

Understanding the origin of Bunny-Hop light curves of periodic methanol masers

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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 December 2023

Acknowledgements

I would like to express my gratitude to my supervisors Prof James Chibueze and Prof Johan van der Walt for introducing me to the field of radio astronomy and providing guidance throughout the span of the research project. I would like to also express my gratitude to Dr van den Heever and the team at HartRAO who assisted throughout my MSc with data collection guidance within the observational field, your diligence was instrumental throughout my project. I would like to thank the faculty, staff, colleagues, and friends at the Centre for Space research at North-West University for their collective support throughout this degree. I would also like to thank the NRF for providing funding throughout the span of this project. Finally, I would like to acknowledge and thank my parents, family, partner, and those closest to me; your support and encouragement was pivotal throughout my academic journey.

Abstract

Class II 6.7 GHz methanol maser emission, first discovered by [Menten \(1991\)](#), is exclusively associated with high-mass star-forming regions. Long-term observational studies have shown that masers are variable on numerous timescales; a surprising follow-up finding was that of the periodic methanol masers originally reported by [Goedhart et al. \(2003\)](#) and [Goedhart et al. \(2004\)](#). Maser source G358.460 - 0.391 was previously identified as periodic by [Maswanganye et al. \(2015\)](#); this research involved long-term monitoring of this 6.7 GHz methanol maser source using the 26-metre HartRAO telescope. This extended monitoring, which included high cadence observations, was necessary to characterise the behaviour of this source fully. The maser source displayed distinct bunny-hop shape periodicity in the primary and secondary features and velocity drifting in the primary feature. Furthermore, archival maser sources were studied for evidence of periodicity and velocity drifting; 19 of the archival sources were identified as good candidates for velocity drifting. A large portion of the archival sources also displayed velocity drifting leading to the conclusion that velocity drifting may be more common of a phenomena in maser sources. It is not yet clear what the underlying cause of the bunny-hop periodicity is, it may be linked to the face-on orientation of the maser region and periodic changes in seed photon density. Velocity drifting may be due to spectral blending of features, motion of gas, or disc precession. Extended observations of maser sources are essential in understanding the nature of masers and their star forming environments.

Keywords: Methanol masers, star formation, Interstellar Medium (ISM), ISM clouds, HII regions, radio lines, maser variability, velocity drifting

Contents

1	Introduction	1
1.1	Maser source G358.460 - 0.391	2
1.2	Motivation and Problem Statement	3
1.3	Layout of Dissertation	4
2	Star Formation	5
2.1	Introduction	5
2.2	Molecular clouds	6
2.2.1	Giant molecular clouds	6
2.2.2	Chemistry in Molecular Clouds	7
2.3	Evolution of molecular cloud environments	8
2.4	HII regions	9
2.4.1	Hypercompact HII regions	10
2.4.2	Ultracompact HII regions	10
2.4.3	Formation of ionised hydrogen	10
2.5	High-Mass Star Formation	12
2.5.1	The initial mass function	13
2.5.2	Virial theorem and Jeans mass	14
2.5.3	Protostar formation and evolution	15
2.5.4	Stellar feedback in high mass star formation	17
2.5.5	Circumstellar discs	18

2.5.6	Bipolar outflows	19
2.5.7	Episodic accretion and disc instabilities	20
3	Astronomical Masers	21
3.1	Introduction	21
3.2	Radiative Transfer	22
3.2.1	Emission, Absorption and Einstein Coefficients	22
3.2.2	Radiative Transport equation	26
3.2.3	Population inversion	28
3.2.4	Optical depth	28
3.3	Maser Emission	30
3.3.1	Maser Saturation	31
3.4	Observations of Masers in Massive Star-Forming Regions	31
3.5	Methanol	32
3.6	Methanol Masers	34
3.6.1	Class I Methanol Masers	35
3.6.2	Class II Methanol Masers	35
3.7	6.7 GHz Methanol Masers	36
3.8	Line Profiles	36
3.8.1	Natural or radiation broadening	37
3.8.2	Collisional or Pressure broadening	38
3.8.3	Doppler broadening	38
3.9	Hyperfine structure and Zeeman splitting	39
3.10	Polarisation of Masers	39
3.11	Maser Variability	40
3.11.1	Accretion events	41
3.11.2	Periodic variability	41
3.12	Velocity drifts observed in Maser sources	43

4	Observation and Data Analysis	45
4.1	Introduction	45
4.2	Fundamentals of a single dish radio telescope	46
4.2.1	Beam pattern of radio telescope	49
4.2.2	Telescope gain and effective area	51
4.2.3	Antenna temperature	52
4.2.4	System temperature	53
4.2.5	Observed signal	53
4.2.6	Observations of Masers	54
4.3	Observations by the 26m HartRAO telescope	56
4.4	Data Calibration	57
4.4.1	Flux density calibration	58
4.4.2	Calibration Sources Hydra A and 3C123	59
4.5	Maser observation and Data Processing	59
4.5.1	Baseline subtraction	62
4.5.2	Combining Spectra	63
4.5.3	RMS noise	63
4.6	Summary of Observations and Data Calibration process	64
4.7	Time series analysis techniques	65
4.7.1	Velocity drifts	66
4.8	Gaussian validation of light curves and Velocity drifts	67
4.9	Statistical analysis	67
5	Maser source G358.460 - 0.391 Results	70
5.1	Introduction	70
5.2	Spectra and light curves of G358.460 - 0.391	71
5.3	Time-series analysis	71
5.4	Kernel-Density Estimation	76

5.5	Investigation of behaviour around minima	76
5.6	Gaussian validation, Dynamic Spectra, and Velocity Drifts	83
5.7	Summary	86
6	Survey of Masers Sources	89
6.1	Introduction	89
6.2	Notes on Individual Sources	90
6.2.1	G9.62 + 0.2	91
6.2.2	G10.33 - 0.17	94
6.2.3	G12.68 - 0.18 (W33B)	96
6.2.4	G12.91 - 0.26 (W33A)	99
6.2.5	G35.20 - 1.74	101
6.2.6	G174.20 - 0.08	103
6.2.7	G188.95 + 0.89	105
6.2.8	G192.60 - 0.05 (S255IR-NIRS3)	107
6.2.9	G196.45 - 1.68	109
6.2.10	G308.92 + 0.12	111
6.2.11	G318.95 - 0.2	113
6.2.12	G328.24 - 0.55	115
6.2.13	G328.81 + 0.63	117
6.2.14	G331.13 - 0.24	120
6.2.15	G337.92 - 0.46	123
6.2.16	G338.93 - 0.06	125
6.2.17	G339.62 - 0.12	128
6.2.18	G339.88 - 1.26	130
6.2.19	G340.79 - 0.10	132
6.2.20	G345.00 - 0.22	134
6.2.21	G345.50 + 0.35	136

6.2.22	G351.58 - 0.35	138
6.2.23	G354.61 + 0.47	139
7	Discussion	141
7.1	Maser source G358.460 - 0.391	141
7.1.1	Periodicity and light curve behaviour of G358.460 - 0.391	142
7.1.2	Separation of maser spots	143
7.1.3	Bipolar outflows	144
7.1.4	Orientation of maser region	145
7.1.5	Episodic accretion	146
7.1.6	Stellar Pulsation and Periodic variability	146
7.1.7	Velocity drift of G358.460 - 0.391	147
7.1.8	In summary	148
7.2	Discussion of archival data results	148
7.2.1	Variability in maser sources	150
7.2.2	Maser velocity drifts	150
7.2.3	Line blending in maser features	151
8	Summary and Conclusion	152
8.1	Maser source G358.460 - 0.391	152
8.2	Archival data	153
8.3	Recommendations for Future Work	153
A	Survey of Masers Sources	168
A.1	Notes on individual sources	169
A.1.1	G12.89 + 0.49	169
A.1.2	G23.01 - 0.41	171
A.1.3	G23.44 - 0.18	172
A.1.4	G45.07 + 0.13	173

A.1.5	G52.668 - 1.09	174
A.1.6	G69.54 - 0.98	176
A.1.7	G189.03 + 0.79	178
A.1.8	G287.36 + 0.64	178
A.1.9	G291.27 - 0.71	180
A.1.10	G309.92 + 0.48	182
A.1.11	G312.11 + 0.26	184
A.1.12	G316.64 - 0.09	186
A.1.13	G322.16 + 0.64	188
A.1.14	G331.278 - 0.188	190
A.1.15	G335.55 - 0.31	192
A.1.16	G336.99 - 0.03	193
A.1.17	G344.23 - 0.57	193
A.1.18	G359.61 - 0.24	196

List of Figures

2.1	Expanding HII region with shock front	10
2.2	Saha relation describing ionisation fraction of pure hydrogen as a function of temperature	12
3.1	Thermal equilibrium and Population Inversion	25
3.2	Three level maser	30
3.3	Structure of methanol molecule	33
3.4	Body-fixed coordinate system of methanol	34
3.5	The figure shows a schematic representation of a line profile defined by a Gaussian function. This figure is a qualitative representation and does not represent a specific line profile or molecular transition.	37
3.6	Orientation effects on masers	42
4.1	Atmospheric transmission	46
4.2	Specific intensity diagram	47
4.3	The beam pattern of a radio telescope	49
4.4	Full width at half maximum	50
4.5	Cassegrain telescope	56
4.6	Determined pointing offsets	58
4.7	PSS values at 6.7 GHz using calibrators Hydra A and 3C123	60
4.8	Simulated PSS values at 6.7 GHz using calibrators Hydra A and 3C123	61
4.9	Baseline subtraction	63
4.10	Averaged spectra	64
4.11	Gaussian validation	68

5.1	Averaged spectra of G358.460 - 0.391	72
5.2	Light curve of maser G358.460 - 0.391 at $v_{\text{cen}} \sim 1.00 \text{ km.s}^{-1}$	72
5.3	Light curve of maser G358.460 - 0.391 at $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$	73
5.4	Light curve of maser G358.460 - 0.391 at $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$	73
5.5	Light curve of maser G358.460 - 0.391 at peak flux density measurements . .	74
5.6	Light curve of maser G358.460 - 0.391 at $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$	74
5.7	Light curve of maser G358.460 - 0.391 at $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$	75
5.8	Light curve of maser G358.460 - 0.393 at $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$	75
5.9	Lomb-Scargle periodicity search	77
5.10	Lomb-Scargle periodicity search	78
5.11	KDE of G358.460 - 0.391 maser light curve at $v_{\text{cen}} \sim 1.00 \text{ km.s}^{-1}$	78
5.12	KDE of G358.460 - 0.391 maser light curve at $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$	79
5.13	High cadence points with KDE fit for $v_{1.00 \text{ km.s}^{-1}}$ and $v_{1.129 \text{ km.s}^{-1}}$	79
5.14	KDE of G358.460 - 0.391 maser light curve at $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$	79
5.15	Light curve of G358.460-0.391 at $V_{\text{Peak km.s}^{-1}}$	79
5.16	High cadence points with KDE fit for $v_{1.70 \text{ km.s}^{-1}}$ and v_{Peak}	80
5.17	Minima between 57020 MJD and 57200 MJD	80
5.18	Minima between 58320 MJD and 58480 MJD	81
5.19	Minima between 59240 MJD and 59430 MJD	81
5.20	Minima between 59440 MJD and 59600 MJD with KDE estimation	82
5.21	Minima between 59690 MJD and 59850 MJD	82
5.22	Minima between 59690 MJD and 59850 MJD with KDE estimation	83
5.23	Folded light curves	84
5.24	Dynamic Spectra of G358.460 - 0.391	84
5.25	Dynamic Spectra of G358.460 - 0.391 and G358.460 - 0.393	85
5.26	Velocity drift of G358.460 - 0.393 determined using Gaussian validation . . .	85
5.27	Distribution of central velocity measurements for G358.460 - 0.391	86

5.28	Velocity drift of G358.460 - 0.391 determined using Gaussian validation . . .	87
5.29	Noise behaviour	87
7.1	Dynamic Spectra of G358.460 - 0.391	143
7.2	Maser spot map of G358.460-0.391	144
7.3	Bipolar outflow of G358.460 - 0.391	145
7.4	Velocity drifts in G358.460 - 0.391	147

List of Tables

1.1	Maser features G358.460 - 0.391 and G358.460 - 0.393	3
2.1	Phases of the ISM	7
2.2	Properties of Interstellar Molecular clouds	8
2.3	Classification of HII regions	9
4.1	Technical Parameters of the 26 m HartRAO Telescope	55
4.2	Observing parameters of HartRAO telescope	57
4.3	Spectral fits for calibration sources	59
5.1	Maser features G358.460 - 0.391 and G358.460 - 0.393	71
5.2	Time series analysis of maser feature G358.460-0.391	76
6.1	List of known periodic methanol masers	90
6.2	Observing parameters for archival HartRAO sources	91
7.1	Summary of maser sources displaying velocity drifts	148
A.1	Summary investigated maser sources which did not yield velocity drifts . . .	168

Table of abbreviations

A table containing a list of abbreviations that will be used throughout text.

yr	year
d	day
K	Kelvin
H₂	Molecular Hydrogen
HI	Neutral Hydrogen, H
HII	Ionised Hydrogen, H ⁺
UCHII	Ultracompact HII region
HartRAO	Hartebeesthoek Radio Astronomy Observatory
GMC	Giant Molecular Cloud
HMC	Hot Molecular Core
YSO	Young Stellar Object
HMYSO	High mass young Stellar Object
MJD	Modified Julian date
V_{lsr}	Velocity reference frame (local-standard of rest)
CH₃OH	Chemical formula of Methanol
MMI	Class I methanol maser
MMII	Class II methanol maser

Physical Constants

Constants	Symbol	Value (in CGS units)
Astronomical unit	AU	= 1.496×10^{13} cm
Parsec	pc	= 3.086×10^{18} cm
Speed of light	c	= $2.99792458 \times 10^{10}$ cm s ⁻¹
Plank constant	h	= $6.6260755(40) \times 10^{-27}$ erg s
Gravitational constant	G	= $6.67259(85) \times 10^{-8}$ cm ³ g ⁻¹ s ⁻²
Electron charge	e	= $4.8032068(14) \times 10^{-10}$ esu
Mass of electron	m_e	= $9.1093897(54) \times 10^{-28}$ g
Mass of proton	m_p	= $1.6726231(10) \times 10^{-24}$ g
Mass of neutron	m_n	= $1.6749286(10) \times 10^{-24}$ g
Mass of hydrogen	m_H	= 1.6733×10^{-24} g
Atomic mass unit	amu	= $1.6605402(10) \times 10^{-24}$ g
Boltzmann constant	k_B	= $1.380658(12) \times 10^{-16}$ erg K ⁻¹
Stefan-Boltzmann constant	μ	= $5.67051(19) \times 10^{-5}$ erg cm ⁻² K ⁻⁴ s ⁻¹
Rydberg constant	R_∞	= 1.0974×10^5 cm ⁻³
Solar mass	$M_\odot$	= 1.98847×10^{33} g
Solar radius	$R_\odot$	= 6.960×10^{10} cm
Solar luminosity	$L_\odot$	= 3.85×10^{33} erg s ⁻¹

Chapter 1

Introduction

Massive stars ($M_{\text{star}} > 8 M_{\odot}$) and high-mass star-forming regions have consequential impacts on the dynamic and chemical composition of their environment and impact the evolution of their host galaxy; the impact of massive stars is seen through continuum radiation, energetic molecular outflows, stellar winds, heavy element production, and supernova explosions (Ward-Thompson and Whitworth, 2011). Massive stars have remained somewhat of a scientific enigma; however, their fundamental evolutionary roles make massive stars focal points of many theories and studies. Despite their collectively recognised importance, the formation process and much of the early evolutionary stages of massive star formation are poorly understood. In their early stages of formation and evolution, massive stars are obscured from direct observation by surrounding optically thick regions; massive star formation also happens more rapidly and is substantially less common than low-mass star formation, thus making observations more difficult and sparse (Stahler and Palla, 2008; Ward-Thompson and Whitworth, 2011).

Class II 6.7 GHz methanol maser emission, first discovered by Menten (1991), is exclusively associated with high-mass star-forming regions (Breen et al., 2013). Maser emission is visible to radio observations; this makes maser species, such as methanol, excellent candidates for studying and tracing high-mass star formation as observations can be performed despite the maser location being in these optically thick molecular clouds. Class II methanol masers are incredibly sensitive to changes in their surrounding physical environment (Goedhart et al., 2004). While their observed changes may have a quantum mechanically detailed explanation, utilising the observed maser behaviour to work towards an accepted understanding of the conditions in the surrounding star-forming environment is advantageous. Furthermore, since masers can be observed in the radio band, which is less susceptible to environmental disruptions than other observational bands, observations can be performed during the daytime; radio band maser observations are a seemingly optimal means to study these regions of high-mass star formation (Sutton, 2011; Wilson et al., 2009). Mid- and far-infrared observations as well as millimetre and sub-millimetre observation are excellent to use in tandem with radio observations, as these observation ranges can be utilised in observing star-forming cores (Goedhart, 2004). Since massive stars are embedded in optically thick regions, radiation propagates by continuous absorption and re-emission via dust grains (Stahler and Palla,

2008). This continuous absorption and re-emission will cause radiation to shift to a longer wavelength; often, this shift is from ultraviolet to infrared (Stahler and Palla, 2008; Gray, 2012).

