the region. The ALMA data included two sets of observations: dust continuum emission at 0.8 mm, taken with the ALMA compact array (ACA), which is sensitive to faint emission, and 0.8 mm dust continuum emission observed with ALMA in an extended configuration. Raw files of 1.3 mm dust continuum observations from the ALMA database were obtained, reduced and imaged. A 3.6 cm free-free continuum data, and 9 mm dust continuum data from VLA, were also utilized to gain a multi-wavelength perspective on the region's morphology. Water maser positions were taken from literature and plotted over the previously mentioned continua maps; to obtain a detailed picture of the water masers and their distribution in the region. In general, the dust continuums showed three dominant continuum peaks, which coincide with near-infrared sources NGC 2071-IRS3 and NGC 2071-IRS1. The water masers in NGC 2071-IR underwent a strong flare in 2019, which the community of maser monitoring researchers known as M20 reported as a potential accretion burst. The possibility of the flaring being a result of an accretion burst was explored.

7.2 Conclusions

The major conclusions of this study are outlined below:

1. The point source sensitivity (PSS) values, obtained from observations of Jupiter, required to calibrate the water maser spectra from antenna temperature T_A to flux density F_ν exhibited periodic variations via periodic increases in the PSS values. A Lomb-Scargle periodogram fitting estimated a 394-day period. The jumps are caused by variations in the distance between the Earth and Jupiter. The synodic period of Jupiter is 398.88 days, which is close to the period derived from the Lomb-Scargle fit. The increase in PSS values is also seen to occur during the South African summer months, suggesting an increase in moisture content in the atmosphere is also a contributing factor to the periodic jumps in PSS values.
2. The dust continuum of NGC 2071-IR from ALMA showed seven continuum cores distributed over a $16'' \times 25''$ area. The recently detected source VLA 1, which does not have any infrared emission associated with it, was resolved in the dust continuum images bar the ACA image. The VLA 9 mm dust continuum resolved IRS 3 into a binary system. The average masses of the dominant cores were estimated as $\sim 4 M_\odot$, $2 M_\odot$, and $0.3 M_\odot$ for IRS 3, IRS 1 and VLA 1, respectively.
3. No methanol maser emission was detected at 6.7 GHz towards NGC 2071-IR. Although the HartRAO 26-m telescope has comparatively poor sensitivity, high sensitivity observations by Xu et al. (2008) with the Effelsberg 100 m telescope, also reported no detection of 6.7 GHz masers towards the region. 6.7 GHz masers are reported to be exclusively associated with high-mass stars (Breen et al., 2013). The absence of 6.7 GHz methanol masers in NGC 2071-IR suggests that the NGC 2071-IR star-forming region is populated by low to intermediate-mass protostars.
4. Water masers in the NGC 2071-IR region were detected at 3σ and revealed strong variability on the scales of weeks and months. The variability index of the dominant water maser features was estimated using the equation and method described by Goedhart et al. (2004) after grouping the spectra based on the calendar year of observation. The highest variability indexes in the HartRAO data were in the 2020 time series, with the highest value being 21,626 for the 15.03 km s^{-1} maser feature.
5. The 2019 to 2022 water maser spectra from HartRAO show a strong flare from the $V_{lsr} = 14.4 \text{ km s}^{-1}$ feature occurring in 2019 with a steep increase in intensity which reached $4722 \pm 4 \text{ Jy}$ during its peak. The flare profile exhibited a gradual rise over 341 days to reach a maximum, followed by a rapid decline to reach a minimum over 79 days. The total duration of the flare was 420 days.
6. A maser feature occurring at $V_{lsr} = -6.3 \text{ km s}^{-1}$ exhibited a peculiar behaviour; the appearance of this maser feature always coincides with a strong maser flare

of other (red-shifted) features. This feature has remained undetected by all high-angular resolution water maser observations made towards the NGC 2071-IR region, and its position remains unknown.

7. Water maser positions were obtained from the literature and plotted over the dust continuum maps of the region, revealing a large clustered distribution of masers mainly around two NIR sources, IRS 3 and IRS 1.
8. The water masers associated with IRS 3 appear to be tracing a circumstellar disk; while the water masers associated with IRS 1 appear to be tracing both a circumstellar disk and the edges of an outflow.
9. The ^{12}CO $J=3-2$ spectral line channel maps showed outflows emanating from IRS 3 and IRS 1. The blue-shifted flow from IRS 1 is not as clearly visible as that from IRS 3. An outflow in the southwest direction is proposed to originate from VLA 1 and an outflow in the northwest direction appears to arise from IRS 1. The presence of the latter two outflows is not vigorously confirmed. Hints of the interaction of collimated outflows are also seen in the ^{12}CO $J=3-2$ emission maps.
10. The integrated ^{13}CO $J=3-2$ spectral line channel maps reveal a bi-polar outflow, with the blue-shifted lobe exhibiting a ring-shaped shell structure. The structure of the red-shifted lobe is not discernible. It is unclear which protostar(s) is responsible for this outflow.
11. Multiple outflows detected in the region suggest the presence of multiple disks, with IRS 1 showing multiple outflows from the direction of its dust continuum, hinting at multiplicity in IRS 1.
12. The presence of multiple outflows in the region indicates that the high variability observed in the water masers may be due to not only turbulence in the gas medium but also the complex interactions of these outflows. Frequent shocks resulting from the interactions of the outflows may act as pumping mechanisms for the water masers.
13. The strong flare in the 2019 HartRAO observations was analyzed in the context of a potential accretion burst. The NIR magnitude during the flare, specifically Ks-band magnitude, was measured from observations with the Kanata/HONIR telescope and revealed a 0.2 magnitude increase compared to the 2MASS Ks-band magnitude. The increase is insufficient to conclude the occurrence of an accretion burst in NGC 2071-IR. Ks-band magnitude from the 2017 observation of IRS 1 (protostar associated with the flared maser feature) measured a magnitude of 10.99. The same value was estimated from the HONIR observations thus suggesting there was no increase in NIR luminosity (Ks-band magnitude) during the 2019 maser flare, ruling out the possible occurrence of an accretion burst in NGC 2071-IR.

7.3 Recommendations for future work

The NGC 2071-IR region presents a complicated picture of a star-forming region, albeit an interesting one. Further work to build on this study may thus be in the direction of additional high-resolution observations of outflow tracers to confirm or refute the existence of the putative outflows proposed in Chapter 6. A thorough investigation into the orientation of the outflows in the region should be implemented. Given the presence of multiple directional outflows emanating from IRS 1, it would be useful to investigate whether IRS 1 is a binary or multiple system. Identifying any companions could help explain the complex dynamics of the outflows.

Monitoring the water masers in the NGC 2071-IR region should continue to enable the detection of future flares. Multiple maser species should be monitored towards the region as flaring of multiple maser species within a short period will be an indicator of an accretion burst.

Finally, 6.7 GHz masers should be searched towards the region with a frequency of at least one observation per year, due to the possibility of the young protostars growing into high-mass protostars due to episodic accretion.

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Appendix A

Appendix A: Derivations

A.1 A.1 Derivation of Virial theorem

The derivation of Virial theorem is taken from Stahler and Palla (2004).

The equation describing the motion of fluids with negligible viscosity, taking into account ambient magnetic field effects and fluid acceleration, is given as:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P - \rho \nabla \Phi_g + \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B} - \frac{1}{8\pi} \nabla |\mathbf{B}^2|. \quad (\text{A.1})$$

Further, Cartesian coordinates are adopted, and $\mathbf{r}$ is expressed to have Cartesian components x_i ($i=1, 2, 3$). Adopting $\partial_i \equiv \frac{\partial}{\partial x_i}$, and following Einstein's summation convention for repeated indices and using $\partial_i x_i = 3$ and $\partial_i x_j = \delta_{ij}$, the change induced by transporting an element to a new location with differing velocity, with the full time derivative of fluid velocity $\mathbf{u}$, including its rate of change at a fixed spatial position $\mathbf{x}$, is given as:

$$\frac{D\mathbf{u}}{Dt} = \left(\frac{\partial \mathbf{u}}{\partial t} \right) + (\mathbf{u} \cdot \nabla) \mathbf{u}. \quad (\text{A.2})$$

Rewriting equation A.1 using equation A.2 results in:

$$\int \rho x_i \left(\frac{\partial v_i}{\partial t} \right) d^3 \mathbf{x} + \int \rho x_i v_j \partial_j v_i d^3 \mathbf{x}. \quad (\text{A.3})$$

Taking only the first part of the expression and rewriting gives:

$$\rho x_i \left(\frac{\partial v_i}{\partial t} \right)_{\mathbf{x}} = \rho \left[\frac{(\partial x_i v_i)}{\partial t} \right]_{\mathbf{x}}, \quad (\text{A.4})$$

the second integrand as:

$$\begin{aligned}
 \rho x_i v_j \partial_j v_i &= \rho v_j \partial_j (x_i v_i) - \rho v_j v_i \partial_j x_i, \\
 &= \partial_j (\rho v_j x_i v_i) - (x_i v_i) \partial_j (\rho v_j) - \rho \delta_{ij} v_j v_i, \\
 &= \partial_j (\rho v_j x_i v_i) + \left(\frac{\partial \rho}{\partial t} \right)_x (x_i v_i) \rho v_i v_j,
 \end{aligned} \tag{A.5}$$

where $\partial_j (\rho v_j) \equiv \nabla \cdot (\rho \mathbf{v})$.

The first term on the right-hand side of equation A.5 represents the divergence of a vector. When integrated across the volume, it becomes a surface integral. The divergence disappears without an external mass flux.