Masers have become an independent area of study and have revealed themselves to be more peculiar than we may have thought initially. Masers arise in various astrophysical environments, and many different molecules lend themselves to the formation of masers (Gray, 2012). Class II 6.7 GHz methanol maser sources are radiatively pumped by mid-infrared photons emitted in their local astrophysical environment (Cragg et al., 2005; Urquhart et al., 2015); they are associated with the earliest evolutionary phases of high-mass star formation and are found superimposed on ultra-compact HII regions (Gray, 2012). Milliarcsecond imaging has revealed that emission of 6.7 GHz maser sources typically arises in regions between the protostellar disc and envelope, in the circumstellar disc, and are associated with outflows (Gray, 2012). These maser sources typically have a distance of ~ 1000 AU from the protostar, and individual maser cloudlets have sizes of ~ 10 AU (Goddi et al., 2011; Bartkiewicz et al., 2016).

Long-term observational studies have shown that masers are variable on a myriad of timescales; this finding was somewhat unsurprising as masers¹ are incredibly sensitive to the changes in their local physical environment. A more surprising finding was that of the periodic methanol masers originally reported by Goedhart et al. (2003) and Goedhart et al. (2004). There are now close to thirty periodic maser sources known to us; see table 6.1 and references therein for a comprehensive list of the maser sources. Observing these periodic sources over time has revealed that the light curve behaviour differs between the various maser sources; some light curves have an almost symmetric profile where there is a rapid increase and subsequent decrease in flux density, others a *saw-tooth* behaviour where there is a more gradual increase in flux-density and then a more rapid decline, or alternatively a rapid increase and then a more gradual decline. Sinusoidal type behaviour has also been observed, as well as the *bunny-hop* behaviour which resembles an absolute cosine (Goedhart et al., 2003, 2004). Several proposed scenarios attempt to explain the observed periodic behaviour of these methanol masers (Araya et al., 2010; van der Walt, 2011; Inayoshi et al., 2013; van der Walt et al., 2016; Parfenov and Sobolev, 2014). Sources belonging to the group of bunny-hop methanol masers include G25.411 + 0.105 (Szymczak et al., 2015), G339.62 - 0.12 (Goedhart et al., 2014), G338.93 - 0.06 (Goedhart et al., 2014), and G358.460 - 0.391 (Maswanganye et al., 2015).

1.1 Maser source G358.460 - 0.391

Maser sources G358.460 - 0.393 and G358.460 - 0.391 were identified by Caswell et al. (2010) in the methanol multibeam maser (MMB) catalogue, the coordinates and velocity ranges of these masers are given in table 1.1. Maswanganye et al. (2015) observed both G358.460 - 0.393 and G358.460 - 0.391 at 6.7 GHz and 12.2 GHz and found that maser source G358.460 - 0.391 was periodic and displayed light curve behaviour which resembled an absolute cosine function.

¹Please note that unless otherwise stated ‘maser’ refers only to unsaturated masers.

Maser source G358.460 - 0.393 on the other hand was relatively stable. [Maswanganye et al. \(2015\)](#) investigated the maser features associated with $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$ ² and found periodicities of $\sim 220 \pm 14$ days and $\sim 224 \pm 18$ days respectively. [Maswanganye et al. \(2015\)](#) also found that the maser spots associated with G358.460 - 0.391 take on an elliptical distribution. Maser sources G358.460 - 0.393 and G358.460 - 0.391 are separated by ~ 7 arcsec ([Caswell et al., 2010](#)) and are located at a distance of ~ 2.9 to 3.9 kpc from the Sun ([Chen et al., 2013](#); [Caswell et al., 2010](#); [Ugwu et al., 2023](#)).

Table 1.1: Maser features G358.460 - 0.391 and G358.460 - 0.393 coordinates and velocity ranges as in [Caswell et al. \(2010\)](#).

Source name	Equatorial coordinates		Velocity range	
	RA (2000) (h m s)	Dec (2000) (° ' ")	V_L (km.s ⁻¹)	V_H (km.s ⁻¹)
G358.460 - 0.391	17 43 26.76	-30 27 11.3	-0.5	4.0
G358.460 - 0.393	17 43 27.24	-30 27 14.6	-8.5	6.0

1.2 Motivation and Problem Statement

This dissertation consists of two primary objectives: firstly, continued observations of 6.7 GHz methanol maser source G358.460 - 0.391, previously identified as periodic by [Maswanganye et al. \(2015\)](#). Observations were conducted using the HartRAO 26m radio telescope, including high cadence observations around the predicted flux minima; these high cadence observations were requested to examine maser behaviour with a higher confidence level and with the hopes that the maser behaviour could be more accurately characterised. Extended monitoring periods of individual maser sources are of significant value as maser sources can have long-term variability on which observed flares or periodic behaviour are superimposed; such variability may only be visible over long observational periods. Another behaviour which may require substantial observation periods to observe is velocity drifting; velocity drifting is a behaviour characterised by the associated central velocity of a maser feature slowly becoming more red- or blue-shifted over time. Since periodic sources are relatively new discoveries, longer-term monitoring is essential to refine theories about their behaviour and origin.

The second objective of this project involves revisiting archival data of maser observations performed at HartRAO and initially reported on by [Goedhart \(2004\)](#). Hundreds of 6.7 GHz methanol masers have been identified since the initial discovery by [Menten \(1991\)](#); however, only a small fraction of these display periodicity. It remains unclear what is driving the underlying periodicity or whether methanol masers have a common driving factor behind their periodicity. The archival data will also be used to investigate if velocity drifting is a common phenomenon in class II methanol masers; this was not included during the initial evaluation of these sources. Velocity drifting has yet to be widely reported on in literature; therefore, using the archival data to determine the prevalence of this phenomenon will be a significant contribution. Discoveries continue to be made in the field of masers; therefore, there is value in revisiting archival data and examining these with renewed interest and excitement.

²Maser features are often described using their central velocity position v_{cen} .

1.3 Layout of Dissertation

This chapter briefly introduces the dissertation, motivation, and problem statement. Chapter 2 and chapter 3 are introductory chapters. Chapter 2 focuses on star formation, a necessary prerequisite for this research project and encompasses discussions about molecular clouds, giant molecular clouds, the chemistry within these clouds, the stages of high-mass star formation, and HII regions. Chapter 3 focuses on astronomical masers with a significant emphasis on methanol masers, as this is the main maser species of interest in this research project. Chapter 3 includes discussions on radiative transfer, maser pumping, methanol as a molecular species, methanol masers, polarisation of masers, and maser variability. Chapter 4 focuses on the observational techniques used to observe the maser sources using a single-dish radio telescope and the calibration and data processing techniques employed to achieve meaningful results from the data. Chapter 5 presents the observational results of the maser sources G358.460 - 0.391 and G358.460 - 0.393. Chapter 6 includes the survey of methanol maser sources; the survey is completed using archival data and is primarily focused on detecting velocity drifts and any other interesting artefacts in the data. Chapter 7 includes a discussion of the outcomes of the observation of maser source G358.460 - 0.391 as well as discussions of the maser survey presented in chapter 6. Chapter 8 presents the summary and conclusion of the dissertation and recommendations for future work.

Chapter 2

High-Mass Star Formation

This chapter aims to provide the reader with a conceptual understanding of high-mass star formation. An understanding of high-mass star formation (HMSF) is necessary for discussions presented in later chapters of this dissertation since the masers of interest in this project are primarily associated with high-mass star forming regions. This chapter includes an introduction to star formation, high-mass star formation, the environments in which star formation takes place, molecular clouds, and the initial conditions facilitating star formation.

2.1 Introduction

High-mass stars, $M_{\text{star}} \gtrsim 8 M_{\odot}$, shape the dynamic and chemical evolution of the Galaxy as they pass through their different evolutionary stages (Stahler and Palla, 2008). The influence of massive stars is seen through ionising radiation, stellar winds, expanding HII regions, powerful outflows, production of heavy elements, and supernovae explosions (Zinnecker and Yorke, 2007; Stahler and Palla, 2008; Arcones and Thielemann, 2023). The life of a high-mass star ends in a supernova explosion, disseminating a large amount of elements, including heavier elements, into the surrounding environment, providing chemical enrichment which is necessary for the formation of more complex astrophysical structures (Stahler and Palla, 2008). Stellar winds drive the motion of gas and dust leading to the formation of filaments and shells, ultimately impacting or initiating subsequent star formation (Ward-Thompson and Whitworth, 2011). Massive protostars, deeply embedded within molecular clouds, produce ionised regions, known as HII regions, when the star exceeds $\sim 10 M_{\odot}$ and resembles the spectral type of an O or early type B star, collectively called OB stars (Peters et al., 2010). Massive stars and protostars are embedded in optically thick regions of molecular clouds and cannot be seen directly by some methods of astronomy such as optical observations; however, as a result of the stellar radiation which travels through the molecular cloud by continued absorption and emission by molecules and dust grains, the radiation will reach the edge of the cloud often observed in the mid- and far-infrared range (Stahler and Palla, 2008). Maser observations are indispensable when studying these regions since masers are sensitive to changes in their environment and masers residing in these regions can be observed in the radio band revealing information about the otherwise obscured stellar environment.

2.2 Molecular clouds

The following section draws from discussions in [Ward-Thompson and Whitworth \(2011\)](#), [Stahler and Palla \(2008\)](#), and [Elitzur \(1992\)](#). Molecular clouds are the environments wherein all star formation occurs; therefore any understanding of star formation is inextricably linked to an understanding of molecular clouds. Molecular clouds are cold, dense regions of the interstellar medium (ISM) composed of atomic and molecular gas, and dust. These clouds are opaque and optically thick since dust and gas block and attenuate the passage of light in some wavelengths. Present day star forming regions have molecular hydrogen densities of $n \sim 10^4 - 10^5 \text{ cm}^{-3}$ and temperatures of ~ 10 to 50 Kelvin. Molecular clouds are considered ‘cold’, since on average the regions have physical temperatures between 10 and 30 Kelvin ([Burke et al., 2019](#)). The molecular cloud is cooler in comparison to other regions of the ISM, such as warm ionised gas, which can have temperatures in the range of ten thousand Kelvin or more, as well as being cooler than the warm neutral medium which has temperatures which range between a few hundred to a few thousand Kelvin; see table 2.1 for the characteristics of the various phases of the ISM. The cooler temperature of molecular clouds is a result of dust grains which absorb, scatter, and re-radiate a large portion of the stellar radiation, thereby reducing the likelihood that the radiation will heat surrounding gas. In addition to the shielding of stellar radiation by dust another key component is the cooling effect caused by the rotational lines of molecules. This low temperature is integral in forming more complex molecules such as methanol, as more complex molecules form on the icy mantles of dust grains, this is discussed further in section 2.2.2. Thermal emission from dust is one of the primary sources of continuum radiation in molecular clouds as it absorbs ultra-violet (UV) radiation originating from the stellar source and re-emits radiation in the mid- and far-infrared range characteristic of the dust temperature, T_d .

Molecular clouds are inhomogeneous in nature, containing clumped regions of higher density, various temperatures, and chemical compositions. This inhomogeneity is a result of several factors, such as turbulence, gravity, and magnetic fields. Turbulence can create dense clumps and gaseous filaments which collapse under the influence of gravity forming dense cores, which are precursors of star formation. The turbulent velocity structure of molecular clouds has been verified through observations of molecular line radiation; observed molecular line profiles have additional broadening which cannot be exclusively attributed to thermal broadening, the additional broadening is attributed to bulk or turbulent motions within the cloud. Magnetic fields influence interactions between charged particles, gas, and dust within the cloud. The inhomogeneity of molecular clouds ultimately provides the necessary conditions for star formation, where dense cores and filamentary structures form and collapse, providing the seeds for star formation.

2.2.1 Giant molecular clouds

The following discussion on giant molecular clouds draws from [Gray \(2012\)](#), [Stamatellos et al. \(2014\)](#), [Gerner et al. \(2014\)](#), and [Stahler and Palla \(2008\)](#). Molecular clouds are constantly being formed and destroyed with Giant molecular cloud (GMC) expected lifespans less than

Table 2.1: Various phases of the interstellar medium (ISM) as presented in [Beech \(2019\)](#).

Phase	Temperature (K)	Number density (cm^{-3})	Characteristic size (pc)
Coronal gas	10^6	$10^4 - 10^2$	Galactic (50%)
Warm neutral	10^4	5×10^5	Galactic (15%)
Warm ionised	10^4	5×10^5	Galactic (25%)
HII	10^4	$10^8 - 10^{10}$	1 - 10 (<1%)
Cold neutral	100	5×10^7	Galactic (5%)
GMC	15	10^8	20 - 150 (<1%)
MC	10	5×10^6	10
MC clump	10	10^9	5
MC core	10	10^{11}	0.25

3×10^7 years, masses ranging between $5 \times 10^4 M_\odot$ and $10^6 M_\odot$, and sizes of between 20 and 150 parsecs. See table 2.2 for a summary on the properties corresponding to molecular clouds of different sizes. The star formation rate in a galaxy is directly linked to the formation rate of GMCs, as stars of all stellar masses form in GMCs. The densest condensations existing in GMCs are termed ‘prestellar cores’ and it is when these cold, dense, gaseous, and dusty prestellar cores gravitationally collapse that the star formation process begins ([Rosen et al., 2020](#)). Within any GMC actively undergoing star formation, there are a number of individual massive pre- and protostellar objects which will become stars. Massive clouds exhibiting the majority of the star formation are primarily located in the galactic disc. The galactic disc is the flattened region of the Milky Way which contains a large percentage of the galaxy’s stellar and gaseous material; therefore, due to the abundance of interstellar material in the galactic disc, it makes sense that the majority of high-mass star formation would be found here.

Galaxy-wide surveys have revealed that giant molecular clouds have a filamentary structure similar to the interstellar medium (ISM). These filaments are known to fragment serving as seeds for star-forming cores, and can feed high-mass star formation by funnelling gas into star-forming regions. Gas flow rates which could support substantial accretion rates have been observed along high-mass filaments ([Lu et al., 2018](#)). This is important as massive stars must be fed by the larger scale environment in order for them to reach their final masses ([Beuther et al., 2015](#)). In GMCs, these filaments typically extend sizes of $\gtrsim$ one parsec, contain dense gas masses $\gtrsim 3 M_\odot$, and the filaments are observed to fragment along their major axes wherein the signatures of embedded high-mass protostars have been observed ([Lu et al., 2018](#)). Massive filaments have been observed to have strong turbulence and powerful outflows, which point to continuous dynamical processes; these massive filaments are unlikely to be supported by thermal pressure alone and likely rely on additional turbulent pressure or magnetic fields ([Beuther et al., 2015](#); [Lu et al., 2018](#)). This compilation of results suggests that high-mass stars are born of giant infrared dark clouds which display filamentary structures.

2.2.2 Chemistry in Molecular Clouds

Complex molecules such as methanol form on the icy grain mantles prior to the hot molecular core (HMC) stage of star formation, this is known as ‘grain-surface chemistry’. In molecular

Table 2.2: Properties of Interstellar Molecular clouds (Bally, 1986; Rathborne et al., 2006)

Type of cloud	Mass ($M_{\odot}$)	Size (pc)	Star formation (SF)
Globules	1 to 500	0.1 to 10	Little SF
Small molecular clouds	1 to 10^3	1.0 to 10	Low mass
Small cloud complexes	10^2 to 5×10^4	10 to 50	Low to intermediate mass
IRDC	120 to 16×10^3	1 to 10	Low to high mass
GMCs	5×10^4 to 10^6	20 to 150	All stellar masses form
GMC complexes	10^6 to 10^7	100 to 300	

clouds gas-phase molecules are accreted onto the surface of dust grains forming a layer of icy mantles. Once on the grain surface molecular species can diffuse and react, producing more complex molecules such as methanol, formaldehyde, and ammonia, amongst others (Turner, 1998; Van Dishoeck and Blake, 1998). These molecules which have formed on the icy-grain mantles of dust can then be injected back into their surrounding environment. During the hot molecular core (HMC) stage of star formation, the central hot molecular core heats its surrounding environment evaporating the molecular-rich ice grains releasing gas phase molecules such as methanol back into the environment (Stamatellos et al., 2014; Gerner et al., 2014). This process leads to a rich molecular environment often observed in star forming regions.

2.3 Evolution of molecular cloud environments

The following discussion draws from Ward-Thompson and Whitworth (2011), Stamatellos et al. (2014), Gerner et al. (2014), and Stahler and Palla (2008). The evolutionary sequence of high-mass star-forming regions (HMSFRs) can be separated into four distinct stages: firstly, the formation of quiescent infrared dark cloud (IRDC), which are observed as dark silhouettes in the mid-infrared (MIR) range due to the contrast of their absorption against the bright emission of the Galactic background. IRDCs are associated with the densest regions of molecular clouds. The formation of a hot molecular core (HMC) follows the IRDC stage; high-mass protostellar objects (HMPOs) then form; and finally an HII region forms as a result of ionising radiation from the stellar object. An IRDC is a type of molecular cloud characterised by limited stellar activity and a lack of infrared emission; IRDCs are dense and optically thick, and their mass can be hundreds to thousands of solar masses. Dense dark cores are often observed within these clouds; the cores can have masses up to $\sim 100 M_{\odot}$ and radii of 0.1 parsec or less. IRDCs are primarily detected at sub-millimetre wavelengths due to their low temperatures $\sim 10 - 20$ Kelvin. An IRDC will collapse under the influence of gravity, resulting in an increase in temperature and the progression to the HMC stage.