Adding equations A.4 and A.5 gives:

$$\int \rho x_i \left(\frac{\partial v_i}{\partial t} \right)_x d^3 \mathbf{x} + \int \rho x_i v_j \partial_j v_i d^3 \mathbf{x} = \frac{\partial}{\partial t} \int \rho x_i d^3 \mathbf{x} - 2T, \tag{A.6}$$

Where T represents the kinetic energy of the particles in the fluid, defined as:

$$T \equiv \int \rho |\mathbf{u}|^2 d^3 \mathbf{x}. \tag{A.7}$$

Integrating the right-hand side results in:

$$\begin{aligned}
 \rho x_i v_i &= \frac{1}{2} \rho v_i \partial_i (x_j x_j), \\
 &= \frac{1}{2} \partial_i (\rho v_i x_j x_j) - \frac{1}{2} x_j x_j \partial_i (\rho v_i), \\
 &= \frac{1}{2} \partial_i (\rho v_i x_j x_j) + \frac{1}{2} \left(\frac{\partial \rho}{\partial t} \right)_x x_j x_j.
 \end{aligned} \tag{A.8}$$

In the absence of external mass flux:

$$\int \rho x_i v_i d^3 \mathbf{x} = \frac{1}{2} \left(\frac{\partial I}{\partial t} \right), \tag{A.9}$$

where I is the moment of inertia expressed as:

$$I \equiv \int \rho x_j x_j d^3 \mathbf{x}. \tag{A.10}$$

Using equation A.8, equation A.10 can be rewritten as:

$$\int \rho x_i v_j \partial_j v_i d^3 \mathbf{x} + \int \rho x_i \left(\frac{\partial v_i}{\partial t} \right) d^3 \mathbf{x} = \frac{1}{2} \left(\frac{\partial^2 I}{\partial t^2} \right) - 2T. \quad (\text{A.11})$$

Taking the right-hand terms of equation A.1 separately leads to:

$$\begin{aligned} - \int x_i \partial_i P d^3 \mathbf{x} &= - \int \partial_i (x_i P) d^3 \mathbf{x} + \int (\partial_i x_i) P d^3 \mathbf{x}, \\ &= - \int P \mathbf{r} \cdot \mathbf{n} d^2 \mathbf{x} + 3 \int P d^3 \mathbf{x}, \end{aligned} \quad (\text{A.12})$$

where $\mathbf{n}$ represents the normal vector pointing outward in the surface integral. For non-relativistic fluid particles, the internal pressure is 2/3 of the energy density in thermal motion, thus:

$$- \int x_i \partial_i P d^3 \mathbf{x} = \int P \mathbf{r} \cdot \mathbf{n} d^2 \mathbf{x} + 2U, \quad (\text{A.13})$$

where U is the total thermal energy.

The second term on the right-hand side in equation A.1 represents the gravitational term. Rewriting the gravitational potential in terms of the total mass elements in the fluid volume:

$$\Phi_g(\mathbf{r}) = -G \int \frac{\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} d^3 \mathbf{x}. \quad (\text{A.14})$$

This leads to:

$$- \int \rho \partial_i x_i \Phi_g d^3 \mathbf{x} = -G \int \frac{x_i (x_i - x'_i)}{|\mathbf{r} - \mathbf{r}'|^3} d^3 \mathbf{x}. \quad (\text{A.15})$$

Applying the below expansion:

$$\partial_i \frac{1}{|\mathbf{r} - \mathbf{r}'|^3} = - \frac{x_i (x_i - x'_i)}{|\mathbf{r} - \mathbf{r}'|^3}. \quad (\text{A.16})$$

Switching $\mathbf{r}$ and $\mathbf{r}'$ within the double integral and doubling them by adding the switched variables, we arrive at:

$$\begin{aligned}
-\int \rho \partial_i x_i \Phi_g d^3 \mathbf{x} &= -\frac{1}{2} G \iint \rho(\mathbf{r}) \rho(\mathbf{r}') \frac{|\mathbf{r} - \mathbf{r}'|^2}{|\mathbf{r} - \mathbf{r}'|^3} d^3 \mathbf{x}' d^3 \mathbf{x}. \\
&= \frac{1}{2} G \int \rho(\mathbf{r}) \Phi_g(\mathbf{r}) d^3 \mathbf{x} = W
\end{aligned} \tag{A.17}$$

where W is the gravitational potential energy.

The last two terms of equation A.1 represent the magnetic terms. By using Maxwell's equation, $\partial_j B_j \equiv \nabla \cdot \mathbf{B} = 0$, and integrating these terms, we obtain:

$$\begin{aligned}
\frac{1}{4\pi} \int x_i B_j \partial_j B_i d^3 \mathbf{x} &= \frac{1}{4\pi} \int \partial_j (x_i B_j B_i) d^3 \mathbf{x} - \frac{1}{4\pi} \int B_i \partial_j (x_i B_j) d^3 \mathbf{x}, \\
&= \frac{1}{4\pi} \int \partial_j (x_i B_j B_i) d^3 \mathbf{x} - \frac{1}{4\pi} \int B_i B_i d^3 \mathbf{x}, \\
&= \frac{1}{4\pi} \int \mathbf{B} (\mathbf{r} \cdot \mathbf{B}) \cdot \mathbf{n} d^2 \mathbf{x} - 2M,
\end{aligned} \tag{A.18}$$

where M is the magnetic energy. Integrating equation A.18 gives:

$$\begin{aligned}
-\frac{1}{8\pi} \int x_i \partial_j (B_j B_j) d^3 \mathbf{x} &= \frac{1}{8\pi} \int \partial_j (x_i B_j B_i) d^3 \mathbf{x} + \frac{1}{8\pi} \int (\partial_j x_i) B_j B_j d^3 \mathbf{x} \\
&= -\frac{1}{8\pi} \int B^2 \mathbf{r} \cdot \mathbf{n} d^2 \mathbf{x} + 3M
\end{aligned} \tag{A.19}$$

Finally, adding equations A.11, A.13, A.17, A.18, and A.19 gives the Virial theorem:

$$\frac{1}{2} \frac{\partial^2 I}{\partial t^2} = 2T + 2U + W + M - \int \left(P + \frac{B^2}{8\pi} \right) \mathbf{r} \cdot \mathbf{n} d^2 \mathbf{x} + \frac{1}{4\pi} \int (\mathbf{r} \cdot \mathbf{B}) \mathbf{B} \cdot \mathbf{n} d^2 \mathbf{x}. \tag{A.20}$$

Dropping the last two terms leads to the simplified version of the theorem:

$$\frac{1}{2} \frac{\partial^2 I}{\partial t^2} = 2T + 2U + W + M \tag{A.21}$$

A.2 A.2 Derivation of the gravitation potential energy W

For a spherical giant molecular cloud of uniform constant density, the gravitational potential can be derived as follows (Carroll and Ostlie, 2017):

To bring a particle from infinity, which was initially at rest close to a point mass m at the center of coordinates, the work done by the gravitational force $\vec{F}$ is defined as the net change in potential energy of the particle. This work is given by the expression:

$$\text{Work} = \int \vec{F} \cdot d\vec{r} = \int_{\infty}^r \frac{Gm^2}{r^2} dr = -\frac{Gm^2}{r}, \quad (\text{A.22})$$

where r is the radial distance and m is the mass of the particle.

Extending equation A.22 to an ensemble of masses, for two particles with mass m and M , the gravitational potential W is defined as:

$$W = G \frac{Mm}{r}. \quad (\text{A.23})$$

If the assumption of an infinitesimal point of mass dM positioned on the surface of a spherical symmetric shell of mass M_r , the gravitational force acting on the point towards the center of the sphere will be:

$$F_{g,i} = G \frac{M_r dM}{r^2}. \quad (\text{A.24})$$

The gravitational potential of the system will be:

$$W_{g,i} = -G \frac{M_r dM}{r}. \quad (\text{A.25})$$

The volume of the shell can be defined as $V = 4\pi r^2 dr$, if the thickness of the spherical shell is taken as dr . Assuming a uniform distribution of the point masses in the shell, the mass can thus be written in terms of density ρ as:

$$dM = 4\pi r^2 \rho dr. \quad (\text{A.26})$$

substituting A.26 into A.25 gives:

$$dW_g = -G \frac{4\pi M_r r^2 \rho}{r} dr = -4\pi G M_r r \rho dr. \quad (\text{A.27})$$

The total gravitational potential energy can be obtained from integrating over the entire sphere, which results in:

$$W_g = -4\pi G M_r \int_0^R M_r r \rho dr. \quad (\text{A.28})$$

The spherical symmetrical mass M_r can be expressed in terms of volume of a sphere $\frac{4}{3}\pi r^3$ as:

$$M_r = \frac{4}{3}\pi r^3 \rho, \quad (\text{A.29})$$

substituting equation A.29 into equation A.28 gives:

$$\begin{aligned} W_g &= -\frac{16\pi^2 G}{3} \int_0^R r^4 \rho^2 dr, \\ \Rightarrow W_g &= -\frac{16\pi^2 G}{3 \cdot 5} \rho^2 R^5. \end{aligned} \quad (\text{A.30})$$

Assuming a sphere of constant density, $\rho = \frac{3M_r}{4\pi R^3}$, and substituting:

$$\begin{aligned} W_g &= -\frac{16\pi^2 G}{3 \cdot 5} \left[\frac{3M_r}{4\pi R^3} \right]^2 R^5, \\ \Rightarrow W_g &= -\frac{3G(M_r)^2}{5R}. \end{aligned} \quad (\text{A.31})$$

Equation A.31 is the gravitational potential energy.

A.3 A.3 Derivation of the free-fall time

The local acceleration $\mathbf{a}$ due to gravity of a spherically symmetric shell of gas with radius r and mass M , and a uniform density is given by:

$$\mathbf{a} = \frac{d^2 r}{dt^2} = v \frac{dv}{dr} = -G \frac{M}{r^2}, \quad (\text{A.32})$$

where v is the velocity of the infalling material and G is the gravitational constant. Integrating both sides of equation A.32 gives:

$$\begin{aligned} \int v dv &= -G \int_r^R \frac{M}{r^2} dr, \\ v &= \left[\frac{2GM}{r} \Big|_r^R + C \right]^{\frac{1}{2}}. \end{aligned} \quad (\text{A.33})$$

In the case that the infall velocity is $v = 0$, which occurs just before collapse commences when $r = R$, equation A.33 simplifies to:

$$C = -G \frac{M}{r}. \quad (\text{A.34})$$

The velocity v at the surface can be obtained by solving equation A.33 for v , which gives:

$$\frac{v^2}{2} = -GM \left[\frac{1}{r} - \frac{1}{R} \right]^{\frac{1}{2}},$$

$$v = \sqrt{\frac{2GM}{R} \left[\frac{R}{r} - 1 \right]^{\frac{1}{2}}}. \quad (\text{A.35})$$

The position of the spherical surface over time can be described by solving equation A.35 with the boundary conditions of the surface at different times. Approximating $r = R \sin \theta$ and setting the boundary conditions for the surface of the cloud to $\theta = 0$ and $r = 0$, and $\theta = \frac{\pi}{2}$ and $r = R$, leads to:

$$\frac{dr}{dt} = \frac{d}{dt} [R \sin \theta] = 2R \sin \theta \cos \theta d\theta. \quad (\text{A.36})$$

Substituting into equation A.35 gives:

$$2R\theta \cos \theta d\theta = \sqrt{\frac{2GM}{R} \left[\frac{1 - \sin^2 \theta}{\sin^2 \theta} \right]^{\frac{1}{2}}} dt,$$

$$\sin^2 \theta d\theta = \sqrt{\frac{2GM}{R}} dt. \quad (\text{A.37})$$

A cloud undergoing free fall collapse will take a specific amount of time to collapse from an initial radius r (at infinity) to a final, finite radius R . This time is known as the free-fall time (Carroll and Ostlie, 2017). Setting the boundary conditions as $r = R$ at time $t = 0$ to when the cloud was at initial radius $r = 0$ and finally at $t = t_{ff}$, the equation for the collapse time can be derived using the trigonometric identities, $\sin^2 \theta = \frac{1}{2}[1 - \cos 2\theta]$ and integrating over time, equation A.37 becomes:

$$\frac{1}{2} \int_0^{\frac{\pi}{2}} [1 - \cos 2\theta] d\theta = \int_0^{t_{ff}} \sqrt{\frac{GM}{2R^3}} dt,$$

$$\frac{\pi}{2} = \sqrt{\frac{GM}{2R^3}} t_{ff},$$

$$\text{The free-fall time } t_{ff} = \sqrt{\frac{\pi R^3}{8GM}}. \quad (\text{A.38})$$