A hot molecular core typically follows the IRDC stage; HMCs are dense interstellar clouds wherein star formation has just begun or will soon begin and are precursors to ultracompact HII regions (Zapata et al., 2010; Osorio et al., 2015). Hot molecular cores evolve from IRDCs, as dense cores within the IRDC collapse under the influence of gravity (Hirota, 2018). During the collapse gravitational potential energy is converted to thermal energy, which heats up the dense core; as the environment heats up, grain mantle evaporates resulting in a

chemically enriched environment. In the HMC phase, complex organic molecules are detected alongside maser emission. Following the formation of an HMC, material continues to be accreted onto this region, eventually forming a protostellar object. The material that forms the protostar is initially low angular momentum, while high angular momentum material forms the circumstellar disc around the protostellar object. At this point in the evolutionary stage, this is a classical protostellar object; a classic protostellar object does not yet have sufficient luminosity to ionise its surrounding environment. The circumstellar disc feeds the protostellar object, and the protostar displays outflows at its poles; the outflows carry away excess angular momentum as material is accreted onto the protostellar object. Magnetic fields and radiation pressure may also influence outflows. The protostellar object will grow and eventually have sufficient energy to ionise the surrounding environment, thus forming an UCHII region. The HII region will expand into its surrounding environment as the stellar object continues to emit ionising radiation.

Table 2.3: Characteristics and classification of HII regions (Wood and Churchwell, 1989; Hoare et al., 2007).

HII region	Size (pc)	Densities n_e (cm^{-3})	Emission measures (pc cm^{-6})
Classic HII	~ 10	$\geq 10^2 - 10^3$	$\geq 10^2 - 10^3$
Ultra-compact (UC) HII	≤ 0.1	$\geq 10^4$	$\geq 10^7$
Hyper-compact (HC) HII	≤ 0.03	$\geq 10^6$	$\geq 10^8$

2.4 HII regions

The following section draws from discussions in Stahler and Palla (2008), Ward-Thompson and Whitworth (2011), and Elitzur (1992). HII regions are found in regions surrounding stars with sufficient output luminosity, such as OB spectral type stars, to ionise present molecular hydrogen. These associated stars are massive, luminous ($\geq 10^4 L_\odot$), and hot ($\geq 2 \times 10^4$ K). HII regions have large amounts of, and get their name from, ionised hydrogen¹. The ionised hydrogen forms as a result of the OB type star producing a significant amount of energetic UV photons. Energetic photons, $h\nu > 11.2$ eV, photo-dissociate molecular hydrogen to form neutral HI atoms; HI atoms are then ionised by photons, $h\nu > 13.6$ eV, to form HII. This leads to the formation of a photoionised HII region. Electrons and protons in this region will also recombine back into atomic hydrogen and molecular hydrogen. This bubble of HII gas is heated to temperatures in the range of $\sim 10^4$ Kelvin, which is approximately a three orders of magnitude increase, from $T_{\text{gas}} \leq 100$ Kelvin. The particle number density also increases by an approximate factor of four due to the dissociation and ionisation process where each H_2 molecule is split into two protons and two electrons. This causes a pressure increase of a factor of $\sim 4 \times 10^3$, as demonstrated by the equation $P = nkT$. This pressure increase stimulates the HII region to rapidly expand with a velocity of $\sim 10 \text{ km.s}^{-1}$, characteristic of the speed of sound in the ionised gas (Peters et al., 2010). The rapidly expanding region sweeps up a shocked layer of dense neutral gas around its edge, see figure 2.1.

¹Ionised hydrogen, H^+ is a positively charged hydrogen atom; the positive charge is the result of losing its electron. Ionised hydrogen is referred to as HII, pronounced ‘H-two’, which should not be confused with the molecular form of hydrogen H_2 .

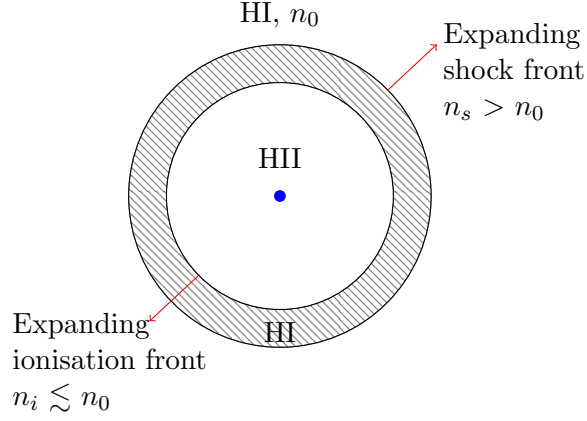


Figure 2.1: In the evolution of an HII region, there is initially an expanding ionisation front. This initial expansion phase is rapid and the density of the ionised material n_i remains approximately the same as the surrounding ambient material n_0 . As the ionisation front continues to expand, hot ionised gas also expands, creating a shock front which moves through the ambient medium.

2.4.1 Hypercompact HII regions

The discussion draws from [Stahler and Palla \(2008\)](#), [Ward-Thompson and Whitworth \(2011\)](#), and [Elitzur \(1992\)](#). As a massive star nears the end of its rapid accretion stage and becomes more powered by hydrogen burning than disc accretion, the accretion disc will start to photoionise and partially photoevaporate, forming a gravitationally bound Hypercompact HII (HCHII) region around the protostar. The HCHII region is confined to the vicinity of the protostar and is the first stage of producing a detectable HII region ([Keto, 2007](#); [Zinnecker and Yorke, 2007](#)).

2.4.2 Ultracompact HII regions

The discussion draws from [Stahler and Palla \(2008\)](#), [Ward-Thompson and Whitworth \(2011\)](#), and [Elitzur \(1992\)](#). Ultracompact HII (UCHII) regions follow the HCHII region and likely represent a stage when the MYSO has finished accreting and has dissipated its disc. Massive stars begin hydrogen burning whilst they are still actively accreting; however, UCHII regions can only form once accretion has ceased. Once the UV radiation is no longer dampened the stellar ionising radiation can photoionise the star's surrounding envelope and form an expanding bubble of ionised gas termed an UCHII region ([Zinnecker and Yorke, 2007](#)). During the main sequence life of the central star the UCHII region will expand becoming larger and more diffuse, ultimately forming a classical HII region ([Churchwell, 2002](#); [Zinnecker and Yorke, 2007](#)).

2.4.3 Formation of ionised hydrogen

The following section draws from discussions presented by [Flower \(2007\)](#) and [Saha \(1921\)](#). In thermodynamic equilibrium the Saha relation is given by,

$$\frac{n[A(n)]}{n(A^+)n_e} = \frac{g_n}{2g_+} \left(\frac{h^2}{2\pi m_e k_B T} \right)^{\frac{3}{2}} \exp \left(\frac{h\nu_n}{k_B T} \right), \quad (2.1)$$

where g_n is the degeneracy corresponding to atom A and g_+ is the degeneracy of ion A^+ ; if we are looking at two ions of the same element the degeneracies can also be expressed as g_{i+1} and g_i with corresponding number densities n_{i+1} and n_i respectively. The energy required to ionise A^+ from the ground state is $h\nu_n$ sometimes expressed as χ ; in the case of atomic hydrogen $\chi = h\nu_n = 13.6$ eV.

Assuming that the neutral hydrogen is in the ground state the degeneracy will be $g_n = g_I = 2$, since g_I is representing the statistical weight of the ground state. Ionised hydrogen consists of only a proton, therefore $g_+ = g_{II} = 1$. The Saha relation will then follow as,

$$\begin{aligned} \frac{n[\text{HI}]}{n(\text{H}^+)n_e} &= \frac{g_n}{2g_+} \left(\frac{h^2}{2\pi m_e k_B T} \right)^{\frac{3}{2}} \exp \left(\frac{h\nu_n}{k_B T} \right) \\ &= \frac{(2)}{2(1)} \left(\frac{h^2}{2\pi m_e k_B T} \right)^{\frac{3}{2}} \exp \left(\frac{13.6 \text{ eV}}{k_B T} \right). \end{aligned}$$

If there are n hydrogen atoms/ions per unit volume then, as a result of charge conservation, the electron number density is given by,

$$n_e = \frac{N_{II}}{N_I + N_{II}} n. \quad (2.2)$$

Noting the following $N_{II} = n(\text{H}^+) = n(\text{HII})$ and $N_I = n(\text{H}_2) = n(\text{HI})$. Ultimately, we want an expression for the degree of ionisation in an HII region; therefore, rewriting the Saha relation as follows,

$$\begin{aligned} \frac{n[\text{HI}]}{n(\text{H}^+)n_e} n_e &= n_e \left(\frac{h^2}{2\pi m_e k_B T} \right)^{\frac{3}{2}} \exp \left(\frac{13.6 \text{ eV}}{k_B T} \right) \\ \Rightarrow \frac{N_{II}}{N_I} n_e &= \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left(\frac{-13.6 \text{ eV}}{k_B T} \right). \end{aligned}$$

Following from equation above,

$$\Rightarrow \frac{N_I^2}{N_I(N_I + N_{II})} = \frac{1}{n} \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left(\frac{-13.6 \text{ eV}}{k_B T} \right).$$

Defining $N = N_I + N_{II}$ and $x = N_{II}/N$, where x is the degree of ionisation. The final expression of Saha relation can be written,

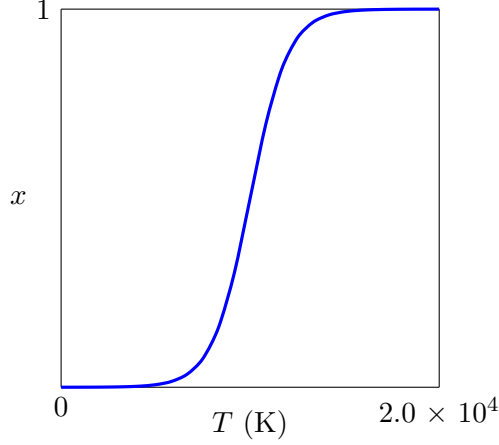


Figure 2.2: A figure qualitatively demonstrating the ionisation fraction of pure hydrogen gas as a function of temperature in Kelvin as predicted by the Saha relation. The values in this plot correspond to hydrogen number densities typical of stellar atmosphere, $\sim 10^{26} \text{ cm}^{-3}$.

$$\begin{aligned} \frac{N_{\text{II}}^2}{N_{\text{I}}(N_{\text{I}} + N_{\text{II}})} &= \frac{N_{\text{II}}^2}{N(N - N_{\text{II}})} = \frac{1}{n} \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left(\frac{-13.6 \text{ eV}}{k_B T} \right), \\ \Rightarrow \frac{x^2}{1-x} &= \frac{1}{n} \left(\frac{2\pi m_e k_B T}{h^2} \right)^{\frac{3}{2}} \exp \left(\frac{-13.6 \text{ eV}}{k_B T} \right). \end{aligned} \quad (2.3)$$

As can be seen in figure 2.2, the Saha relation predicts, after some tipping point, an exponential dependence of the fraction of ionised hydrogen present in an HII region on the temperature of the gas; the function of the Saha relation resembles a hyperbolic tangent. At lower gas temperatures the ionisation energy required is representative of a significant portion of the thermal energy of the gas; however, as the gas temperature increases the probability of hydrogen being ionised dramatically increases. From the figure it can also be seen that there is an upper limit to this effect where the gas becomes so dense that recombination of ions and electrons equals or exceeds ionisation. The upper limit is where the graph plateaus at $x = 1$, i.e., this is where the degree of ionisation will equal one.

2.5 High-Mass Star Formation

The following discussion on high-mass star formation follows from [Stahler and Palla \(2008\)](#), [Zinnecker and Yorke \(2007\)](#), and [Ward-Thompson and Whitworth \(2011\)](#). The Milky Way galaxy is a spiral-type galaxy with a significant star formation rate at the current epoch; spiral galaxies have more interstellar material in comparison to other galaxy types, such as elliptical and lenticular galaxies, and therefore have higher star formation rates. Star formation in spiral galaxies takes place mainly in the spiral arms of the galactic disc, where a higher density of interstellar material is gathered; the density is sustained by spiral density waves rotating about the galactic centre, which compress material into giant molecular clouds ([Gray, 2012](#)). As previously discussed, it is within these molecular clouds that star formation takes place. Low-mass stars are the primary stellar constituent of galaxies as they are favoured by the initial mass function (IMF); in contrast, high-mass stars represent only one per cent

of the stellar population.

The current understanding of high-mass star formation dictates the following summary of events. High-mass young stellar objects (HMYSOs) or protostars form in dense giant molecular clouds via the gravitational collapse of massive cores and accrete at rates between 10^{-5} to $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$. The protostars then rapidly complete their Kelvin–Helmholtz contraction² after which the stellar object radiates ultra-violet (UV) photons which ionise the surrounding environment producing a hypercompact (HC) HII region. After some time, the accretion will effectively cease, stellar winds and radiation will then disband remaining envelope material. After much of the material has been dispersed, a high-mass main sequence star surrounded by a classic HII region will remain (Zapata et al., 2010; Guzmán et al., 2016). See table 2.3 for the characteristics of different HII regions.

The complete paradigm of high-mass star formation remains inadequately understood despite the significance of high-mass stars in galactic evolution. This is because high-mass star formation is more difficult to study as high-mass star formation is a relatively rare and rapid process, with timescales of $\leq 10^6$ years (Hirota, 2018). High-mass star formation is also difficult to observe as it occurs within dense and optically thick environments deep within GMCs on relatively large distance scales (Paulson and Pandian, 2020).

2.5.1 The initial mass function

The initial mass function (IMF) describes the stellar mass distribution within a region, i.e., the relative number of stars formed with different masses. The IMF is typically represented with a power law function $\xi(m) \propto m^{-\alpha_i}$ where the index of the power law depends on the stellar masses within the considered region. The Salpeter index, $\alpha_s = 2.35$, is valid for mass ranges $0.4 \text{ M}_{\odot} - 10 \text{ M}_{\odot}$ (Salpeter, 1955; Ward-Thompson and Whitworth, 2011; Galván-Madrid, 2012). The IMF is steep on the high-mass end, meaning that the number of stars rapidly decreases with increasing mass; star-formation favours low-mass stars over high-mass stars (Salpeter, 1955). Masers are primarily associated with high-mass stars; the minimum stellar mass of an associated stellar object varies with molecular species, but for the majority of maser species, the lower limit of an associated star exceeds $1 \text{ M}_{\odot}$ (Gray, 2012). For 6.7 GHz methanol masers, the lower limit on the stellar mass of an associated star Minier et al. (2003) as $\sim 3 \text{ M}_{\odot}$, however, observational data suggests that the real lower limit is closer to $8 \text{ M}_{\odot}$ (Breen et al., 2013). As a result of this association with more massive stars and protostars, maser emission is only associated with a small fraction of stellar objects. This may result from smaller stellar objects emitting insufficient radiation to support population inversion and masing to any observable extent.

²The Kelvin–Helmholtz timescale dictates the time it would take for protostars to become main-sequence stars as a consequence of the Kelvin–Helmholtz mechanism. The Kelvin–Helmholtz mechanism describes the process where the surface of a stellar object cools; the cooling causes an internal pressure drop which in turn causes contraction of the stellar object. The contraction of the stellar object then causes the core of the stellar object to heat up.

2.5.2 Virial theorem and Jeans mass

The following discussion draws from [Carroll and Ostlie \(2017\)](#) and [Ward-Thompson and Whitworth \(2011\)](#). The Virial theorem relates the total kinetic energy of a self-gravitating body to the gravitational potential energy of a body. Several simplifying assumptions on the Virial theorem, such as neglecting turbulence, effects of rotation, and magnetic fields, the virial theorem is written as,

$$2K + U = 0, \quad (2.4)$$

and describes the condition of equilibrium for a stable, gravitationally bound system, where K is the internal kinetic energy of the molecular cloud and U is the gravitational potential energy. If it is assumed that the molecular cloud is spherical and of a constant density, then the approximate gravitational potential energy can be written by the following equation,

$$U \sim -\frac{3}{5} \frac{GM_c^2}{R_c}, \quad (2.5)$$

where, M_c and R_c are the mass and radius of the cloud respectively, and G is the gravitational constant. The internal kinetic energy of the cloud can be estimated as,

$$K = \frac{3}{2} N k T, \quad (2.6)$$

where N is the total number of particles, k is the Boltzmann constant and T is the temperature of the gas. The number of particles can also be written as,

$$N = \frac{M_c}{\mu m_H}, \quad (2.7)$$

where, μ is the mean molecular weight and m_H is the mass of hydrogen. Assuming the density ρ_0 is constant throughout the cloud, the cloud radius can be defined as,

$$R_c = \left(\frac{3M_c}{4\pi\rho_0} \right)^{\frac{1}{3}}. \quad (2.8)$$

According to the Virial theorem, the condition for collapse is if the gravitational potential energy exceeds two times the kinetic energy, i.e., $2K < |U|$,

$$2 \frac{3}{2} \left(\frac{M_c}{\mu m_H} \right) k T < \frac{3}{5} \frac{GM_c^2}{R_c}. \quad (2.9)$$

The above equation simplifies as follows,

$$\begin{aligned}
&\Rightarrow 5 \left(\frac{M_c}{\mu m_H} \right) kT < \frac{GM_c^2}{R_c}, \\
&\Rightarrow 5 \left(\frac{3M_c}{4\pi\rho_0} \right)^{\frac{1}{3}} \left(\frac{M_c}{\mu m_H} \right) kT < GM_c^2, \\
&\Rightarrow \left(\frac{3}{4\pi\rho_0} \right)^{\frac{1}{3}} \left(\frac{5kT}{G\mu m_H} \right) < M_c^{\frac{2}{3}}, \\
&\Rightarrow M_c > \left(\frac{5kT}{G\mu m_H} \right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho_0} \right)^{\frac{1}{2}}.
\end{aligned}$$

Jeans criterion is the mass required to initiate the spontaneous collapse of a molecular cloud,

$$M_c > M_{\text{Jeans}}, \quad (2.10)$$

Therefore the Jeans mass can be written as,

$$M_{\text{Jeans}} \simeq \left(\frac{5kT}{G\mu m_H} \right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho_0} \right)^{\frac{1}{2}}. \quad (2.11)$$

When a cloud of interstellar gas reaches this critical mass, gravitational forces will dominate forcing the cloud to contract under its own weight.