Appendix B

Appendix B: Supplementary figures

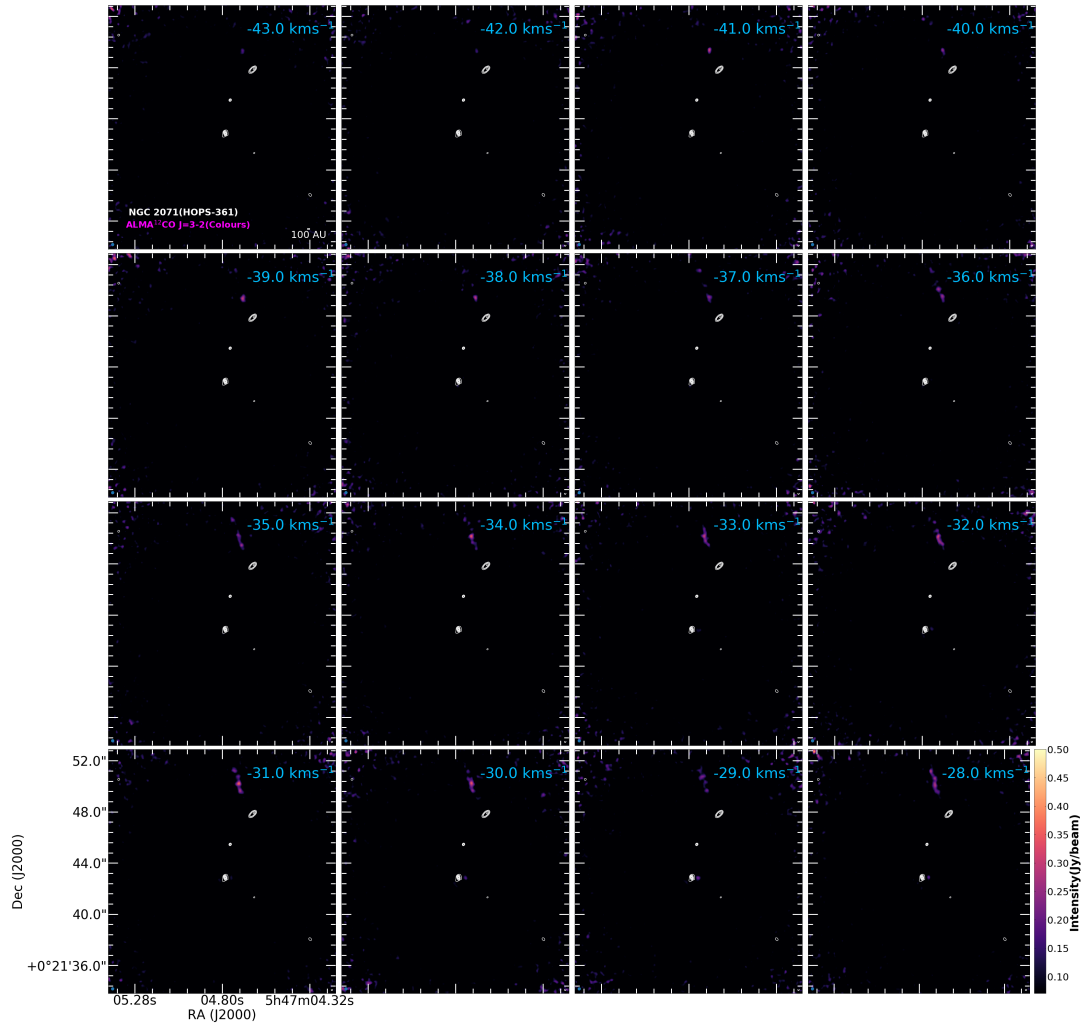
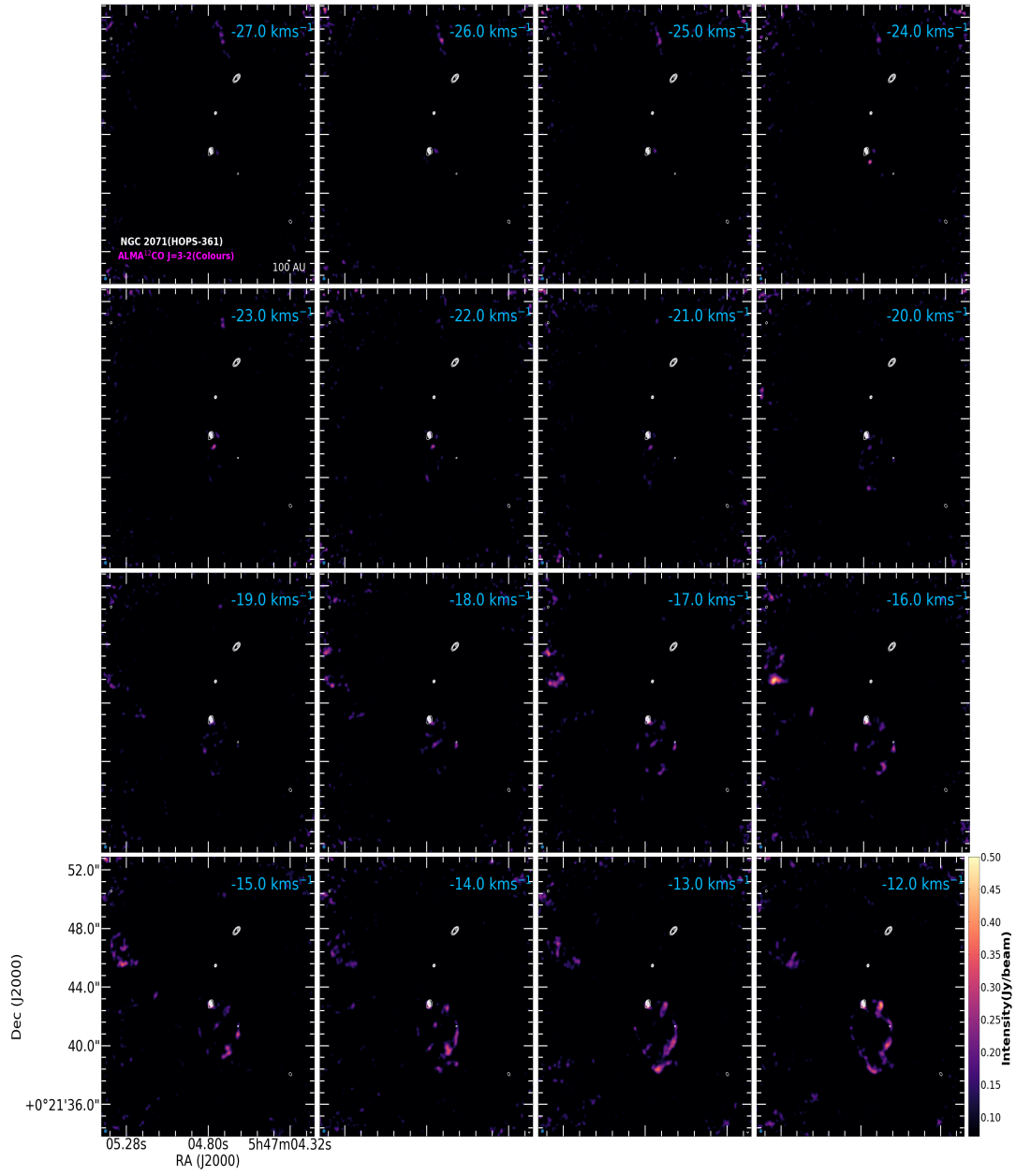
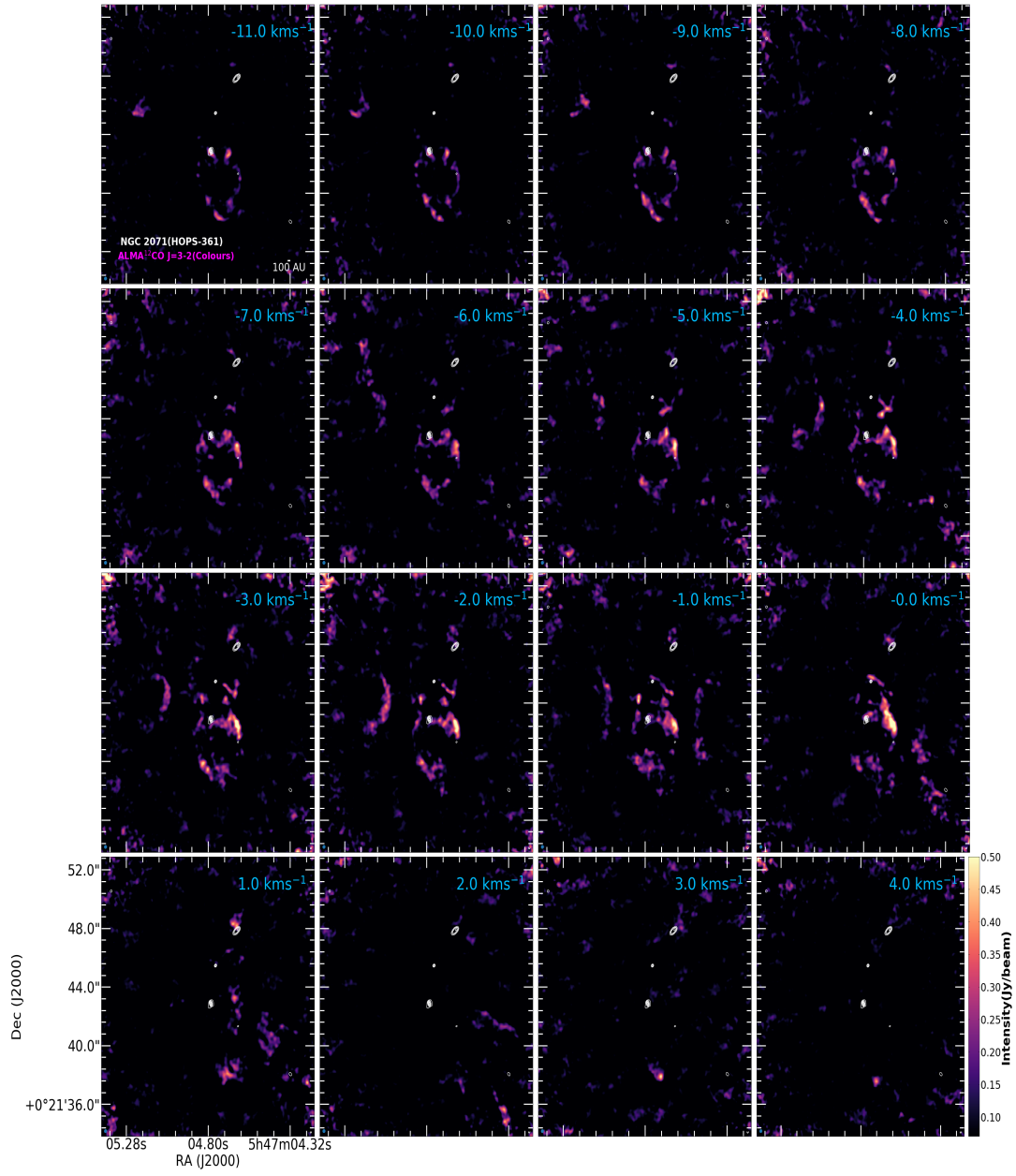
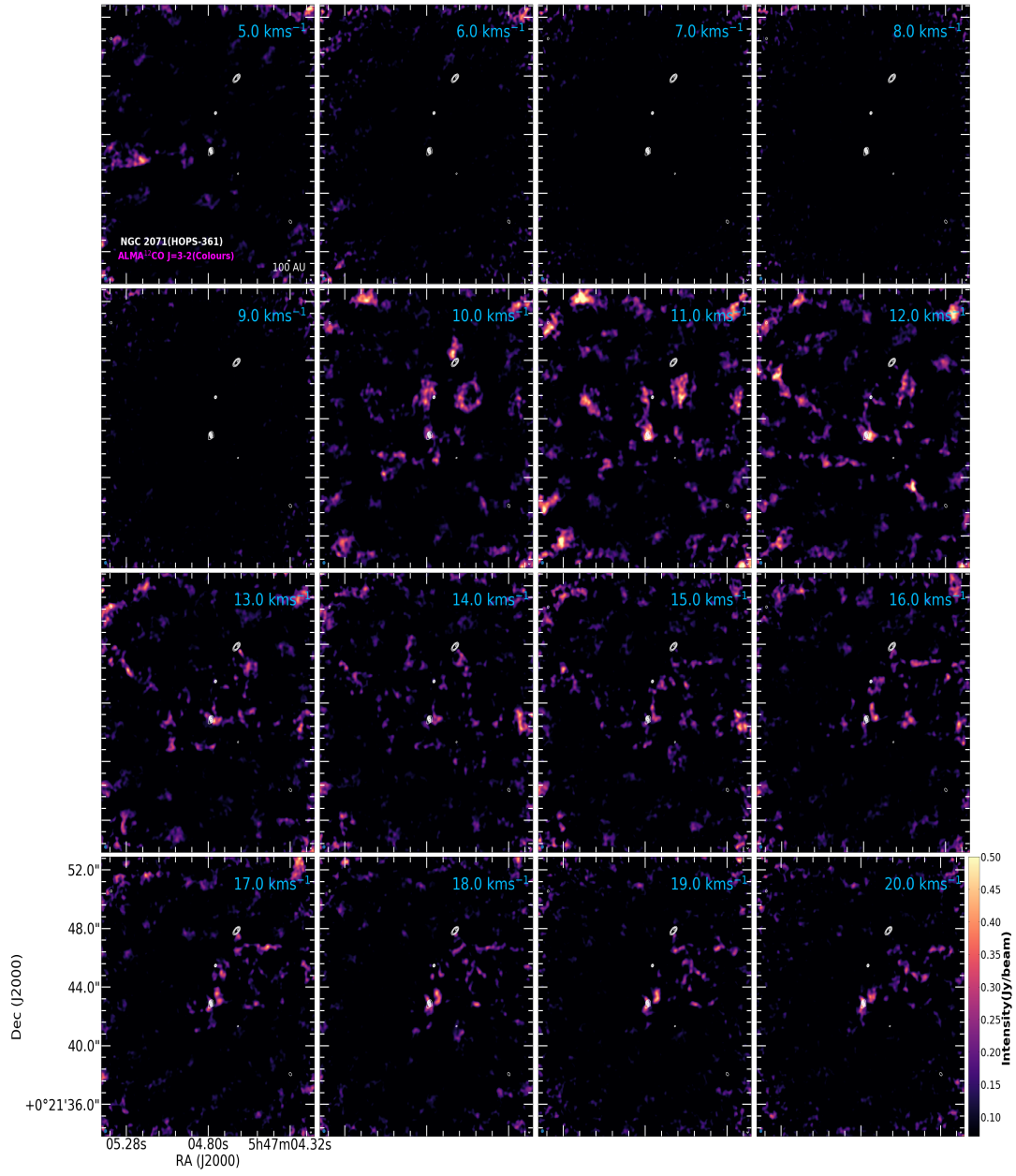
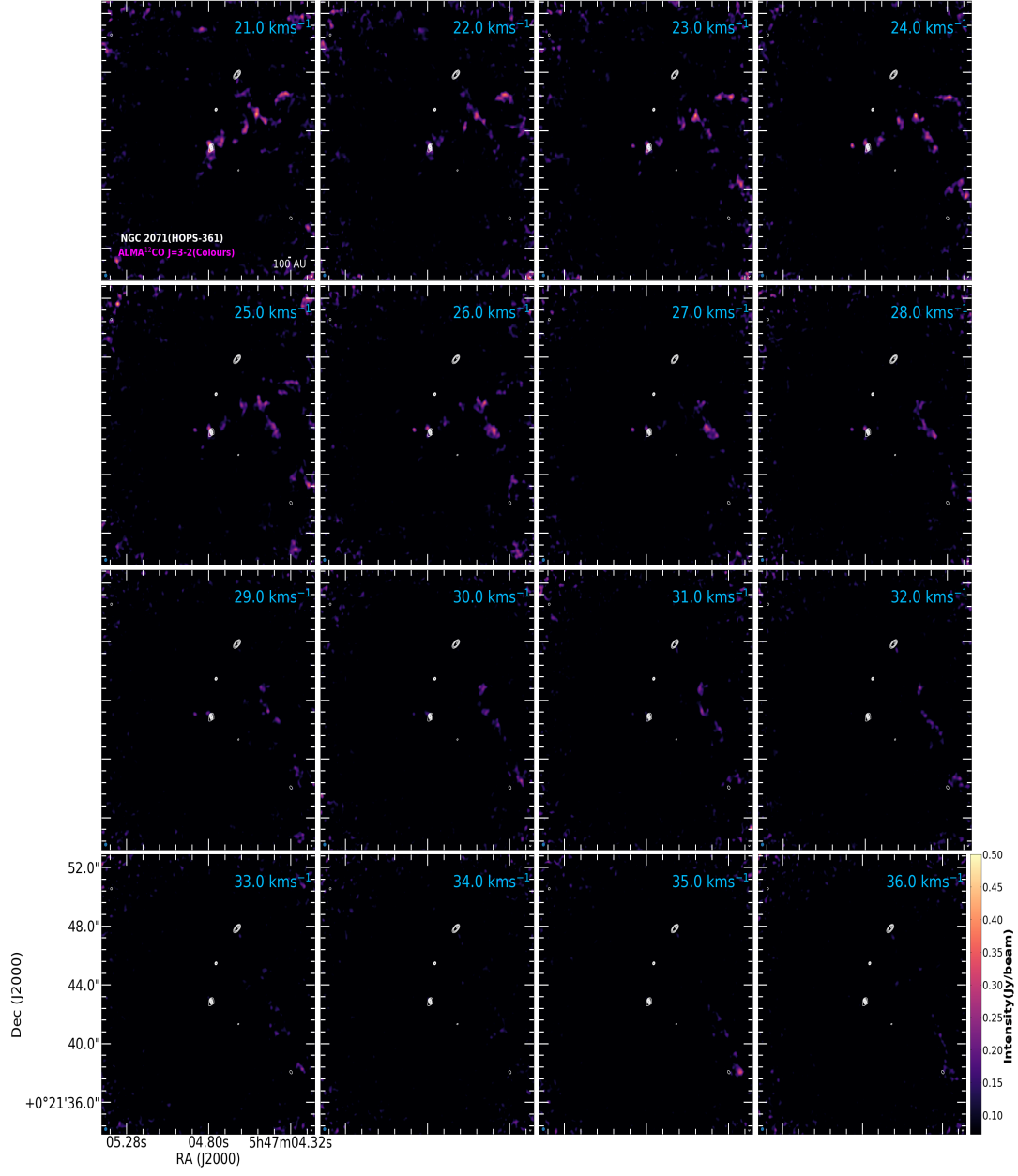


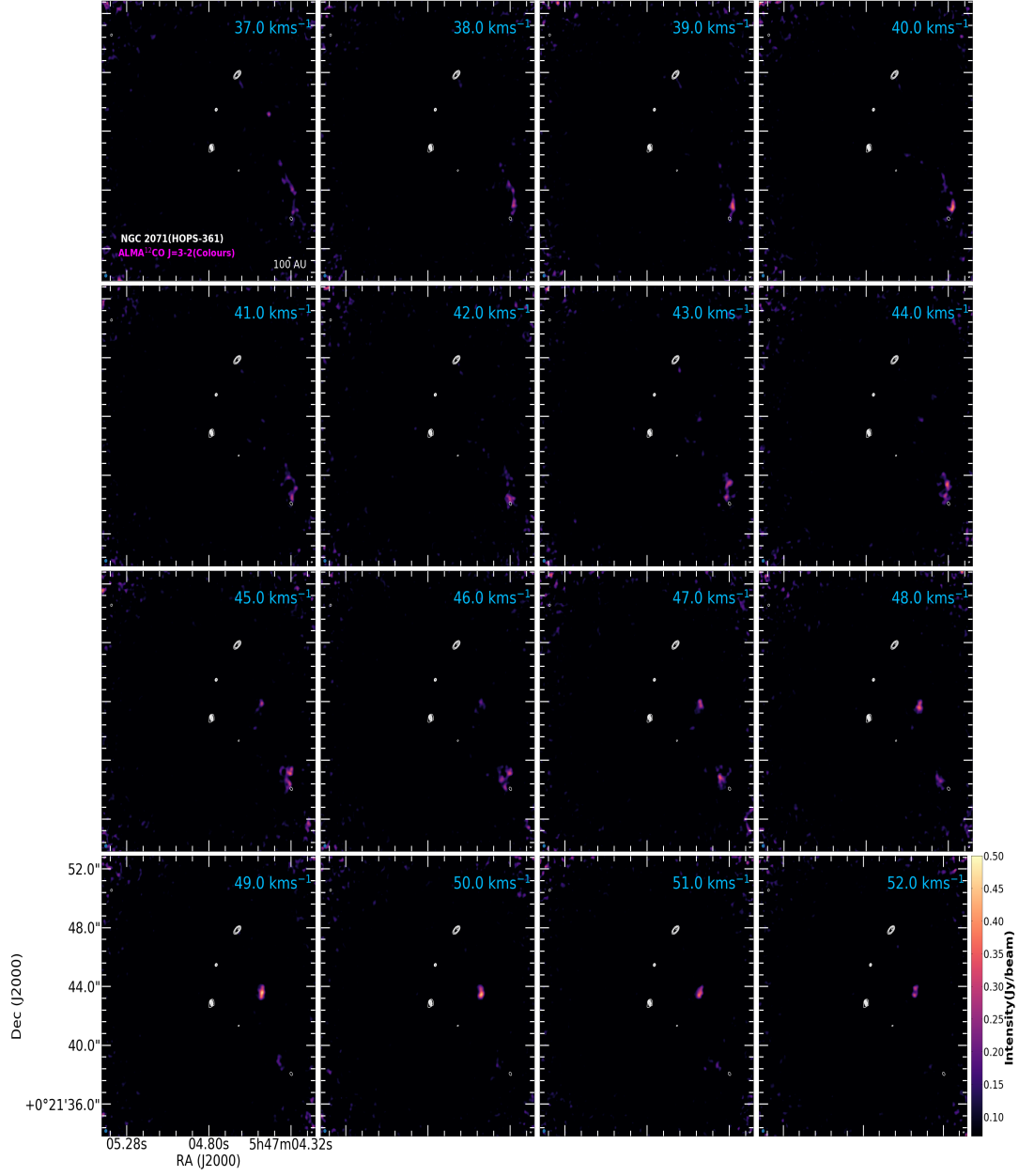
Figure B.1: ^{12}CO channel maps: -43 km s^{-1} to -28 km s^{-1}

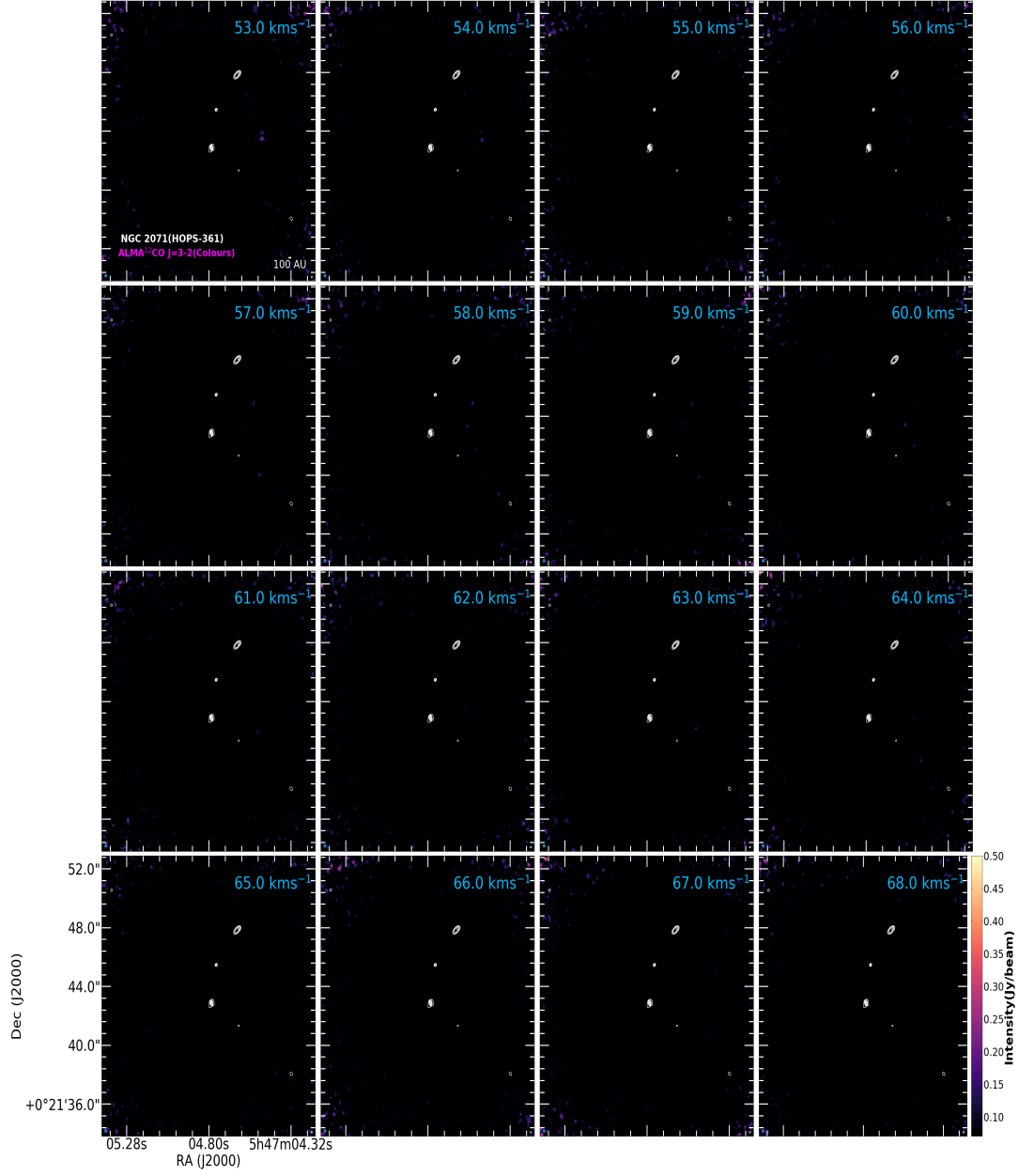
Figure B.2: ¹²CO channel maps: -27 km s⁻¹ to -12 km s⁻¹

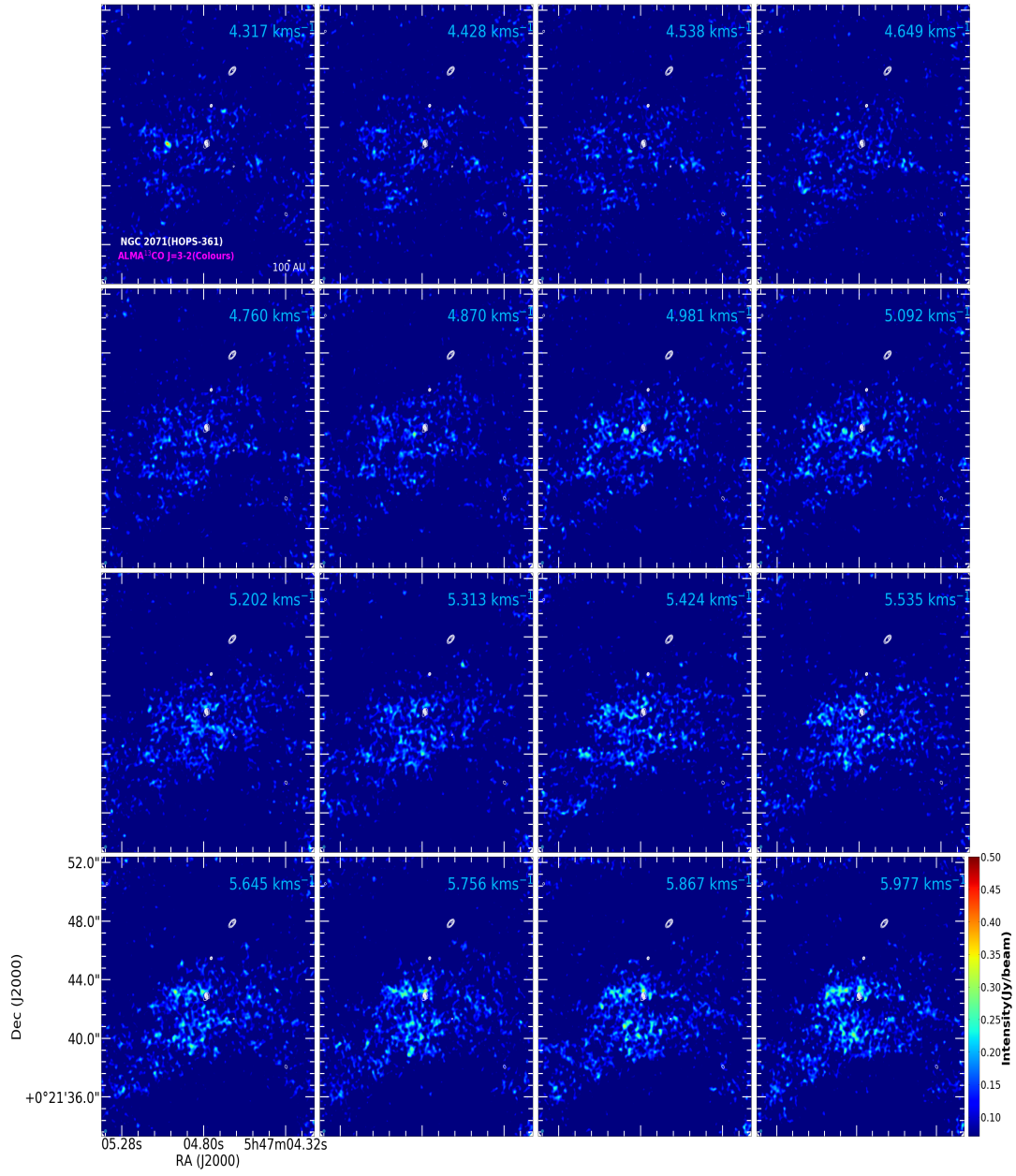
Figure B.3: ^{12}CO channel maps: -11 km s^{-1} to 4 km s^{-1}