2.5.3 Protostar formation and evolution

The following section draws from discussions in [Ward-Thompson and Whitworth \(2011\)](#), [Zinnecker and Yorke \(2007\)](#), and [Carroll and Ostlie \(2017\)](#). A protostar is a gaseous object in hydrostatic equilibrium which accretes material onto itself and will grow in mass, temperature, and luminosity; however, it has not yet begun hydrogen burning, only once hydrogen burning commences will the object be referred to as a main sequence star. A high-mass protostar will have a mass $\geq 8 M_{\odot}$. Prestellar cores located in molecular clouds are one of the earliest identifiable stages of the star formation process; prestellar cores are dense, gravitationally bound molecular cloudlets undergoing quasistatic gravitational contraction. Star formation begins when a prestellar core, located deep within a giant molecular cloud, gravitationally collapses and forms a protostar ([Rosen et al., 2020](#)). As the prestellar core collapses, conservation of angular momentum results in infalling material forming a circumstellar disc around the protostar; the stellar disc system is embedded within an infalling envelope of dust and gas ([Rosen et al., 2020](#)); after gravitational collapse, protostars grow by accreting material from their surrounding environment ([Kuffmeier et al., 2018](#); [Meyer et al., 2017](#)).

When a prestellar core begins to collapse, gravitational energy is freely radiated away, and the collapsing fragment remains at an approximate consistent, isothermal, temperature. The Jeans Mass is a fundamental concept in the study of star formation and represents the minimum mass which would support gravitational collapse. The Jeans mass, M_{Jeans} , is

proportional to temperature T and inversely proportional to density ρ ,

$$M_{\text{Jeans}} \propto T^{3/2} \rho^{-1/2}; \quad (2.12)$$

therefore, a cool, dense region will collapse and form stars more readily. Consequently, the Jeans mass for high-mass protostars is greater than that of their low-mass counterparts; due to higher temperatures and pressure in their collapse conditions, high-mass stars form from more massive and denser prestellar cores.

Once gravity becomes the dominant force over pressure and magnetic forces, as dictated by the Jeans mass, gravity remains the dominant force and the gas will collapse on a free-fall timescale defined as,

$$t_{\text{ff}} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}, \quad (2.13)$$

where G is the gravitational constant and ρ_0 is the initial density of the gas cloud. In the case of gravity being the dominant force the densest parts of the cloud will collapse at the fastest rate. The collapse is nonhomogenous until the densest components become optically thick and allow for adiabatic heating of the gas which in turn leads to an increase of gas pressure. As a result of conservation of angular momentum, centrifugal forces increase and accretion disks, alongside other flattened structures form. Accretion disks are an expected outcome of gravitational collapse, not just in the context of star formation but also black holes and other massive objects.

As the slowly rotating cloud fragment of molecular material continues to follow a non-homologous collapse, the density increases causing the cloud to become opaque and trap infrared radiation. This trapped radiation heats the constituting gas of the increasing pressure and forcing the cloud core to adopt a state of quasi-hydrostatic equilibrium, thus slowing the dynamical collapse to a quasistatic contraction which ultimately results in the formation of a protostar. The quasi-hydrostatic core continues to grow in mass whilst simultaneously contracting on a thermal Kelvin-Helmholtz timescale toward hydrogen-burning densities and temperatures. The Kelvin-Helmholtz timescale is defined as,

$$t_{\text{KH}} \sim \frac{GM_*^2}{R_*L_*}, \quad (2.14)$$

where G is the gravitational constant, M_* is the mass of the sphere, R_* is the radius of the sphere, and L_* is the luminosity of the sphere. The formation of massive stars requires the collapse of massive interstellar gas clouds with accretion rates exceeding $10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$ (Beuther et al., 2002; Beltrán et al., 2006) otherwise these stellar objects will not reach high-mass final masses before exhausting nuclear fuel reserves (Keto and Wood, 2006).

The protostellar objects rapidly complete their Kelvin-Helmholtz contraction and reach the main sequence (Norberg and Maeder, 2000; Keto and Wood, 2006), after which the star ra-

diates UV photons and ionises the surrounding molecular gas leading to the formation of a hyper-compact (HC) HII region emission measures $> 10^8 \text{ pc cm}^{-6}$, and hydrogen recombination line widths $\gtrsim 50 \text{ km s}^{-1}$ (Hoare et al., 2007). The accretion flow will eventually cease, UV radiation and stellar wind will disperse envelope material leaving behind an OB-type star surrounded by a classical HII region (Zapata et al., 2010).

The accretion phase of massive star formation is accompanied by circumstellar disks and bipolar outflows, further discussed in sections 2.5.5 and 2.5.6. The method by which massive stars grow is less constrained than our present understanding of low mass star formation. Mechanisms for massive star formation presented in previous literature include accretion by means of massive circumstellar discs (Keto, 2002), competitive accretion in dense clusters (Bonnell et al., 2004), ionized accretion (Keto and Wood, 2006), and mergers of low-mass stars (Bonnell et al., 1998). The accretion picture is the most supported hypothesis by observations and is largely accepted in the field at present; spectral line observations indicate substantial infall rates (Zhang and Ho, 1997; Zapata et al., 2008; Keto and Wood, 2006; Keto, 2002; Fuller et al., 2005; Beltrán et al., 2006).

2.5.4 Stellar feedback in high mass star formation

Stellar feedback is the injection of energy and momentum into the interstellar medium (ISM) by stellar objects; stellar feedback originates at the small scales of individual stars and stellar clusters, $\lesssim 1 \text{ pc}$, but shapes the ISM on large scales, $\gtrsim 1 \text{ kpc}$ (Olivier et al., 2021). Stellar feedback is responsible for low star formation efficiencies observed in GMCs (Olivier et al., 2021). High-mass stars contract quickly and reach main sequence luminosities whilst still actively accreting; as a result they are influenced by numerous mechanisms of stellar feedback, more than their low-mass counterparts (Rosen et al., 2020). In addition to stellar outflows, feedback mechanisms include: radiation pressure, photoionisation, and radiatively driven stellar winds (Rosen et al., 2020, 2016). These feedback mechanisms all influence how material is delivered to and accreted onto the star.

Dust is the primary absorber of stellar radiation as a result of its large opacity in dense star forming environments; early theoretical work suggested that high-mass stars should not form as a result of radiation pressure revoking accretion flow (Rosen et al., 2020). However, modern observations have disproven this and numerous simulations have proven that in the case of non-spherical accretion it is possible for stars to grow to very large masses. Protostellar outflows are ubiquitous with both low-mass and high-mass star formation; simulations predict that the momentum injected by outflows can entrain and expel 20 to 50% of the gas in dense high-mass star forming cores (Kuiper et al., 2016). Accreting high-mass protostars emit photoionising radiation ($E_\nu \geq 13.6 \text{ eV}$) due to their high surface temperatures; the circumstellar accretion disk partially self-shields itself against photoionization, instead the magnetically launched outflows become photoionized and are confined within the protostellar outflows (Rosen et al., 2020). Outflows tend to become photoionised very rapidly, on timescales of $t \sim 10^3$ to 10^4 years, after formation of the HII region (Tanaka et al., 2016). As the HII regions expands, thermal pressure from the ionised gas will squeeze the accretion disc, temporarily increasing the accretion rate onto the star (Kuiper and Hosokawa, 2018). Stellar feedback

associated with stellar winds results when a high-mass protostar reaches a sufficiently high surface temperature, $\sim 12.5 \times 10^3$ K, and the high luminosity drives fast ultra-violet winds from the stellar surface (Vink et al., 2001). Stellar winds collide with infalling material and shock-heat the gas to $\sim 10^7$ K; the shock heated gas will then adiabatically expand and push on the infalling gas (Rosen et al., 2014; Geen et al., 2020). Similarly, stellar radiation can produce line-driven winds in the surface layers of the accretion disc; these winds will erode the accretion disc producing a strong feedback effect for massive protostars (Kee and Kuiper, 2019).

2.5.5 Circumstellar discs

Low-mass stars grow through spherical accretion; however in the case of more massive stars, $\gtrsim 8 M_{\odot}$, there is a theoretically expected upper mass limit at which point powerful stellar radiation will inhibit spherical accretion (Beltrán et al., 2006). However, since high-mass stars do in fact exist, they must grow by means of non-spherical accretion with stellar photons escaping along the symmetry axis where the density is lower. This leads us into our discussion of circumstellar discs and bipolar outflows which follows from discussions in Stahler and Palla (2008) and Ward-Thompson and Whitworth (2011).

There are a number of theoretical models which suggest that a circumstellar accretion disc can channel material onto a stellar object and by doing so overcome the powerful feedback from the central protostar (Krumholz et al., 2009; Kuiper et al., 2011; Rosen et al., 2016). These theoretical models predict that the circumstellar discs possess sub-structures such as large-scale spiral arms and bound fragments (Klassen et al., 2016; Jankovic et al., 2019). In recent years the presence of circumstellar discs around early B-type stars have been confirmed, improving the understanding of high-mass star formation (Beltrán and de Wit, 2016); showing that B-type stars grow via disc mediated accretion and confirming a number of theoretical models (Bonnell and Bate, 2006; Keto, 2007; Krumholz et al., 2009).

A significant portion of the mass accreted onto protostars does not occur in a direct or spherically symmetric manner. Therefore, material accumulates in a circumstellar disc, often termed an accretion disk, due to conservation of net angular momentum. As a cloud of gas collapses, the particles will move towards the centre due to gravitational force; however these particles must conserve angular momentum and thus will begin to orbit the central object. Gas particles closer to the protostar move faster and those particles further out will move more slowly, creating a rotationally flattened disc structure. Material is accreted from the accretion disc onto the stellar object over some time scale. When material is accreted from the disc onto the stellar object potential energy is converted to kinetic energy, and the kinetic energy is released as heat at the accretion shock or stored in the rotational energy of the star (Kuffmeier et al., 2018).

The mechanism behind accretion of matter from the the disc onto the protostar remains poorly understood (Meyer et al., 2017). Early spherical collapse models which neglect the disc formation phase, fail to describe the variety of accretion rates observed (Vorobyov, 2009) and predict luminosities 10 to 100 factors greater than measured luminosities in nearby star

forming regions (Meyer et al., 2017). The luminosity problem can be solved if the accretion history onto the protostar is highly time variable as seen in self-consistent models which follow the transition from clouds to protostellar discs (Dunham and Vorobyov, 2012); these models describe protostars as spending the majority of their time in the quiescent phase with low accretion rates, interspersed with short high-intensity accretion bursts (Meyer et al., 2017).

Circumstellar discs around massive protostars are more massive than discs around low-mass protostars; the circumstellar discs around massive protostars are also more prone to instability and fragmentation (Zhao et al., 2018). Accretion makes the disc unstable and spiral arms will periodically form. When accretion rates are high balance cannot be maintained and the disc can fragment. The fragmentation of the disc may cause episodic mass accretion burst events. These bursts are postulated to be the most likely cause of flares in the emission of the 6.7 GHz methanol masers (Fujisawa et al., 2015; MacLeod et al., 2018; Szymczak et al., 2018b). Thus, maser flares constitute an ideal probe to identify the initial phase of accretion bursts. The formation of disks is often accompanied by the launching of jets and outflows, which transport away the angular momentum from the accreting material.

2.5.6 Bipolar outflows

The following discussion follows from Stahler and Palla (2008) and Ward-Thompson and Whitworth (2011). Bipolar outflows are powerful outflows of gas and dust often associated with young stellar objects including protostars. Bipolar outflows tend to have a distinctive hourglass shape, with two lobes aligned along the rotation axis of the stellar or protostellar system, perpendicular to the circumstellar discs; bipolar outflows associated with young stellar objects is a well established phenomenon as the outflows have a direct link to accretion. Bipolar outflows contain ionised, atomic and molecular gas that is excited (Hirota et al., 2017). Bipolar outflows are thought to be driven by the release of energy and momentum from the central stellar object. As the stellar object accretes material from its surrounding disc, some material falls onto the stellar surface, where it is heated and ionised. The resulting radiation and powerful magnetic fields then launch jets of ionized gas and dust perpendicular to the disc plane, which form the bipolar outflow. Bipolar outflows can have velocities of hundreds of kilometers per second, and can extend over several parsecs. They are thought to play an important role in regulating the growth of young stars and shaping the surrounding molecular cloud. The outflows inject energy and momentum into surrounding gas, heating and ionizing it, and creating shock fronts which trigger further star formation. It should be noted that the mechanisms by which bipolar jets are launched is not yet fully constrained and is still the subject of theoretical modelling.

These outflows take on various forms: on scales close to the star $\sim 10^{14}\text{m}$ (~ 6685 AU) the outflows take the form of highly collimated jets; on scales $\sim 10^{15}\text{m}$ (~ 66845 AU) the outflows take on the form of Herbig-Haro (HH) objects which are shock heated knots; finally on large scales, $\sim 10^{15}\text{m}$ (~ 66845 AU) or greater, the outflows take on the form of broad diffuse lobes of high-velocity emission, these lobes are likely gas swept up and accelerated by the highly collimated jets. Observations of bipolar outflows are commonly used to study the early stages of star formation, as they can provide important insights into physical processes involved in

the accretion of material onto protostars and the feedback mechanisms which regulate the star formation process.

2.5.7 Relationship between episodic accretion and disc instabilities

Episodic accretion is characterized by periods of intense accretion or accretion bursts followed by periods of quiescence (Meyer et al., 2017, 2021). Accretion bursts impact the evolution of protostars; when there is a sudden increase in accretion a large fraction of the protostellar envelope will be covered by a dense hot shell of accreting material which inhibits radiation and cooling of the material prior to it being added to the star (Kley and Lin, 1996; Kuffmeier et al., 2018). The sudden influx of material onto the star and increase in heat disrupts the equilibrium dominating the stellar dynamics (Geroux et al., 2016; Jensen and Haugbølle, 2018; Kuffmeier et al., 2018). Numerical hydrodynamics simulations of primordial disc formation have revealed that accretion bursts can be caused by gravitational fragmentation of the disc followed by the rapid accretion of these fragments onto the protostar (Meyer et al., 2017).

The accretion disc is subject to a number of instabilities, including the magneto-rotational instability, which can cause turbulence and the formation of clumps and spiral arms in the disk. These clumps and spiral arms can become gravitationally unstable if their mass exceeds a certain threshold, leading to their fragmentation into smaller objects. As the clumps or fragments migrate inwards towards the central protostar, they can trigger episodes of intense accretion (Caratti o Garatti et al., 2017). During these periods of intense accretion, the protostar can grow rapidly in mass and luminosity. However, the intense radiation and outflows generated by the protostar during these periods of intense accretion can also disrupt the surrounding accretion disk, creating gaps and cavities in the disk and temporarily halting the accretion process. Episodic accretion is thought to be a common feature of the early stages of star formation, especially for high-mass stars, which are believed to form via rapid accretion (Meyer et al., 2021). The episodic nature of accretion can have important implications for the evolution of protostars and for the formation of planetary systems (Meyer et al., 2021).

Chapter 3

Astronomical Masers

The goal of this chapter is to provide an introduction and outline to astronomical masers; included in this section is an introduction to the environmental conditions which lead to maser formation, intrinsic properties of masers, a closer look into methanol masers which are of particular interest in this research project. We will also look into some open questions surrounding this area of research, such as driving mechanisms behind maser variability, periodic maser variability, which has been observed in methanol maser sources, and velocity drifts, which are more recent questions of interest in the field.

3.1 Introduction

Microwave amplification by stimulated emission of radiation, MASER, is a naturally occurring phenomenon in numerous astrophysical environments (Gray, 2012; Elitzur, 1992). Masers are sources of intense, coherent, narrow beams of electromagnetic radiation, in the radio or microwave band of the electromagnetic spectrum (Gray, 2012). There are several different molecular species which are known to constitute interstellar masers; known maser molecules include silicon monoxide (SiO), hydroxyl (OH), hydrogen cyanide (HCN), ammonia (NH₃), water (H₂O), formaldehyde (CH₂O), and methanol (CH₃OH) (Gray, 2012). Hydroxyl, methanol, formaldehyde, and water masers are associated with star-forming regions (Ellingsen, 2006). Methanol is the most complex maser molecule known to date; methanol has six constituent atoms and over thirty known maser transitions. Masers can often be utilised as diagnostic tools with a high degree of accuracy due to their distinctive characteristics, such as: compact size, high luminosity, polarised radiation, persistence over long periods, and molecular properties such as spectral lines and Zeeman splitting (Gray, 2012; Elitzur, 1992). Masers often show some degree of variability, which is intrinsically linked to their surrounding environment (Cragg et al., 2005); this characteristic makes masers good tracers of environmental properties which would otherwise be challenging to observe.