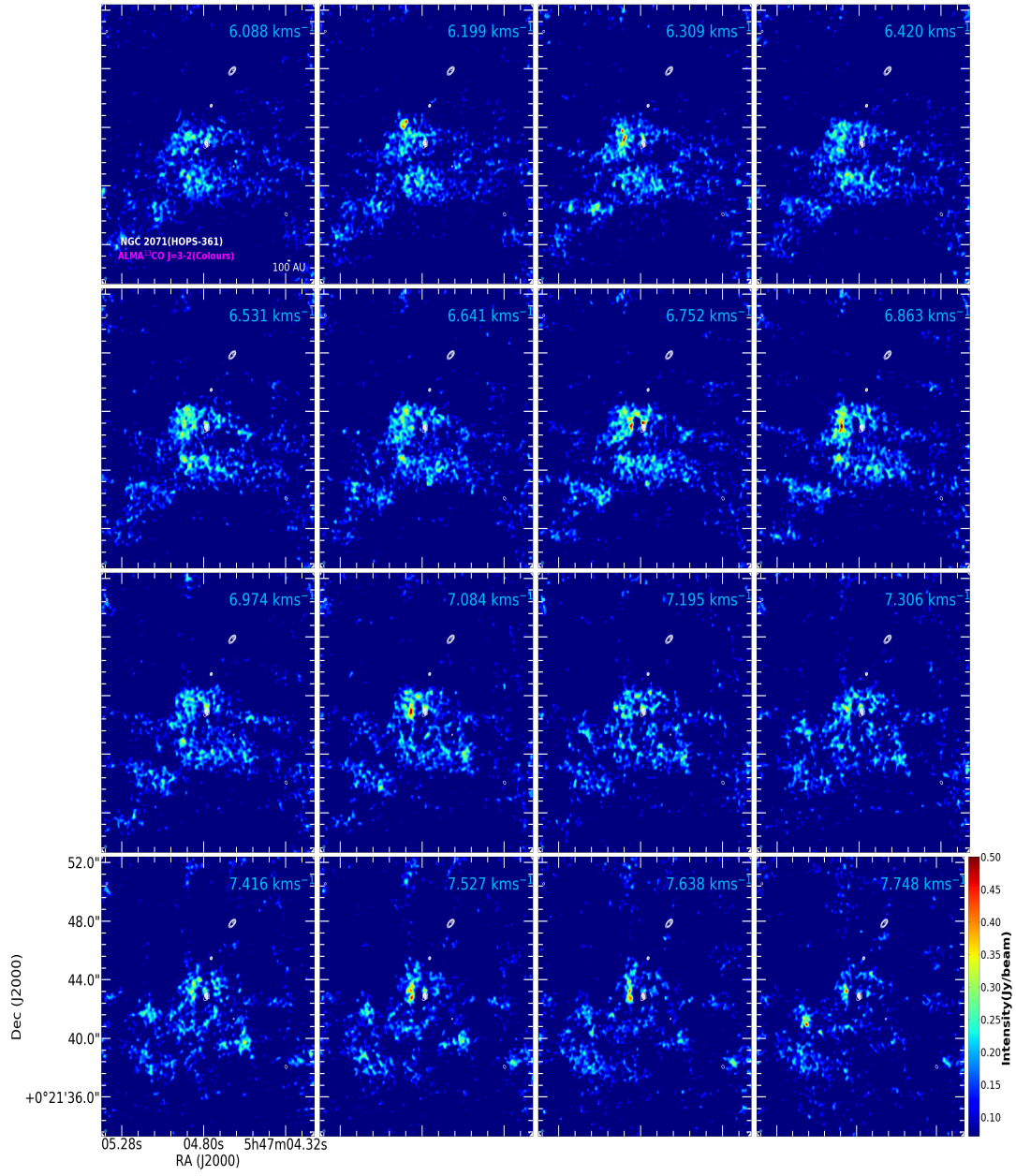
Figure B.4: ^{12}CO channel maps: 5 km s^{-1} to 20 km s^{-1}

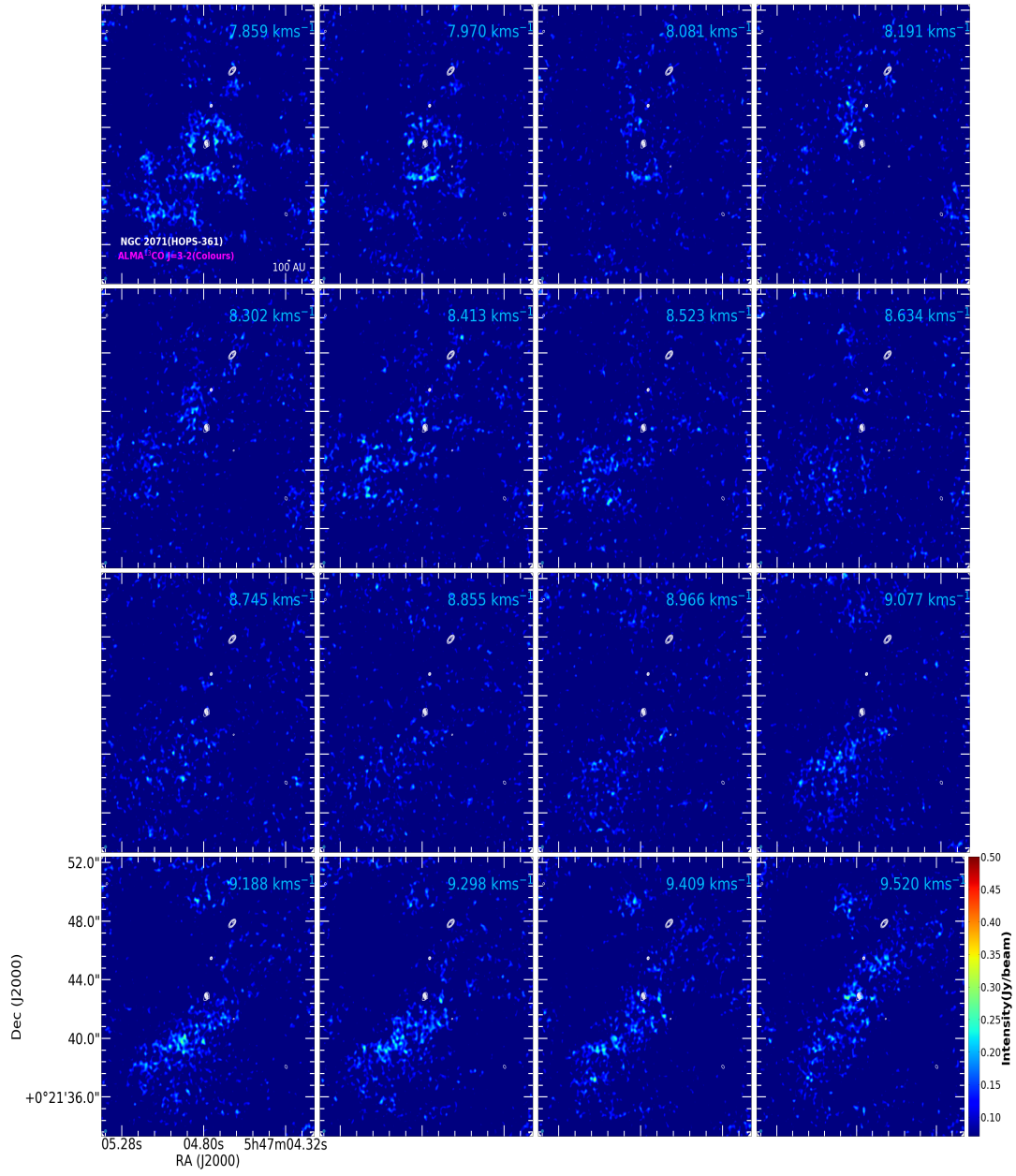
Figure B.5: ^{12}CO channel maps: 21 km s^{-1} to 36 km s^{-1}

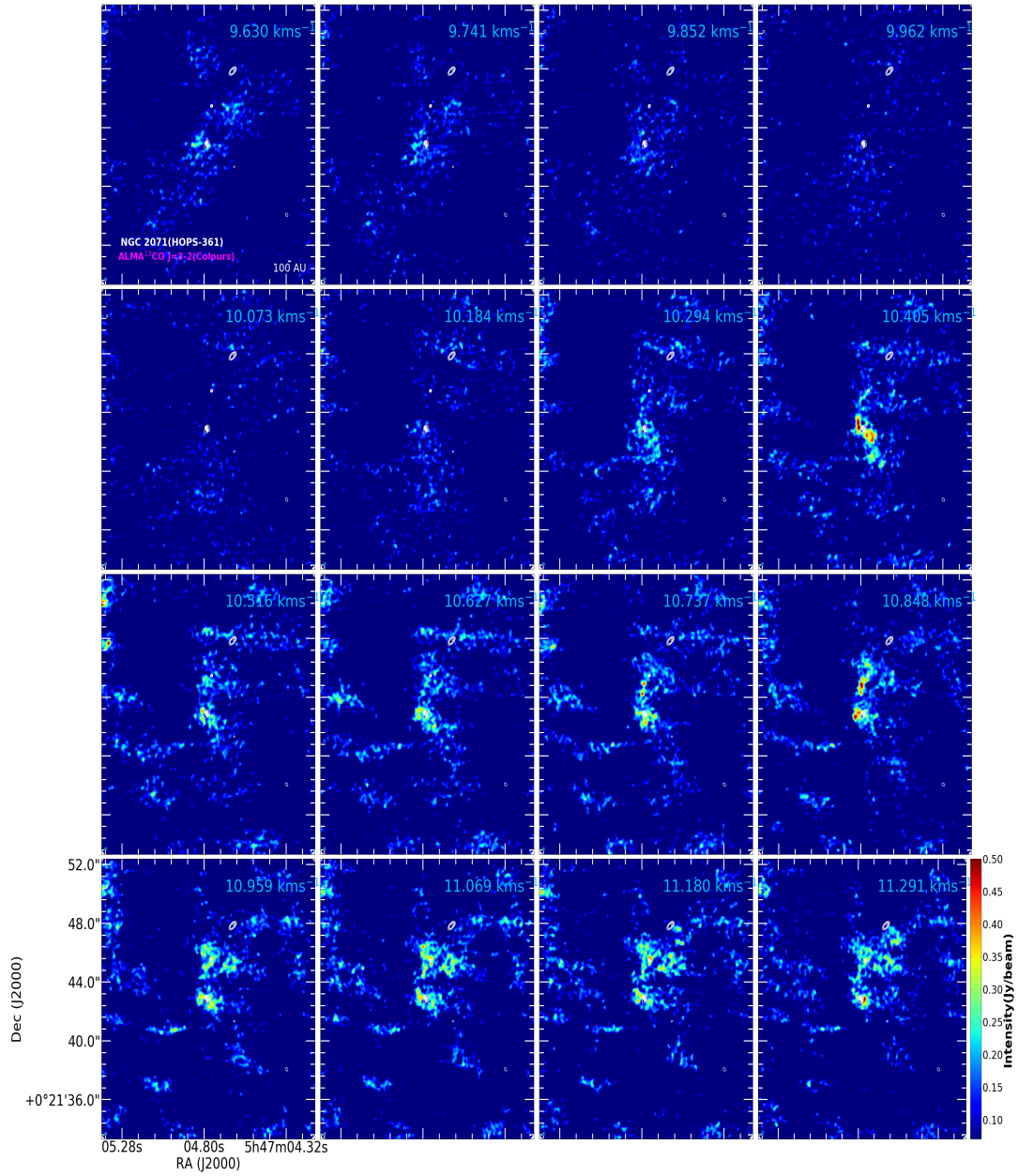
Figure B.6: ^{12}CO channel maps: 37 km s^{-1} to 52 km s^{-1}

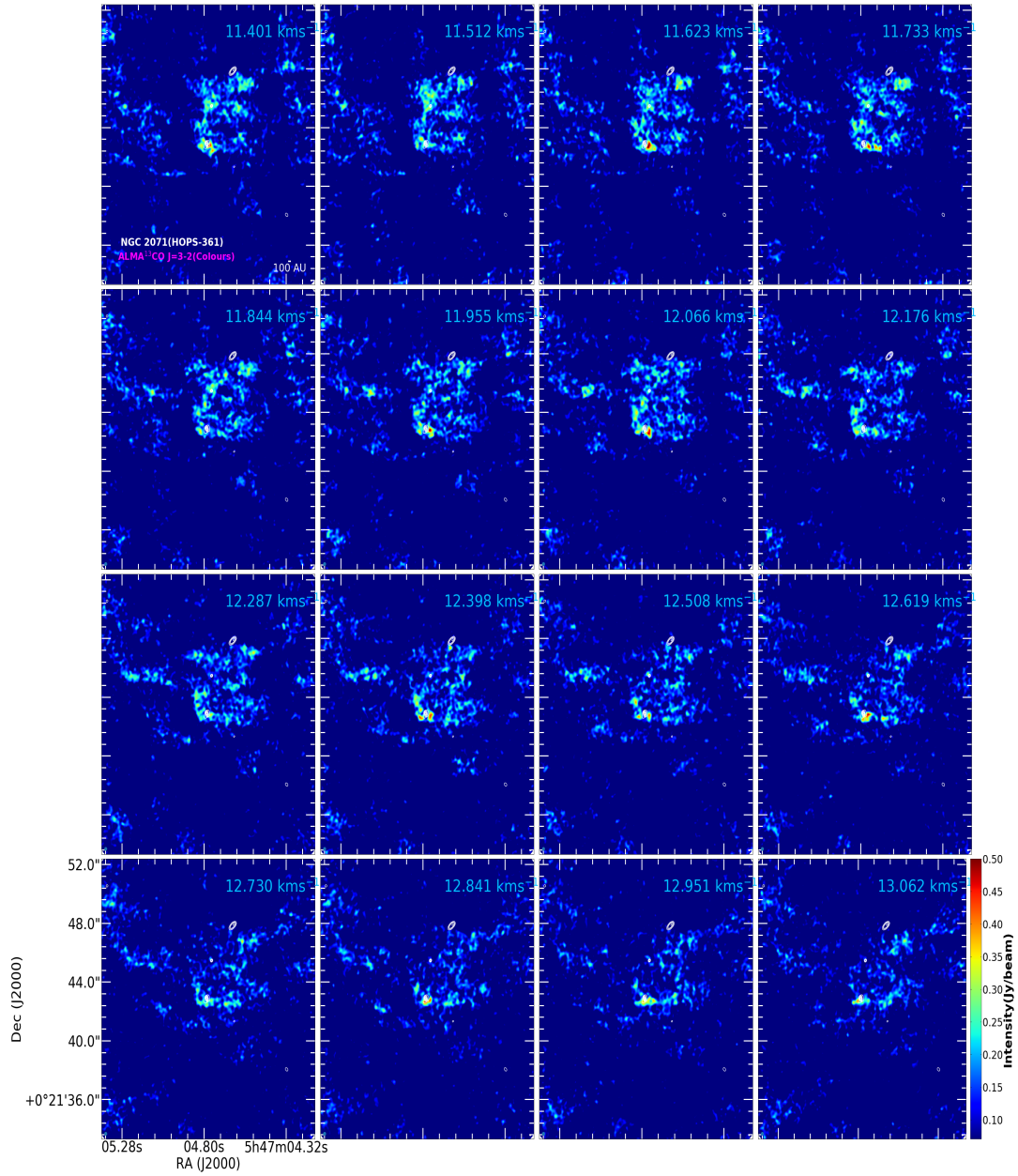
Figure B.7: ^{12}CO channel maps: 53 km s^{-1} to 68 km s^{-1}

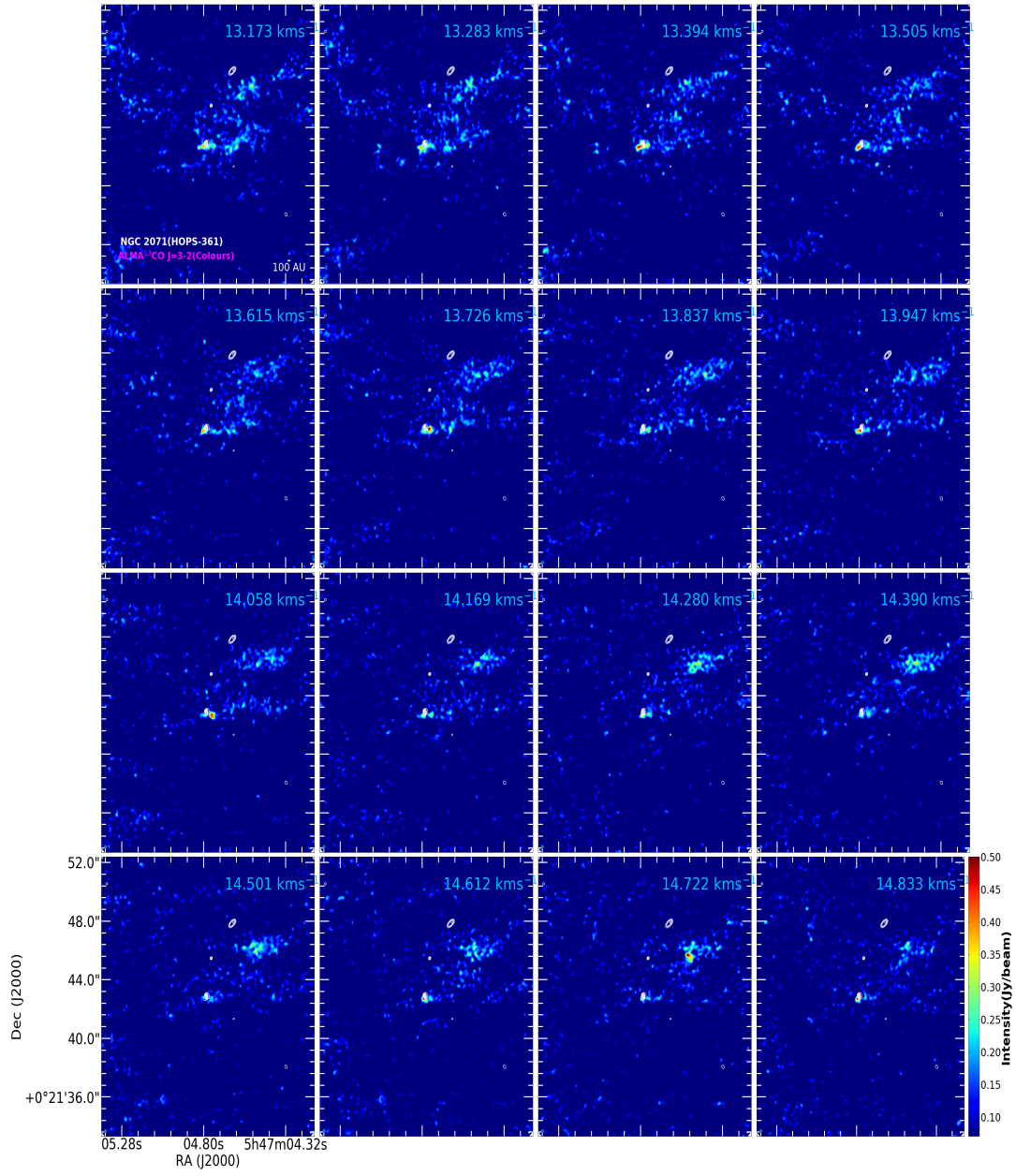
Figure B.8: ^{13}CO channel maps: 4.32 km s^{-1} to 5.98 km s^{-1}