3.2 Radiative Transfer

Prior to entering the world of masers, some background on radiative transfer is needed. Radiative transfer is the study of the propagation of electromagnetic radiation through a medium and the interactions which arise as a result. This section follows from discussions presented by [Wilson et al. \(2009\)](#), [Burke et al. \(2019\)](#), [Carroll and Ostlie \(2017\)](#), [Emerson \(1998\)](#), [Elitzur \(1992\)](#), [Sutton \(2011\)](#), [Flower \(2007\)](#), [Pannuti \(2020\)](#), and [Gray \(2012\)](#). In free space the intensity of electromagnetic radiation I_ν will remain constant as it traverses a distance; however, if the radiation passage is not through free space its intensity will be altered through interactions such as absorption, emission and scattering by the medium. If we consider cool molecular gases, $T_{\text{gas}} \leq 100$ K, surrounding a luminous stellar source, photons emitted in the stellar environment can excite atoms or molecules¹ in the surrounding environment to higher energy levels, this process is known as radiative pumping. Over time the atoms will decay to lower energy levels and photon emission will occur. In order for a maser to form the following environmental conditions must be met: sufficient density of atoms or molecules capable of maser action, population inversion where more maser molecules are in an excited energy state than in the ground state energy level, a pumping mechanism such as a stellar source which provides stimulating photons, and velocity coherence along the line-of-sight. In a state of local thermal equilibrium (LTE) a maser cannot form as the probability of absorption is equivalent to the probability of emission and therefore the majority of molecules will be found in their ground state.

3.2.1 Emission, Absorption and Einstein Coefficients

The Boltzmann distribution describes the statistical distribution of energy levels among particles in a system in LTE. Consider a molecule with energy levels 1, 2, 3, ... such that $E_1 < E_2 < E_3 < \dots$ and the population densities of the energy levels are $n_1, n_2, n_3, \dots$; in thermal equilibrium at temperature T , the population densities of the energy levels are described by a Boltzmann distribution,

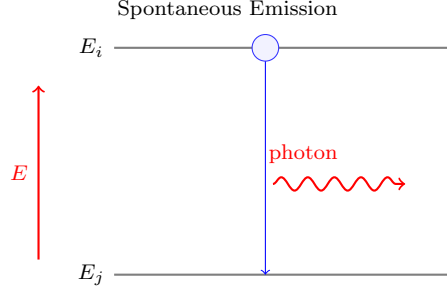
$$\frac{n_2/g_2}{n_1/g_1} = \exp \left[-\frac{(E_2 - E_1)}{k_B T} \right], \quad (3.1)$$

where g refers to the statistical weight or degeneracy of an energy level, k_B is the Boltzmann constant, and n/g is the population density within a degenerate sub-state. When electromagnetic radiation interacts with atoms and molecules, transitions between the constituent energy levels are induced. Transitions between energy levels are due emission and absorption of photons.

Spontaneous emission occurs when an atom in an excited state spontaneously drops to a lower quantum energy state and releases a photon in the process. The photon energy will be equivalent to the energy difference between the two energy levels, i.e., $E_\gamma = h\nu = E_i - E_j$,

¹Henceforth in this chapter, I will refer to either atoms or molecules for ease of reading; however, these words are being used interchangeably and in reference to both atoms and molecules.

where $E_j < E_i$. Einstein coefficients describe the rates at which photons are absorbed and emitted by the atoms or molecules in a system. Einstein coefficients are macroscopic approximations of these processes, therefore they do not describe what processes are occurring in an individual atom within a system, but rather the behaviour of the overall system.



We wish to describe the spontaneous transition of an atom from levels j to i assuming that $E_j < E_i$. Considering a system where the number of atoms in an excited state E_i is equal to n_i at time t . Considering the change of n_i as a function of time; the change in n_i equals the number of excited atoms at $t = 0$ multiplied by a factor which describes the decrease in n_i as the atoms decay from energy level E_i to energy level E_j , this factor is the Einstein coefficient A_{ij} . Mathematically this process is written as,

$$\frac{dn_i}{dt} = -n_i A_{ij}, \quad (3.2)$$

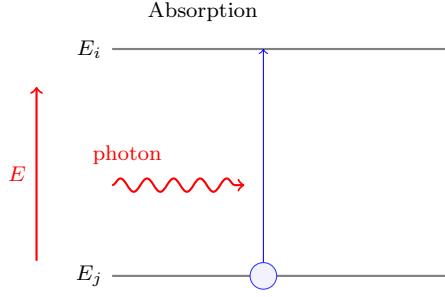
and simplified as follows,

$$\begin{aligned} \frac{dn_i}{dt} &= -n_i A_{ij} \\ \Rightarrow \frac{1}{n_i} dn_i &= -A_{ij} dt \\ \Rightarrow \ln(n_i) &= -A_{ij} t + C \\ \Rightarrow n_i(t) &= n_i(t_0) \exp(-A_{ij} t). \end{aligned}$$

The Einstein coefficient A_{ij} describes how readily an atom will de-excite. If A_{ij} is large the atom will decay faster, i.e., the atom will have a shorter half-life. Coefficient A_{ij} therefore has the unit $[s^{-1}]$ and can be written as the inverse of a characteristic time τ which is intrinsic to a transition, i.e., $A_{ij} \equiv \frac{1}{\tau}$ and the number of excited atoms can be written as,

$$n_i(t) = n_i(t_0) \exp(-t/\tau). \quad (3.3)$$

Absorption occurs when an atom is excited by a stimulating photon to a higher allowed quantum state; the approximate photon energy, E_γ , is equal to the energy difference between the two energy levels, i.e., $E_\gamma = h\nu = E_i - E_j$, where $E_j < E_i$. The rate at which absorption can take place is proportional to the intensity of incoming photons.



The line profile function $\phi(\nu)$ governs the width of the transition which an atom can have; broadening affects the necessary photon energy of the transition. Therefore the photon energy does not need to be exactly the theoretical $h\nu$ value; the line profile function describes the susceptibility of the transition occurring when in the presence of a stimulating photon. Therefore the transition rate is proportional to the intensity of incoming photons I_ν , from all directions Ω , multiplied by the line profile function, i.e., rate $\propto 1/4\pi \int \int I_\nu d\Omega \phi(\nu) d\nu = \bar{J}$. The Einstein coefficient B_{ji} describes the probability of absorption occurring. The change in the number of excited atoms n_i as a function of time is given by the number of available atoms in the lower energy level n_j , multiplied by the probabilistic variable B_{ji} , multiplied by the intensity of photons coming from all directions $\bar{J}$. Mathematically this is written as,

$$\frac{dn_i}{dt} = n_j B_{ji} \bar{J}. \quad (3.4)$$

Similarly, as with emission, absorption transitions happen at the expense of atoms in the lower energy level n_j . Therefore the change in the number of atoms in the lower energy level is as follows,

$$\frac{dn_j}{dt} = -n_j B_{ji} \bar{J}. \quad (3.5)$$

A high density of stimulating photons will excite atoms to higher energy levels; if there are more atoms or molecules in the excited energy state than the ground or less excited state *population inversion* has occurred, see figure 3.1. Population inversion is a prerequisite for maser emission to occur.

Thermal equilibrium implies that the number of atoms entering the excited state must be equal to the number of atoms leaving the excited state, i.e., $n_i A_{ij} = n_j B_{ji} \bar{J}$. In local thermal equilibrium (LTE) the intensity of incoming photons is given by the Plank function,

$$\bar{J} = B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT_P) - 1}, \quad (3.6)$$

where T_P is the thermodynamic temperature. Assuming LTE, substituting both the Boltzmann distribution and the Plank function into $n_i A_{ij} = n_j B_{ji} \bar{J}$ reveals that the functional forms of the left-hand side and right-hand side of the equation are not compatible; from this Einstein drew the conclusion that a B_{ij} coefficient must exist. This assumption turned out

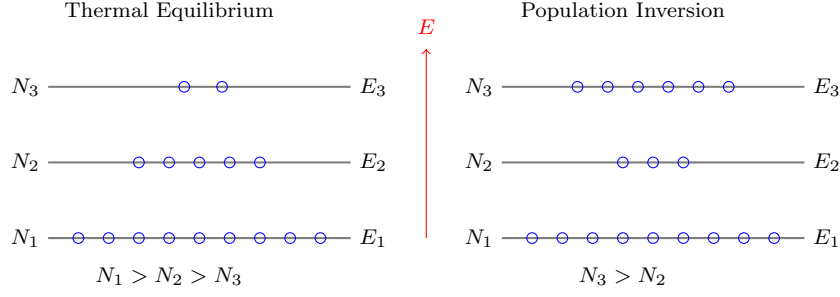
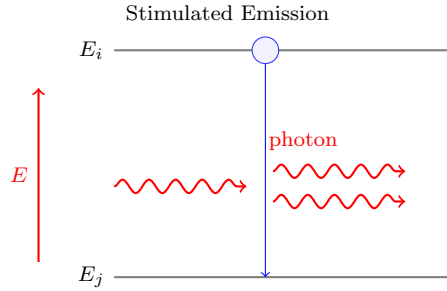


Figure 3.1: The figure schematically displays the difference between the population density in three levels of a hypothetical atom or molecule. On the left a normal distribution which would be seen in thermal equilibrium is shown; in thermal equilibrium the greatest population of electrons in the lowest energy level E_1 and the population densities decrease as the energy levels increase. On the right a hypothetical distribution which represents the concept of population inversion is shown. Here the population of energy level E_3 is larger than the population of energy level E_2 despite the respective energy level value of E_3 being larger than that of E_2 . Population inversion is not possible in the case of thermal equilibrium.

to be correct and brings us to the following discussion on stimulated emission.

Stimulated emission occurs when an atom in an excited state is prompted to de-excite by a stimulating photon of approximate energy E_γ . The de-excitation will prompt a photon of energy E_γ to be emitted, i.e., the system has gone from possessing a single photon of energy E_γ to possessing two photons of energy E_γ . This is the crux of maser and laser emission, the number of photons with approximately equal energies and directions are increased through stimulated emission, hence highly directional monochromatic radiation is observed.



Mathematically, stimulated emission is closely correlated with absorption; the rate of stimulated emission is proportional to the radiation field described by $\bar{J}$ multiplied by the Einstein coefficient for stimulated emission B_{ij} . Einstein therefore proposed that the rate equation $n_i A_{ij} = n_j B_{ji} \bar{J}$ was incomplete without the inclusion of stimulated emission. The rate equation is therefore given by,

$$n_i A_{ij} = n_j \bar{J} B_{ji} - n_i \bar{J} B_{ij}. \quad (3.7)$$

Therefore in LTE it follows that the radiation field can be written as,

$$\bar{J} = \frac{A_{ij}}{\frac{n_j}{n_i} B_{ji} - B_{ij}}.$$

Substituting in the Boltzmann equation yields,

$$\bar{J} = \frac{A_{ij}/B_{ji}}{\frac{g_j}{g_i} \exp\left(\frac{E_i - E_j}{kT}\right) - B_{ij}/B_{ji}}. \quad (3.8)$$

In an LTE system the radiation field $\bar{J}$ must be equivalent to the Plank distribution and from this the Einstein relations can be determined,

$$g_j B_{ji} = g_i B_{ij}, \quad (3.9)$$

$$A_{ij} = \frac{2h\nu^3}{c^2} B_{ij}. \quad (3.10)$$

3.2.2 Radiative Transport equation

The following section draws largely from discussions in [Wilson et al. \(2009\)](#) and [Burke et al. \(2019\)](#). Considering an astrophysical region emitting radiation of intensity I_ν , the radiation travels through an intervening medium such as a cloud of gas prior to reaching Earth where it is recieved and measured. Specific intensity I_ν has units of energy E per unit time s per unit frequency Hz per unit steradian sr, per unit collecting area of the telescope m^2 , i.e., $J s^{-1} Hz^{-1} sr^{-1} m^{-2}$. In free space radiation intensity will not be influenced as it traverses across a distance, i.e., emission and absorption are both zero in free space, $\kappa_\nu = 0$, $\epsilon_\nu = 0$. If we are not considering free space the specific intensity change through processes of emission, absorption and scattering. The influence on intensity is described by the radiative transport equation,

$$\frac{dI_\nu}{ds} = \epsilon_\nu - \kappa_\nu I_\nu. \quad (3.11)$$

In the radiative transport equation the first term represents the change in intensity due to emission while the second term dictates the change in intensity due to absorption, scattering, and stimulated emission. In summary ϵ_ν is the emission coefficient and κ_ν is the absorption coefficient. Each system making a transition from E_i to E_j contributes energy $h\nu_{ij}$ over a solid angle. The specific emissivity ϵ_ν represents the power emitted per unit volume, per frequency interval, per steradian; equivalently ϵ_ν is the specific intensity as a function of distance through the medium and has the units $W m^{-3} Hz^{-1} sr^{-1}$. Specific emissivity can be written as,

$$\epsilon_\nu = \frac{dE}{\Omega d\nu dt dV}. \quad (3.12)$$

The power added within the solid angle Ω is equivalent to $\epsilon_\nu d\nu d\sigma ds \Omega$. Attenuation of specific intensity is described by the linear absorption coefficient κ_ν which dictates the fraction of power loss as the radiation passes through the distance. Power attenuated within the solid

angle Ω is $\kappa_\nu I_\nu d\nu d\sigma ds \Omega$. In order to write the radiative transport equation as well as the emission and absorption coefficients in terms of the Einstein coefficients, we begin by defining the influence spontaneous emission, absorption, and stimulated emission have on the energy of a system.

The total amount of energy emitted *spontaneously* is,

$$dE_e(\nu) = h\nu_0 n_2 A_{21} \phi_e(\nu) dV \frac{d\Omega}{4\pi} d\nu dt. \quad (3.13)$$

The total amount of energy *absorbed* is,

$$dE_a(\nu) = h\nu_0 n_1 B_{12} \frac{4\pi}{c} I_\nu \phi_a(\nu) dV \frac{d\Omega}{4\pi} d\nu dt. \quad (3.14)$$

The total energy emitted by *stimulated emission* is,

$$dE_s(\nu) = h\nu_0 n_2 B_{21} \frac{4\pi}{c} I_\nu \phi_e(\nu) dV \frac{d\Omega}{4\pi} d\nu dt. \quad (3.15)$$

In astrophysics it is usually acceptable to assume that the line profile of the emitted and absorbed radiation are the same, i.e., $\phi(\nu) = \phi_a(\nu) = \phi_e(\nu)$. The volume element is given by $dV = d\sigma ds$, where $d\sigma$ is the unit area perpendicular to the beam direction and ds is the distance through which the radiation will propagate. The energy contributions of emission and absorption can be related to the flux density. Flux density is given by,

$$S_\nu \equiv dE/dAd\nu dt. \quad (3.16)$$

Considering a stationary situation and the energy contributions of spontaneous emission, absorption, and stimulated emission,

$$\begin{aligned} dE_e(\nu) + dE_s(\nu) - dE_a(\nu) &= dI_\nu d\Omega d\sigma d\nu dt \\ \Rightarrow \frac{h\nu_0}{4\pi} \left[n_2 A_{21} + n_2 B_{21} \frac{4\pi}{c} I_\nu - n_1 B_{12} \frac{4\pi}{c} I_\nu \right] \phi(\nu) d\Omega d\sigma ds d\nu dt &= dI_\nu d\Omega d\sigma d\nu dt. \end{aligned} \quad (3.17)$$

Therefore, the radiative transfer equation written in terms of the Einstein coefficients as follows,

$$\frac{dI_\nu}{ds} = -\frac{h\nu_0}{c} (n_1 B_{12} - n_2 B_{21}) I_\nu \phi(\nu) + \frac{h\nu_0}{4\pi} n_2 A_{21} \phi(\nu). \quad (3.18)$$

Comparing the above with equation 3.11, the absorption and extinction coefficients can be defined in terms of the Einstein coefficients. The absorption coefficient can be written as,

$$\kappa_\nu = \frac{h\nu_0}{c} n_1 B_{12} \left(1 - \frac{n_2 g_1}{n_1 g_2} \right) \phi(\nu). \quad (3.19)$$

Similarly, the emission coefficient is determined as,

$$\epsilon_\nu = \frac{h\nu_0}{4\pi} n_2 A_{21} \phi(\nu). \quad (3.20)$$

3.2.3 Population inversion

Population inversion is a prerequisite for maser emission. In this section population inversion is described in the context of the radiative transport equation and the absorption coefficient. Considering the radiative transport equation in the case where we only have absorption, i.e., $\epsilon_\nu = 0$,

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu. \quad (3.21)$$

If $\kappa_\nu > 0$, radiation is attenuated as it traverses a distance s . If $\kappa_\nu < 0$, the intensity of radiation is amplified over a distance s . Therefore, radiation intensity increases in the case of a negative absorption coefficient; it follows that, if the absorption coefficient is negative stimulated emission occurs. Considering the absorption coefficient κ_ν , defined by equation 3.19, population inversion will occur if κ_ν is negative, i.e., if $(g_i/g_j)(n_j/n_i) > 1$.