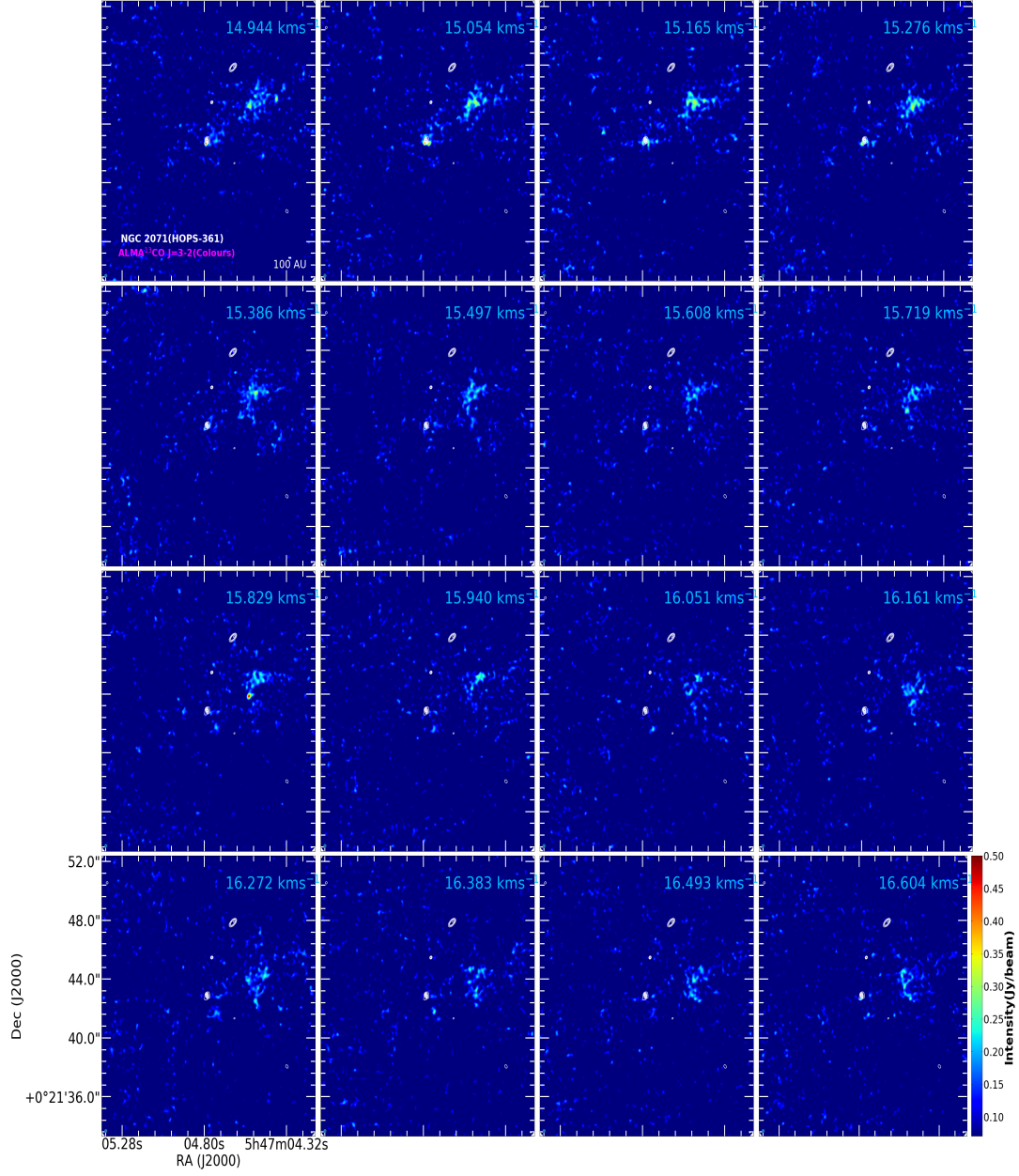
Figure B.9: ^{13}CO channel maps: 6.09 km s^{-1} to 7.75 km s^{-1}

Figure B.10: ^{13}CO channel maps: 7.86 km s^{-1} to 9.52 km s^{-1}

Figure B.11: ^{13}CO channel maps: 63 km s^{-1} to 11.30 km s^{-1}

Figure B.12: ^{13}CO channel maps: 11.40 km s^{-1} to 13.06 km s^{-1}

Figure B.13: ^{13}CO channel maps: 13.17 km s^{-1} to 14.83 km s^{-1}

Figure B.14: ^{13}CO channel maps: 14.94 km s^{-1} to 16.60 km s^{-1}

Appendix C

Appendix C: Supplementary tables

Tables of velocities from interferometric maser maps matched with HartRAO velocities.
Key: ‘Vlos’ - Line of sight velocity, ‘No.’ - Maser number, ‘Hart’ - HartRAO velocity.

Object	No.	Vlos	Hart	No.	Vlos	Hart	No.	Vlos	Hart
	Torrelles et al. (1998)			Trinidad et al. (2009)			Shchurov et al. (2021)		
IRS1	1	0.1	0.07	1	2.8	2.8	1-1	20.5	20.5
IRS1	2	0.8	0.8	2	2.8	2.8	2-1	18.1	18.08
IRS1	3	2.8	2.8	3	16.6	16.6	2-2	17.8	17.76
IRS1	4	5.4	5.44	4	6.7	6.7	2-3	17.7	17.66
IRS1	5	5.42	5.44	5	4.1	4.07	2-4	17.7	17.66
IRS1	6	6.7	6.7	6	-1.2	-1.19	2-5	17.7	17.66
IRS1	7	9.3	9.33	7	-0.5	-0.56	2-6	17.6	17.55
IRS1	8	10	10	8	6	6.07	3-1	16.7	16.71
IRS1	9	11.3	11.34	9	25.8	25.77	4-1	14.8	14.81
IRS1	10	11.31	11.34	10	2.1	2.17	5-1	14.3	14.29
IRS1	11	11.32	11.34	11	17.2	17.24	5-2	14.1	14.08
IRS1	12	12.01	11.97	12	16.6	16.6	5-3	13.8	13.76
IRS1	13	12.02	12.07	13	6	6.07	9-1	4.7	4.7
IRS1	14	13.3	13.34	14	10	9.97			
IRS1	15	14	14.08	15	25.1	25.14			
IRS1	16	14.6	14.6	16	12.6	12.6			
IRS1	17	15.6	15.66	17	10.7	10.7			
IRS1	18	15.3	15.34	18	12.6	12.6			
IRS1	19	16.6	16.6	19	10.7	10.7			
IRS1	20	17.24	17.2						
IRS1	21	20.5	20.5						
IRS1	22	23.03	23.2						

Key: ‘ep-no’ -Epoch and maser number. The rest are same as previous table.

Object	ep-no	Vlos	Hart	ep-no	Vlos	Hart	ep-no	Vlos	Hart	ep-no	Vlos	Hart
Seth et. al. 2002												
IRS3	1-0	18.86	18.82	2-0	25.25	25.24	3-0	24.82	24.82	4-0	27.07	27.03
IRS3	1-1	18.49	18.5	2-1	24.97	25.03	3-1	24.55	24.51	4-1	24.78	24.71
IRS3	1-2	15.39	15.34	2-2	16.72	16.71	3-2	21.74	21.76	4-2	23.08	23.03
IRS3	1-3	15.22	15.23	2-3	16.07	16.08	3-3	16.69	16.71	4-3	15.86	15.87
IRS3	1-4	13.17	13.13	2-4	15.84	15.87	3-4	16.54	16.5	4-4	13.17	13.13
IRS3	1-5	12.75	12.71	2-5	14.85	14.81	3-5	16.33	16.29	4-5	7.49	7.44
IRS3	1-6	12.75	12.71	2-6	13.59	13.55	3-6	16.22	16.18	4-6	5.43	5.44
IRS3	1-7	11.43	11.44	2-7	13.17	13.13	3-7	15.28	15.23	4-7	5.39	5.33
IRS3	1-8	10.64	10.6	2-8	12.71	12.71	3-8	15.08	15.02	4-8	4.91	4.91
IRS3	1-9	7.87	7.865	2-9	11.87	11.867	3-9	14.86	14.81	4-9	4.64	4.7
IRS3	1-10	6.7	6.7	2-10	11.87	11.867	3-10	13.59	13.55	4-10	4.6	4.59
IRS3	1-11	6.04	6.07	2-11	5.61	5.547	3-11	13.37	13.44	4-11	4.41	4.38
IRS3	1-12	5.52	5.54	2-12	5.58	5.547	3-12	13.32	13.34	4-12	3.92	3.96
IRS3	1-13	5.24	5.23	2-13	4.81	4.81	3-13	11.61	11.65	4-13	3.17	3.12
IRS3	1-14	4.74	4.705	2-14	4.74	4.7	3-14	11.16	11.13	4-14	2.61	2.59
IRS3	1-15	4.44	4.38	2-15	4.32	4.28	3-15	8.27	8.28	Torrelles et al. 1998		
IRS3	1-16	4.43	4.28	2-16	4.17	4.17	3-16	8.11	8.18	1	-1.9	-1.93
IRS3	1-17	3.98	3.96	2-17	2.71	2.7	3-17	7.43	7.44	2	1.4	1.43
IRS3	1-18	3.37	3.33	2-18	2.39	2.39	3-18	6.03	6.07	3	3.4	3.4
IRS3	1-19	3.34	3.33	2-19	0	0.07	3-19	5.85	5.86	4	4.1	4.07
IRS3	1-20	3.12	3.12	2-20	-0.46	-0.46	3-20	5.58	5.54	5	5.4	5.44
IRS3	1-21	2.93	2.91	2-21	-3.14	-3.08	3-21	4.76	4.7	6	10	9.97
IRS3	1-22	2.62	2.598	2-22	-7.71	-7.72	3-22	4.63	4.59	7	10.7	10.7
IRS3	1-23	2.21	2.177	2-23	-7.9	-7.93	3-23	4.62	4.59	8	15.3	15.34
IRS3	1-24	-4.74	-4.77				3-24	4.4	4.38	9	14.6	14.6
IRS3	Trinidad et al 2009						3-25	4.33	4.28	10	11.3	11.34
IRS3	1	-1.9	-1.93				3-26	4.32	4.28	11	12	11.97
IRS3	2	6.7	6.7				3-27	4.09	4.07	12	12.6	12.6
IRS3	3	17.9	17.97				3-28	2.9	2.91	13	17.2	17.24
IRS3	4	15.3	15.34				3-29	2.85	2.8			
IRS3	5	13.3	15.34				3-30	2.65	2.59			
IRS3	6	11.3	11.34				3-31	2.21	2.17			
IRS3	7	18.6	18.6				3-32	2.21	2.17			
IRS3	8	12	11.97				3-33	-1.47	-1.4			
IRS3							3-34	-3.32	-3.3			