3.2.4 Optical depth

The following discussion draws largely from Wilson et al. (2009), Pannuti (2020), and Elitzur (1992). Optical depth describes the degree to which a medium, such as dust or gas, attenuates electromagnetic radiation as the radiation propagates through the medium. It is a measure of the medium's opacity to a specific wavelength of radiation. Optical depth, τ_ν , is typically described as the natural logarithm of the incident radiation intensity to the transmitted radiation intensity,

$$\tau_\nu = -\ln \left(\frac{I_{\text{transmitted}}}{I_{\text{incident}}} \right). \quad (3.22)$$

Optical depth is a dimensionless quantity, if $\tau > 0$ then the transmitted intensity is less than the incident intensity. If $\tau = 0$, then the medium is transparent to the radiation, and the transmitted intensity is equal to the incident intensity. Finally, if $\tau < 0$, then the medium is amplifying the radiation and the transmitted intensity is greater than the incident intensity. In thermodynamic equilibrium there is an equilibrium between the radiation and its surroundings. The brightness distribution is described by the Planck function, see equation 3.6, which is solely dependent of the surrounding temperature T . Therefore in thermodynamic

equilibrium,

$$\frac{dI_\nu}{ds} = 0, \quad I_\nu = B_\nu(T) = \frac{\epsilon_\nu}{\kappa_\nu}.$$

In local thermodynamic equilibrium Kirchoff's Law relates $B_\nu(T)$ to ϵ_ν and κ_ν as follows,

$$B_\nu(T) = \frac{\epsilon_\nu}{\kappa_\nu},$$

since Kirchoff's Law of Thermal Radiation, states that at thermal equilibrium an object which is perfect absorber of radiation is also a perfect emitter of radiation at the same wavelength. Optical depth is defined as, $d\tau_\nu = -\kappa_\nu ds$. Therefore the radiative transport equation can be written as,

$$-\frac{1}{\kappa_\nu} \frac{dI_\nu}{ds} = \frac{dI_\nu}{d\tau_\nu} = I_\nu - B_\nu. \quad (3.23)$$

Solving for the above equation,

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} B_\nu(T(\tau)) e^{-\tau} d\tau. \quad (3.24)$$

If the medium isothermal then temperature is constant throughout the medium,

$$T(\tau) = T(s) = T = \text{constant},$$

and the integral can be determined explicitly as,

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T) \left(1 - e^{-\tau_\nu(s)}\right) \quad (3.25)$$

In LTE for a large optical depth, i.e., in the limit $\tau_\nu \rightarrow \infty$,

$$I_\nu = B_\nu. \quad (3.26)$$

Therefore in the optically thick case the observed brightness I_ν is equal to the Plank black-body brightness distribution independent of the material. This behavior is a result of the material being in thermal equilibrium. When a medium, such as an interstellar cloud, is optically thick, the cloud will be highly opaque to radiation, as a result photons emitted within the cloud will be scattered or absorbed before they can escape the medium. Consequently, radiation in the medium comes into thermal equilibrium, with the temperature becoming

uniform throughout the medium.

3.3 Maser Emission

The following section on maser emission follows discussions in [Burke et al. \(2019\)](#), [Gray \(2012\)](#), [Emerson \(1998\)](#), [Pannuti \(2020\)](#), and [Carroll and Ostlie \(2017\)](#). For molecules to form a maser, the following environmental conditions must be met: sufficient density of atoms or molecules capable of molecular excitation, a pumping mechanism, and velocity coherence along the line of sight. The pumping mechanism refers to an external source of photons, such as a stellar object, capable of providing sufficient energy to produce population inversion in the maser molecules and consequently allow masing to occur. Molecules can also be excited through collisions with other atoms and molecules; this is termed collisional excitation. Henceforth pumping will only be discussed in the radiative scheme as it is more relevant to the contents of this research.

In order to better understand maser pumping, the following environmental conditions are considered. Suppose the astrophysical environment is in thermal equilibrium. In that case, masers will not occur since the probability of induced absorption is equivalent to the probability of induced emission. Population density of the lower energy levels will exceed the higher levels; thus, induced absorption predominates over induced emissions, and masing will not be observed. Thermodynamic equilibrium in interstellar environments tends to be an exception rather than a rule; therefore, we consider a state of non-thermal equilibrium.

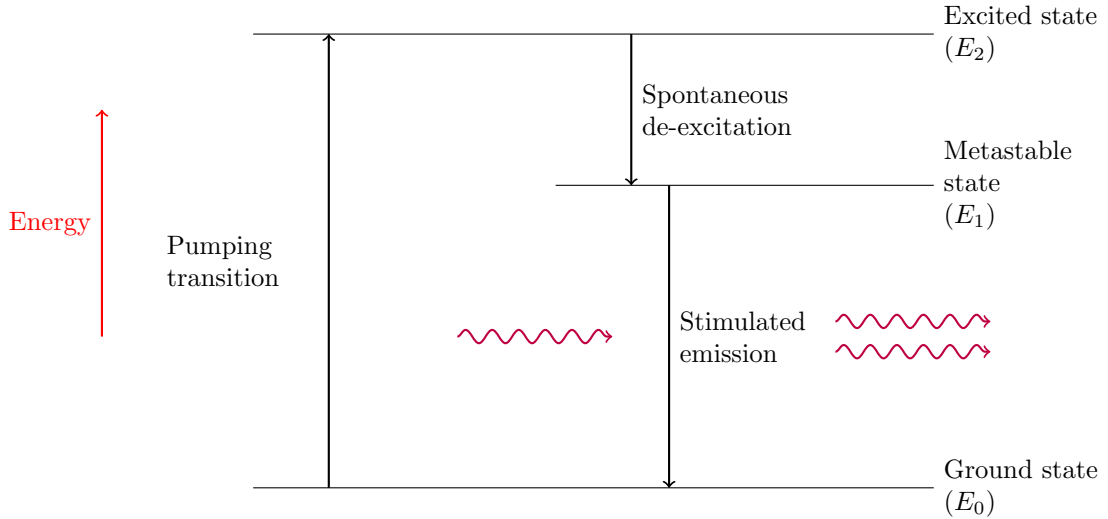


Figure 3.2: Energy level diagram of a hypothetical three-level maser; the ground state E_0 is the lowest energy level at which an electron can populate, and the metastable stable state E_1 provides a route for depopulation to the ground state. Figure adapted from [Zeilik and Gregory \(1998\)](#).

In a state of non-thermal equilibrium, population inversion can now occur, and induced emission transitions can predominate over absorption. Such a system is characteristic of a maser. As previously stated, masers require a pumping mechanism to maintain population inversion; the pumping mechanism must constitute a temperature or energy greater than the difference in the energy level pair corresponding to the maser transition. The source

pumping radiation will likely originate from the central star (Goedhart et al., 2007). Molecules can not remain indefinitely in their excited state but will decay through spontaneous or stimulated emission. When maser molecules are prompted to de-excite, they emit radiation of a consistent energy $E=h\nu$ and frequency ν , which we observe as an amplifying of microwave radiation.

Considering the schematic diagram of a three-level maser in figure 3.2. A molecule may be excited from the ground energy level E_0 to the excited state with energy E_2 by absorbing energy from the photon. Once the molecule is in the excited state E_2 it is more likely to de-excite to the metastable state E_1 than the ground state E_0 ; therefore, a large number of molecules are pumped and settle in the metastable state E_1 . Masing can occur if the relatively long-lived metastable state, E_1 , has a population exceeding the population of the ground level E_0 , i.e., population inversion has occurred. The excited state, level E_2 , provides a route for depopulation of level E_0 , and a route for population of level E_1 . Transitions from the metastable state E_1 to ground state E_0 occur by means of stimulated emission; the stimulating photon has an energy approximate to the energy difference between the two states, $E_\gamma = h\nu = E_1 - E_0$. The molecule will de-excite by emitting a photon with an approximate energy of E_γ , this process is termed stimulated emission. According to this sequence of events, the original photon may be amplified into many photons propagating through the gas; therefore, maser radiation is observed as very intense, narrow in direction and, singular in frequency.

3.3.1 Maser Saturation

Maser intensity will not continue to increase indefinitely as a function of time; maser saturation refers to a state where a maser produces the maximum amount of amplified radiation possible for that specific maser source (Gray, 2012; Elitzur, 1992). When the rate of induced emission is comparable to the intrinsic rates determining population inversion radiative interactions will affect level populations (Elitzur, 1992). There is an excess of induced emissions over absorptions and the inversion decreases. Although population inversion and amplification are reduced by saturation the net stimulated emission rate will increase linearly towards a limit (Elitzur, 1992). It is important to note that the reduced growth rate of maser emission and decrease in population inversion does not indicate a reduced efficiency of the maser. Saturation reflects the highest efficiency possible for any pumping scheme and a saturated maser will always emit more than an unsaturated maser (Elitzur, 1992). Saturation is an essential characteristic of masers as it sets an upper limit to maser output or gain (Gray, 2012; Sobolev et al., 1997).

3.4 Observations of Masers in Massive Star-Forming Regions

Maser emission is emitted from individual maser spots; whilst often found in groups, individual maser spots each have their own well-defined velocity. Definitions for maser spot and maser cloudlet follow from Sanna et al. (2017): a maser spot is a compact region of emission

with typical sizes in the milliarcsecond range; a maser cloudlet or feature is a gas condensation composed of a cluster of maser spots adjacent in both space and velocity. The following section draws from discussions in [Gray \(2012\)](#) and [Elitzur \(1992\)](#). In star-forming regions, masers are observed in numerous locations; water and methanol maser emission are found in outflows and circumstellar discs around high-mass stellar objects. HII regions and shock fronts also host maser species.

As previously discussed, HII regions expand via expanding ionisation and shock fronts, see figure 2.1. It is possible that the cool dense region between the ionisation and shock fronts provide a suitable zone for maser formation, specifically OH masers. Velocity coherence would be provided by the bulk motion of expansion. In this situation masers may have linear or arc-like arrangements. Water masers are fundamentally associated with shocks, and class I methanol masers are associated with outflow shocks in star forming regions, unlike MMHs which are associated with HII regions. Since water and class I methanol masers tend to be found, almost exclusively, in sources without HII regions they are thought to be associated with an earlier stellar evolutionary stage than OH and Class II methanol masers.

Another probable location for masers is within circumstellar discs; this hypothesis was proposed by [Norris et al. \(1993\)](#) and [Norris et al. \(1998\)](#). Velocity coherence for maser emission will stem from the rotation of the sufficiently dense material in the disc. In this case it would be preferable that masers are observed edge-on since the column density will be higher and an edge on observation will have less optically thick regions through which maser emission must pass, i.e., observations of masers are more likely in this scheme than in a perpendicular observation. Milliarcsecond imaging has shown that 6.7 GHz methanol masers are often associated with the regions between the protostellar disk and envelope in a star forming region; the masers typically have distances of ~ 1000 AU from the protostar with individual maser cloudlet sizes of ~ 10 AU ([Goddi et al., 2011](#); [Bartkiewicz et al., 2016](#)). Outflows are ubiquitous with high mass star formation ([Beuther et al., 2002](#)), since if massive stars form via disc accretion, which we believe they do, then massive and powerful outflows are necessary to transport momentum away from the forming star. Water and methanol masers are associated with the same stellar evolutionary phase when outflows are present ([Codella et al., 2004](#); [Minier et al., 2000](#); [Li et al., 2016](#)).

3.5 Methanol

The following discussion on methanol as an interstellar molecule follows discussions in [Flower \(2007\)](#) and [Gray \(2012\)](#). Molecules have intrinsic forms of energy: electronic, rotational, and vibrational. The rotational energy is due to the bodily rotation of the molecule about the centre of mass, and the vibrational energy is due to the periodic displacement of atoms within a molecule from their equilibrium positions. Methanol maser emission associated with more than forty different rotational transitions has been detected ([Müller et al., 2004](#)). Methanol exhibits population inversion, lending itself to maser action. Methanol is the most complex maser molecule currently known and studied, containing six constituent atoms, see figures 3.3 and 3.4. Methanol has been observed in numerous millimetre and sub-millimetre transitions

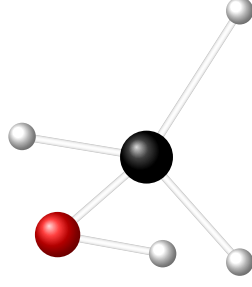


Figure 3.3: Structure of methanol molecule. The diagram makes use of standard CPK color assignments, i.e., oxygen is denoted by red, carbon by black, and hydrogen by white.

within dark molecular clouds. The fractional abundance of methanol in dark molecular clouds, relative to molecular hydrogen, is of the order 10^{-9} ; in environments surrounding high-mass protostellar objects, the fractional abundance of methanol can reach the order of 10^{-6} . Dust found in star-forming regions is ISM dust, i.e., the dust does not originate from the star-forming region; however, the dust is processed within the star-forming region. During the hot-core stage, icy grain mantles are evaporated, releasing numerous molecules in their gaseous phase. Grain-surface reactions are crucial in the production of methanol; methanol forms over time on the icy grain surface and is eventually released as a gas. Molecules can also be released through grain-grain collisions or shock wave-induced sputtering. Sputtering refers to atoms or molecules being released from solid materials due to energetic particles bombarding the solid, often a result of shock waves propagating through the interstellar medium. Methanol is typically found alongside dust condensation since the temperature at which methanol is evaporated, $\sim 100 - 300$ Kelvin, is below the dust sublimation temperature ~ 1500 Kelvin (Sanna et al., 2017). In section 3.7 the importance of the presence of dust in producing 6.7 GHz methanol masers is discussed.

Methanol is a non-linear polyatomic molecule with $3N - 6 = 12$ vibrational modes. Methanol has a near-symmetric top which exhibits internal torsion motion of the CH_3 group relative to the OH group, i.e., methanol is a non-rigid molecule, and the methyl group of the molecule displays internal rotation with respect to the hydroxyl group. See figure 3.4, which presents the general structure of a molecule. The complex structure of the molecule is reflected in the richness of its spectrum; over 30 methanol maser transitions have been observed. Two very distinct types of methanol exist; the non-degenerate A-type methanol and the degenerate² E-type methanol (Sobolev et al., 1997). The two distinct types of methanol result from two different nuclear spin states resulting from the net spin of three protons of the CH_3 group. The three protons of the CH_3 group may display parallel (ortho-) or anti-parallel (para-) spins; these spin states can inter-convert only by proton exchange reactions. In A-type methanol, the total spin is $I = 3/2$ and in E-type methanol, the total spin is $I = 1/2$. The A- and E- methanol species can be referred to by the quantum number σ ; 0 corresponding to A and ± 1 to E. The nuclear spin degeneracy ($2I + 1$) is 4 for A-type methanol and 2 for E-type methanol; however, the E-type methanol has two degenerate forms bringing the number

²In a quantum mechanical context, a degeneracy level refers to an energy level, within a quantum system, which has multiple, i.e., more than one, different measurable states. The number of measurable states which correspond to a distinct energy level is the degree of degeneracy. The degeneracy is represented by the Hamiltonian having more than one linearly independent eigenstate with the same energy eigenvalue (Tipler and Llewellyn, 2012).

of states to 4 as well. Since the two methanol species have different transition frequencies and may arise in different physical environments, they are typically analysed separately in research. Section 3.9 discusses further how spin and degeneracy contribute to observations such as hyperfine structure and Zeeman splitting in molecular source spectra.

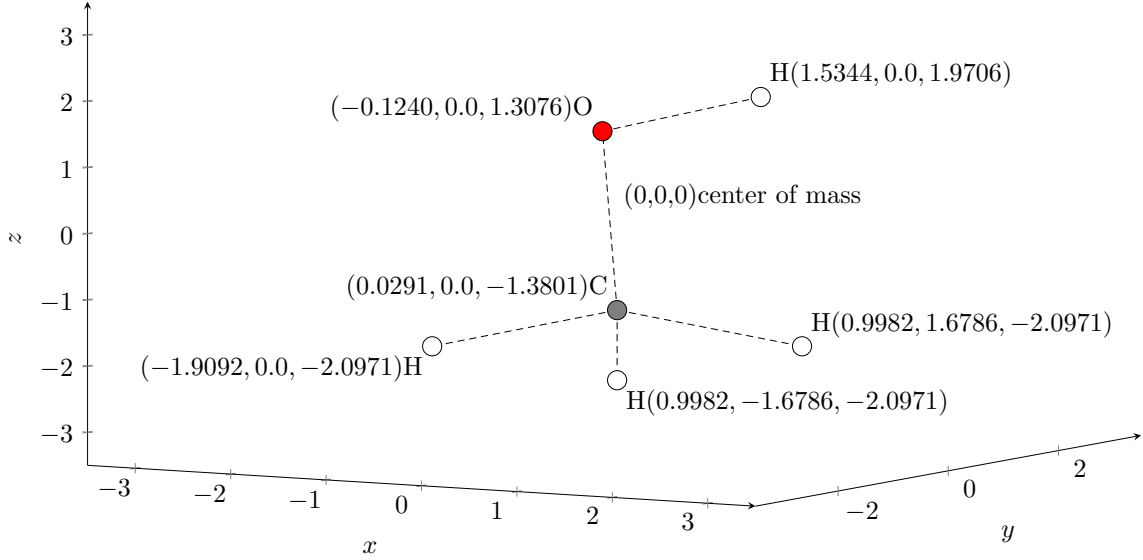


Figure 3.4: Defining the body-fixed coordinate system of methanol (CH_3OH), this figure made reference to a figure presented in Flower (2007). This figure shows the composition of a methanol molecule where we can see the almost symmetric composition of hydrogen atoms and overall asymmetric composition of the molecule.

3.6 Methanol Masers

Methanol masers were originally observed towards sites of active star formation; the first transition observed was the 25 GHz transition observed towards Orion-KL by Barrett et al. (1971). Batrla et al. (1987) and Menten (1991) discovered two of the brightest methanol maser transitions at 12.2 GHz and 6.7 GHz, respectively. Batrla et al. (1987) was the first to introduce a classification system for methanol masers. Methanol masers are classed based on their pumping mechanisms (Menten, 1991). Class I methanol masers (MMIs) are collisionally pumped and are predicted to trace shocked gas; MMIs are offset from ultra-compact (UC) HII regions and are likely associated with protostellar outflows and expanding HII regions (Chen et al., 2020; Stahler and Palla, 2008). Class II methanol masers (MMIIs) are radiatively pumped and found close to compact HII regions; 6.7 GHz methanol masers are a class II maser which is exclusively associated with high-mass star-forming environments (Cragg et al., 1992). Unlike MMIs which tend to be significantly spatially removed from the driving source, MMIIs arise in close vicinity to the high-mass protostellar object (Menten, 2012).

3.6.1 Class I Methanol Masers

Class I methanol masers (MMIs) are collisionally pumped and associated with the very early stages of high-mass star formation, often predating HII regions (Gray, 2012). MMIs are associated with environments and phenomena where shocks compress and heat gas; these environments include supernova remnants (Plambeck and Menten, 1990; Pihlström et al., 2014), protostellar outflows (Cyganowski et al., 2017), and expanding HII regions (Voronkov et al., 2010). MMIs are observed at 36, 44, and 95 GHz frequencies. Early star-forming region (SFR) masers, such as MMIs, are associated with shocks which stem from the bipolar outflows associated with a massive young stellar object (YSO); the expanding HII region often destroys bipolar outflows at an earlier evolutionary stage than the circumstellar disks where later stage masers, such as MMIIIs, are often found (Gray, 2012). MMIs are more numerous than MMIIIs as they have lower temperature and density requirements to form (Sanna et al., 2017; Menten, 2012). Often widely scattered in star-forming regions, MMIs can have linear separation of up to one parsec (Voronkov et al., 2014). Spectral lines associated with MMIs are often studied at 36.1 GHz ($4_{-1} - 3_0$ E) and 44.0 GHz ($7_0 - 6_1$ A⁺). Masers at 36.1 GHz often become quenched as HII regions form and surrounding gas temperature increases. Weak MMIs at 44 GHz, 84 GHz and 95 GHz have been detected towards low-mass protostellar objects and are likely associated with red- and blue-shifted jets of associated bipolar outflows (Kalenskii et al., 2006; Gray, 2012).

3.6.2 Class II Methanol Masers

Class II methanol masers (MMIIIs) are radiatively pumped and are exclusively associated with high-mass star formation (Ellingsen, 2006; Gray, 2012). Sufficiently evolved massive protostellar objects associated with HII regions are able to host MMIIIs (Gray, 2012). As stated above, these masers are radiatively pumped by far-infrared photons which originate from the protostellar object and are processed by dust in the surrounding environment (Olech et al., 2019; Urquhart et al., 2015; Gray, 2012); dust with the necessary properties to pump MMIIIs is known to reside in the vicinity of UCHII regions (Sobolev et al., 1997). The dust acts as a downward frequency converter absorbing ultra-violet radiation and re-radiating photons at characteristic frequencies corresponding to the dust temperature T_d (Gray, 2012). Class II masers are associated with submillimetre and millimetre dust continuum emission; the spectral energy distribution of dust emission is consistent with embedded high-mass young stellar objects (Pestalozzi et al., 2002; Walsh et al., 2003; Minier et al., 2005; De Buizer and Minier, 2005).

MMIIIs are often observed with well-defined, linear velocity gradients (Gray, 2012). If a maser is observed with a linear velocity gradient, the maser emission is shifting in frequency along a specific direction; this frequency shift corresponds to a shift in velocity of the masing gas, and indicates that the velocity is changing at a constant rate in the direction of the gradient (Bartkiewicz et al., 2009; Gray, 2012). Linear velocity gradients are associated with rotating discs and arise as a result of the rotation about a centre of gravity; the gas in the centre of the disc moves at a greater velocity compared to the gas further outward in the disc (Bartkiewicz

et al., 2009). A linear velocity gradient will be observed if the disc rotation is uniform (Gray, 2012).

3.7 6.7 GHz Methanol Masers

Methanol masers at 6.7 GHz, originally discovered by Menten (1991), are the brightest of class II methanol masers and have been found exclusively towards massive star-forming regions and are believed to be exclusively associated with high-mass stars, $M_{\text{star}} > 8 M_{\odot}$ (Breen et al., 2013; Gray, 2012) with a lower luminosity limit for the stellar source of $\sim 10^3 L_{\odot}$ (Bourke et al., 2005). The bright $5_1 - 6_0 A^+$ line at 6.7 GHz results from a transition in the A-type methanol isotope (Gray, 2012). Approximately a third of 6.7 GHz MMHs are associated with ultra-compact HII regions linking these maser emissions to younger stellar objects where ionisation processes are not yet fully developed (Hu et al., 2016). The 6.7 GHz methanol maser line is highly responsive to changes within the maser environment; therefore, changes in maser intensity are directly linked to changes in the surrounding star-forming environment (Goedhart, 2004; Gray, 2012; Breen et al., 2013). The 6.7 GHz methanol maser line is strong, widespread, and exclusively associated with the early stages of massive star formation (Breen et al., 2013); observations of these masers is an invaluable tool in the study of high-mass star formation. The 6.7 GHz methanol maser transition probes dense ($\rho \sim 10^4 - 10^8 \text{ cm}^{-3}$), cool ($T_{\text{gas}} < 150 \text{ Kelvin}$) gas (Sobolev et al., 1997; Cragg et al., 2005). Milliarcsecond imaging of known 6.7 GHz maser sources reveals that maser emission of this frequency frequently arises in the regions between the protostellar disc and envelope at a typical distance of $\sim 1000 \text{ AU}$ from the protostar; maser cloudlets have a typical size of $\sim 10 \text{ AU}$ (Goddi et al., 2011; Bartkiewicz et al., 2016; Sanna et al., 2017). The lifetime of a methanol maser is estimated to be in the range of $2 \times 10^4 - 5 \times 10^4$ years (van Der Walt, 2005; Billington et al., 2019); the estimated lifetimes are comparable to the chemical evolution timescale of methanol in hot cores and the dynamical ages of molecular outflows associated with HMYSOs (Szymczak et al., 2018a). Methanol masers typically display weak polarisation as one would expect from a non-paramagnetic molecule³ (Gray, 2012). Although weak, Zeeman splitting has been observed in the 6.7 GHz methanol maser line.

3.8 Line Profiles

The following section on line profiles and line broadening follows from discussions presented by Wilson et al. (2009), Tipler and Llewellyn (2012), Emerson (1998), Elitzur (1992), Flower (2007), and Gray (2012). The line profile function, often denoted as $\phi(\lambda)$, describes the distribution of the intensity of electromagnetic radiation emitted or absorbed by a medium at various frequencies by an atomic or molecular species which has discrete energy levels.

³Paramagnetism results from a molecule having unpaired electrons in its atomic or molecular orbitals; a non-paramagnetic (or diamagnetic) molecule has no unpaired electrons in its orbitals. Paramagnetic molecules can display zeeman splitting three orders of magnitude larger than non-paramagnetic molecules (Vlemmings, 2007) since the unpaired electrons in a paramagnetic molecule have individual magnetic moments which respond to external magnetic fields, shifting the energy levels associated with different spin orientations.

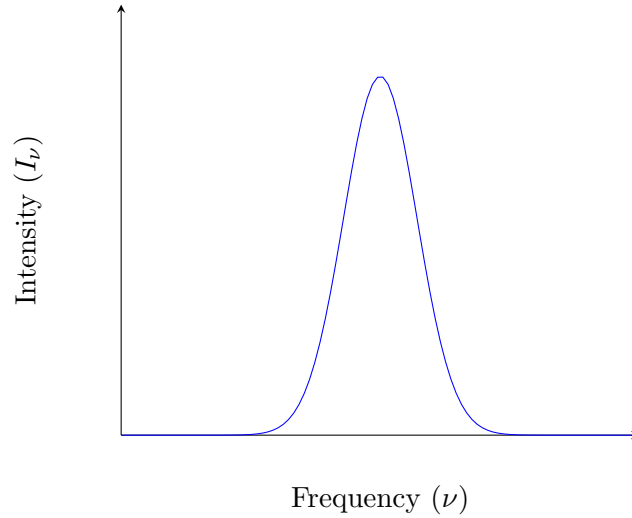


Figure 3.5: The figure shows a schematic representation of a line profile defined by a Gaussian function. This figure is a qualitative representation and does not represent a specific line profile or molecular transition.

Absorption and emission occur at specific frequencies corresponding to the energy differences between the molecular energy levels. These frequencies are termed spectral lines. The absorption and emission lines have a finite width as a result of several factors, which include the natural linewidth of the atom or molecule, Doppler broadening caused by the thermal motion of emitting or absorbing particles, and pressure broadening caused by collisions between the emitting and absorbing particles, as well as other particles in the medium. The line profile function describes the shape of this broadened spectral line as a function of frequency. The most common line profile functions include the Gaussian profile, the Lorentzian profile, and the Voigt profile each of which has a slightly different shape and arises under different conditions. The line profile function is an important concept in radiative transfer as it defines the amount of radiation absorbed or emitted by the medium as a function of frequency, which is crucial for understanding the energy balance and temperature structure of the medium.

3.8.1 Natural or radiation broadening

Natural broadening is a quantum mechanical effect produced by the finite lifetime of excited atomic levels. An atom in an excited state decays to a lower energy state via the spontaneous emission of a photon with energy E , after a certain time interval τ . However, due to the Heisenberg uncertainty principle, there is a limit as to how precisely both the energy of the photon and the lifetime of the excited state can be simultaneously known,

$$\Delta E \Delta t \sim \hbar. \quad (3.27)$$

Therefore, the lifetime of an excited state can not be precisely defined and can vary slightly between individual atoms and molecules. The variability of the lifetimes associated with an excited state results in a spread in the photon energies and frequencies, resulting in a broadened spectral line. For a transition from a state i to a state j , the emitted energy $E_i - E_j$

E_j will be uncertain by an amount,

$$\Delta E = \frac{\hbar}{\tau_j} + \frac{\hbar}{\tau_i}, \quad (3.28)$$

where τ_j and τ_i are the lifetimes of levels j and i respectively.

3.8.2 Collisional or Pressure broadening

Collisional or Pressure broadening is a type of broadening observed in atomic and molecular spectral lines as a result of interactions within a gas. Collisions between atoms and molecules, can shorten the characteristic time of a transition leading to a spread in photon energies and frequencies, resulting in a broadened spectral line. Considering an atom initially in the excited state i , the atom is collisionally de-excited before a spontaneous transition occurs. The lifetime of the state $|i\rangle$ will therefore be smaller than the natural lifetime of the state τ_i . If the number of collisions per second removing electrons from $|i\rangle$ is ν_{col} , then the total number of transitions out of state $|i\rangle$ is $\left(\nu_{\text{col}} + \frac{1}{\tau_i}\right)$ where τ_i is the natural lifetime. The observed line width will then be,

$$\phi_{ij} = \hbar \left(2\nu_{\text{col}} + \frac{1}{\tau_j} + \frac{1}{\tau_i} \right).$$

Through measuring the line shape of a collisionally broadened line, the density or pressure in a plasma can be determined.

3.8.3 Doppler broadening

The thermal motions of atoms within a gas provides another mechanism via the Doppler effect by which spectral lines are broadened. Larger-scale motions such as turbulence or rotation may also broaden lines. Considering thermal motions, at any instant absorbing atoms have a distribution of velocities along the line of sight to the observer. The atoms receding from the observer will absorb frequencies slightly lower than that of the line center ν_0 , while those approaching the observer will absorb slightly higher frequencies. An observer sees the combined effects of absorption by all atoms in the ensemble; the shifting of the rest frequency usually results in the observed line being broadened by a width greater than the natural line width. Consider gas moving with velocity $\mathbf{v}$, then the spectral line will be Doppler shifted with respect to an observer at rest. The direction of the radiation, approaching or receding from the observer, is defined by $\mathbf{n}$. The line profile is then given by

$$\phi_{ij}(\nu, \mathbf{v}) = \phi_{ij} \left[\nu \left(1 - \frac{1}{c} \mathbf{n} \cdot \mathbf{v} \right) \right]. \quad (3.29)$$

3.9 Hyperfine structure and Zeeman splitting

The Zeeman effect (Zeeman, 1897) is the splitting of an observed spectral line into two or more different components as a result of a magnetic field being present. The magnetic field breaks the spherical symmetry of an atom or molecule which has a non-zero magnetic moment (Gray, 2012). The following description of Zeeman splitting follows discussions in Pannuti (2020) and Tipler and Llewellyn (2012). If we consider an atom not present in an external magnetic field, a constituent electron in an excited energy level, say $2p$, may make a transition to a lower energy level and release a photon of energy $h\nu$. If the atom is present in an external magnetic field the $2p$ level may be split as a consequence of Zeeman splitting into three discrete levels $2p_{-1}$, $2p_0$ and $2p_{+1}$ which all have slightly different energies associated with them; therefore when electrons decay from these discrete energy levels to a lower energy level, say the ground energy level, the photons emitted will have slightly different energy values $h(\nu - \Delta\nu)$, $h\nu$ and $h(\nu + \Delta\nu)$ corresponding to $2p_{-1}$, $2p_0$ and $2p_{+1}$ respectively. As the magnitude of the external magnetic field increases the difference between the energy level splits will also increase, i.e., $\Delta\nu$ will increase. Since these energy level splits manifest themselves in observed spectra, astronomers can use their observations to estimate the strength of magnetic fields in interstellar environments.

Hyperfine splitting is small observed energy shifts originating from interactions between an atom's nuclear spin and the magnetic moment due to constituent electron spin; hyperfine splitting is typically much smaller than Zeeman splitting and can be observed in the spectral lines of atoms and molecules using high-resolution spectroscopy. The total angular momentum, $\mathbf{F}$, of a nuclei is an addition of the nuclear spin $\mathbf{I}$, and the angular momentum of constituent electrons $\mathbf{J}$, i.e., $\mathbf{F} = \mathbf{I} + \mathbf{J}$. Possible quantum numbers of F are $(I + J)$, $(I + J - 1)$, ..., $|I - J|$; F follows the selection rule $\Delta F = \pm 1, 0$ and $F = 0 \rightarrow F = 0$ is a forbidden transition. The possible values of F are given by either $(2J + 1)$ or $(2I + 1)$ depending on which is the smaller of the two; each atomic line is split into $(2J + 1)$ or $(2I + 1)$ components. This splitting is known as hyperfine splitting and is a result of interactions between nuclear spins and a nucleon own constituting electrons. A hyperfine structure is observed in both species of methanol, both A- and E-type methanol, in all rotational levels with the exception of those where $J = 0$ (Gray, 2012).

3.10 Polarisation of Masers

Maser radiation typically contains a degree of polarisation; polarisation has been detected in the majority of maser species, including methanol, hydroxyl and water (Dall'Olio et al., 2020). The following section covering polarisation draws from discussions in Gray (2012), Burke et al. (2019), Kraus et al. (1966), and Wilson et al. (2009). Observing the polarised emission from masers allows for obtaining information about the magnetic field present in the masing region; in astrophysical environments such as the regions around massive stars or active galactic nuclei (AGNs); the maser emission will become polarised as a result of the strong magnetic fields present. Polarised radiation is regularly described by means of Stokes parameters which separate polarisation into four distinct intensity like quantities: I , Q , U and V . Specific

intensity I , $I(\nu) = I_\nu$; linear polarisation quantities Q and U ; and circular polarisation V . Stokes parameters represent “an ensemble of averages and correlations between coordinate components of the electric field”, as stated in [Gray \(2012\)](#). Linear polarisation provides information regarding magnetic field direction; circular polarisation provides magnetic field strength information ([Lankhaar and Vlemmings, 2019](#)).

In addition to the physical condition and geometry of the emitting region polarised radiation is also influenced by saturation level, and the paramagnetic or non-paramagnetic nature of the masing molecule. The degree of saturation affects the polarisation properties; if the maser is highly saturated the polarisation will become predominantly linear and lie perpendicular to the magnetic field. This is a result of the saturation causing the population inversion to become more isotropic leading to a more uniform distribution of polarisation vectors perpendicular to the magnetic field. The paramagnetic or non-paramagnetic nature of the molecule will affect polarisation as an unpaired electron can interact with the magnetic field and contribute to the polarisation. This interaction can cause the radiation to become more circularly or elliptically polarised.

Additionally polarisation is influenced by the ratios between Zeeman frequency $g\Omega$, rate of stimulated emission R , and decay rate Γ . Put simply, the Zeeman effect is the splitting of atomic or molecular energy levels in the presence of an external magnetic field; when energy levels split into any number of sub-levels photons of different energies will be emitted; these photons will interact with their environment, influencing the polarisation. The Zeeman frequency can be defined as $g\Omega = 2g\mu B/\hbar$ where g is the Landé g-factor, B is the magnetic field, and $\hbar$ is the reduced Planck constant ([Dall’Olio et al., 2020](#)). In the case of a paramagnetic molecule, such as hydroxyl, μ is given by the Bohr magneton ($\mu_B = e\hbar/2m_e c$); in the case of a non-paramagnetic molecule μ is given by the nuclear magneton ($\mu_N = e\hbar/2m_n c$), where e is the electron charge, and m_e and m_n are the electron and nucleon mass respectively.

Methanol masers are associated with circularly polarised emission; the Zeeman effect is one of the main contributors to circular polarisation of molecular lines. The amount of circular polarisation can be derived from observed Zeeman splitting; Zeeman splitting is proportional to magnetic field strength ([Dall’Olio et al., 2020](#)). Therefore a close connection between circular polarisation in maser emission and the magnetic field strength of the masing region can be inferred.

3.11 Maser Variability

Star forming regions wherein masers are found will change with time as they progress through their natural stages of evolution. Environmental changes alter maser output and intensity. Observed maser variability is not confined to a single or small subset of behaviours; masers may display negligible variation, monotonic or linear increase and decline in intensity, irregular fluctuations such as flaring, as well as quasi-periodic and periodic variations in the observed flux density ([Gray, 2012](#)). Maser flaring and periodic variability tend to be embedded within long-term variability. It is likely that the origin of maser variability is very closely connected with variations in environmental energy availability; ‘energy’ in this context

refers to both photons, which provide the radiative pumping mechanism, as well as kinetic temperature which provides the collisional pumping mechanism.

A number of potential mechanisms have been proposed which attempt to describe the origin of variability in maser brightness. These proposed mechanisms include: changes in dust grain temperature which may be linked to spiral rotation of disk material (Parfenov and Sobolev, 2014; Sobolev et al., 2007), accretion events originating from the circumstellar disk (Araya et al., 2010) or protostellar pulsation instability (Inayoshi et al., 2013). Variability in maser brightness may also result from variation in available seed photons as a result of a colliding wind binary (CWB) system (Van den Heever et al., 2019; van der Walt, 2011; van der Walt et al., 2009) or an eclipsing binary companion (Maswanganye et al., 2015).

3.11.1 Accretion events

Accretion bursts occur when there is a sudden increase in the accretion rate onto the young stellar object; such an event can impact the masers residing in the vicinity of the stellar object (Stahler and Palla, 2008). Firstly, an increase in the accretion rate will increase the luminosity of the stellar object which will increase the ionising radiation and outflows from the stellar object. Following the increase in ionising radiation masers will be impacted in terms of excitation and population inversion (Gray, 2012). Secondly, accretion bursts impact gas kinematics in the circumstellar envelope by forming jets or outflows which can transport maser molecules to regions where environmental and pumping conditions are different (Stahler and Palla, 2008). Finally, accretion bursts may be responsible for shocks which excite some maser species, such as MMIs (Gray, 2012). The exact relationship between accretion bursts and masers is not fully understood; however it is clear that accretion bursts and maser behaviour are closely related (Meyer et al., 2017; Chen et al., 2020).

Theoretical and observational evidence exists which suggests that episodic accretion may be part of many massive stars evolutionary processes. Episodic accretion can be defined as a source experiencing long periods of quiescence punctuated by accretion events (Miao et al., 2022). Episodic accretion can be observed through maser monitoring, specifically MMIs, and by observing periodically spaced knot-like structures in the bipolar outflows of a stellar system (Miao et al., 2022; Reipurth, 1989). In addition to observed accretion bursts in known massive young stellar objects, such as NGC6334I-MM1, S255IR-NIRS3, and G358.93-0.03 (Hunter et al., 2017; Caratti o Garatti et al., 2017; Chen et al., 2020), the luminosity problem mentioned in the previous chapter provides support for episodic accretion (Miao et al., 2022).

3.11.2 Periodic variability of Methanol Masers

Stochastic variability and flaring were initially expected in maser observations due to the highly variable nature of their environments; periodic and quasi-periodic variability however were rather unexpected. Goedhart et al. (2003) were the first to observe periodic variability in methanol masers associated with G9.62+0.20E; since their discovery there have been

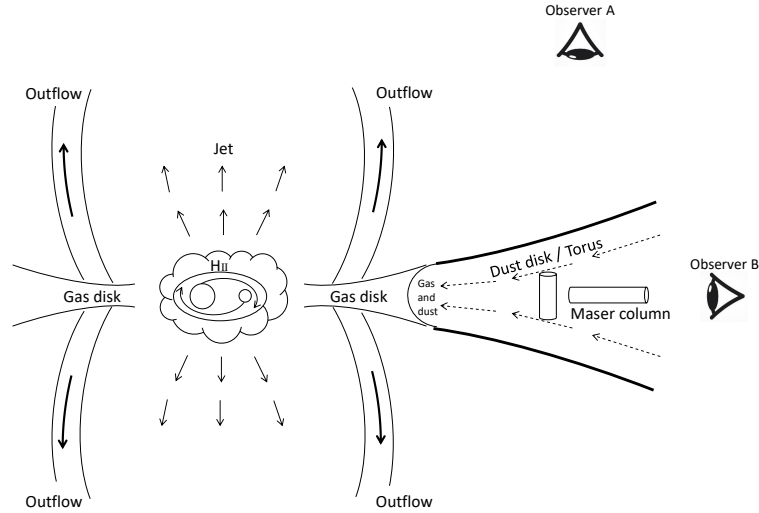


Figure 3.6: Schematic to illustrate the orientation effect of columns of masing gas, as presented by [Morgan et al. \(2021\)](#). Observer A is viewing the disc outflow system face on while observer B is observing the system edge on.

numerous periodic masers discovered and documented, see table 6.1. As discussed above, an interesting property of periodic MMIs is that no single light curve shape characterises all observed periodic masers. There have been several mechanisms proposed which attempt, specifically, to explain observed periodicity. These proposed mechanisms include: a colliding wind binary (CWB) system ([van der Walt et al., 2009](#); [Van den Heever et al., 2019](#); [van der Walt, 2011](#)); pulsation irregularities/instabilities in the young high-mass stars which actively accrete mass ([Inayoshi et al., 2013](#)); binary systems located in the circumstellar disc ([Parfenov and Sobolev, 2014](#)); periodic accretion due to varying infra-red pumping photons as a result of periodic accretion from the circumstellar disc ([Araya et al., 2010](#)); binary system outflows ([Singh and Deshpande, 2012](#)); and an eclipsing binary system ([Maswanganye et al., 2015](#)). [Cragg et al. \(2005\)](#) show that the brightness temperature of Class II methanol masers is highly sensitive to variations in dust temperature, this makes sense since the dust is the source of the infrared pumping emission. [Inayoshi et al. \(2013\)](#) propose that under high accretion rates, the massive protostellar object will pulsate leading to dust temperature variations. [Araya et al. \(2010\)](#) propose that variable accretion rates of material from the circumstellar disc onto the protostar could result in dust temperature variations.

[Morgan et al. \(2021\)](#) discuss the possibility that variations in the shapes of observed light curve behaviour in different maser sources may be due to different orientations of the maser regions. [Morgan et al. \(2021\)](#) specifically consider two distinct orientations of a disc outflow system in the colliding wind binary scenario, the face-on and edge-on observer orientations. The theory discusses how viewing a maser located in the circumstellar disc from an edge-on orientation may increase the probability of observing a maser which displays a flare profile light curve. Alternatively, viewing the disc face-on will increase the probability on masers displaying absolute cosine $|\cos(\omega t)|$ or *Bunny-hop* behaviour. Figure 3.6 is a schematic representing the proposed scenario where a CWB system is viewed either face on (observer A) or edge on (observer B). [van der Walt et al. \(2016\)](#) argue that the underlying mechanism of maser periodicity is reflected in the maser light curves; therefore, the orientation of the maser

region reflects in some way the mechanism underlying the periodicity. Considering a disc outflow system where the masers are located in the rotating circumstellar disc and outflows are perpendicular to the axis of the disc. Considering the disc outflow system is viewed edge on as is the case for observer B in figure 3.6, in this case the maser column will be projected onto the HII region which is a requirement of the CWB scenario proposed by [van der Walt \(2011\)](#) and [Van den Heever et al. \(2019\)](#). Alternatively if the disc outflow system is viewed in the face on orientation the masers cannot be projected onto the HII region and periodicity would likely be a result of periodic changes to the physical conditions of the maser environment and models such as those proposed by [Araya et al. \(2010\)](#) and [Parfenov and Sobolev \(2014\)](#) may be applicable. The models proposed by [Araya et al. \(2010\)](#) and [Parfenov and Sobolev \(2014\)](#) do not rule out the possibility of a CWB but the effect of the CWB on the masers in the environment will differ from the effect seen in an edge on orientation as the variability will not be a result of changes in free-free seed photon flux ([Morgan et al., 2021](#)). [Parfenov and Sobolev \(2014\)](#) propose that the variability observed in Class II methanol masers could be explained by variations in dust temperature caused by a propagating bow shock in a protobinary stellar system with at least one massive stellar component. In the model proposed by [Parfenov and Sobolev \(2014\)](#) the hot dense material behind the bow shock results in strong UV radiation which heats the inner edge of the circumbinary disc, altering maser column density, and producing a light curve with steep increases and slow decays similar to that observed in G9.62 + 0.20E; this model requires an edge-on orientation. The model proposed by [Parfenov and Sobolev \(2014\)](#) is criticised by [van der Walt et al. \(2016\)](#) who states that the model did not accurately reproduce a light curve consistent with sources similar to G9.62 + 0.20E. [Araya et al. \(2010\)](#) propose that periodicity is a result of periodic accretion of material from the circumbinary disc as this process has been observed in some low mass binary systems; in this scenario, material residing in the circumbinary disc is periodically accreted onto the protostars or accretion discs which heats the dust and consequently increases maser gain.

3.12 Velocity drifts observed in Maser sources

It is unclear what the primary mechanism behind observed velocity drifts are or if all observed velocity drifts have the same underlying mechanism. Velocity drifts may be caused by variability of spectrally blended maser components; considering a pair of blended spectral features, one more stable than the other and minimally separated in velocity, a velocity drift may be observed ([Szymczak et al., 2014](#)). [Szymczak et al. \(2014\)](#) state that small velocity drifts associated with periodic flux density variations, as seen in Cepheus A, are more likely due to variations in flux density present in blended components than radial infall or outflow of material. Another explanation may lie in the motion of the surrounding gas ([Goddi et al., 2011](#)). [MacLeod et al. \(2021\)](#) suggest that the velocity drifts observed in G9.62+0.20E may be a result of infalling gas or masers present in a precessing disc. The precession of a Keplerian disc refers to the gradual change in the orientation of the disc's rotation axis. Material in a Keplerian disc rotates around a central gravitational source such as a YSO, if the rotation axis of the disc is not aligned with the axis of the central gravitational source, the disc will experience a precession where there is a slow change in the orientation of the disc rotation

axis.

Chapter 4

Observational techniques and time series analysis

This chapter contains an introduction and discussion regarding the fundamentals of single-dish telescopes, the data collection process using the HartRAO 26-metre single-dish radio telescope, calibration techniques, data reduction, periodicity searches, time series analysis, evaluation of the archival data, and the statistical evaluation of errors.

4.1 Introduction

Astronomical observations carried out in this research involve a single-dish radio telescope, specifically, the 26-metre HartRAO telescope. The radio telescope intercepts and collects electromagnetic signals from astrophysical sources, allowing for scientific research. Radio band observations enable the study of the chemical composition, structure, temperature, and motion of astrophysical objects. Unlike other fields of astronomy, radio astronomy has the advantage of being largely unaffected by the time of day or year as radio waves can penetrate through various atmospheric conditions. However, weather can influence data quality as some weather conditions may introduce noise or signal attenuation ([Burke et al., 2019](#); [Wilson et al., 2009](#)). As can be seen in figure 4.1, which shows atmospheric transmission as a function of frequency, the radio band is minimally affected by atmospheric effects ([Wilson et al., 2009](#); [Sutton, 2011](#)). The radio spectrum is classified as part of the electromagnetic spectrum ranging between 3 Hz to 3 THz ([Gallaway, 2016](#)). This research project specifically utilised 6.7 GHz observations which are C band observations. C band is the range between 4 and 8 GHz ([Burke et al., 2019](#); [Wilson et al., 2009](#)). Any astronomical data received by an antenna or radio telescope must be calibrated for study. Correct and effective calibration allows for results of the highest possible accuracy and enhances the quality of scientific studies. Time-series analysis permits the behaviour and evolution of astrophysical sources to be studied over time, providing valuable insights into the dynamic nature and temporal variations of sources.

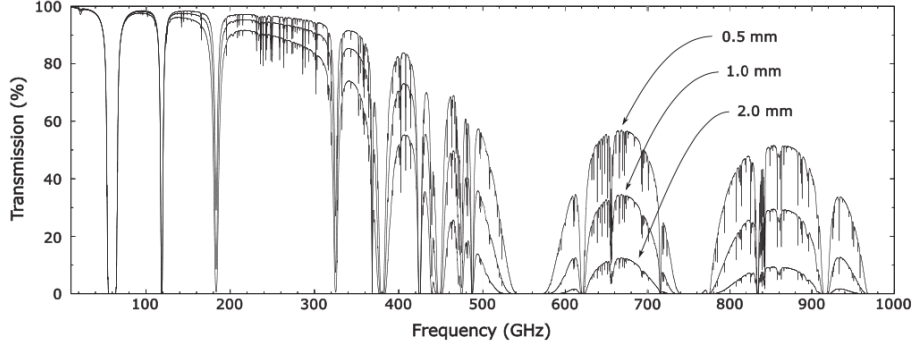


Figure 4.1: Atmospheric transmission as a function of frequency. Image taken from [Sutton \(2011\)](#) and originally provided by Atacama Pathfinder Experiment (APEX).

4.2 Fundamentals of a single dish radio telescope

The following discussion makes reference to [Burke et al. \(2019\)](#), [Elitzur \(1992\)](#), [Kraus et al. \(1966\)](#), [Condon and Ransom \(2016\)](#), and [Wilson et al. \(2009\)](#). The specific intensity¹ is the rate of energy transport, along a defined deirection, over a unit area, per unit solid angle, per unit frequency ([Sutton, 2011](#)). A source's specific intensity I_ν is the brightness per unit frequency. Considering an infinitesimal unit of energy dE emitted by an astrophysical source within the solid angle $d\Omega$, the energy travels through a predicted area $dA = \cos \theta d\sigma$ over time dt with photons falling within the frequency band $d\nu$, then the unit energy can be written as,

$$dE = I_\nu \cos \theta d\sigma d\Omega dt d\nu, \quad (4.1)$$

or equivalently as,

$$dE = I_\nu dA d\Omega dt d\nu. \quad (4.2)$$

Power can be defined as the energy flow per unit time. The infinitesimal power radiated by an astrophysical source, dP , which is intercepted by a surface of infinitesimal size $d\sigma$ can be defined as,

$$dP = \frac{dE}{dt} = I_\nu \cos \theta d\Omega d\sigma d\nu, \quad (4.3)$$

where, dP is the infinitesimal power or brightness measured in watts, $d\sigma$ is the infinitesimal surface area measured in cm^2 , $d\nu$ is the bandwidth of observed photons measured in Hz, θ is the angle between the normal of the detector plate and the line of sight to the source, and I_ν is the specific intensity measured in $\text{W m}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$, see figure 4.2 for a schematic diagram of how specific intensity is defined. I_ν can also be described as the power radiated per unit

¹Note, in some texts specific intensity is referred to as brightness or spectral radiance whilst other texts may differentiate between these terms.

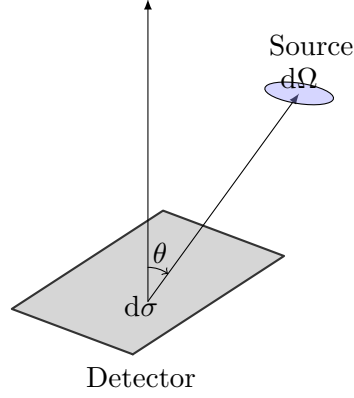


Figure 4.2: Schematic diagram of the specific intensity being measured by a detector plate; θ represents the angle between the normal of the detector plate and the line of sight to the celestial object, and $d\Omega$ represents a unit solid angle which subtends the source or portion of the sky.

area into a unit solid angle over a frequency range $d\nu$ which would be written as,

$$I_\nu = \frac{dP}{\cos \theta d\Omega d\sigma d\nu}, \quad (4.4)$$

or equivalently,

$$I_\nu = \frac{dE}{\cos \theta d\Omega d\sigma dt d\nu}. \quad (4.5)$$

The flux of a source S_ν is the intensity emitted over the solid angle subtended by the source Ω_s , the flux density can therefore be written as an integral of the intensity over the area subtended by the source,

$$S_\nu = \int_{\Omega_s} I_\nu \cos \theta d\Omega. \quad (4.6)$$

The flux density is measured in $\text{W m}^{-2}\text{Hz}^{-1}$ or in Jansky where $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2}\text{Hz}^{-1}$. The radio telescope will intercept a flux S_ν which is equivalent to the rate of energy crossing a unit area perpendicular to the direction of propagation per unit time, given by,

$$S_\nu = dE/dAdt. \quad (4.7)$$

The total flux can be written as

$$S = \int_0^\infty S_\nu d\nu. \quad (4.8)$$

In summary, the specific intensity is a measure of radiation intensity per unit area, per

unit solid angle, per unit frequency, and provides detailed information about the radiation over a specific frequency range and direction. Flux, on the other hand, represents the total amount of radiation received per unit area from all directions over the entire frequency range, providing a measure of the overall energy received from the object.

Following the discussions on specific intensity and flux density, another fundamental measure that must be discussed is brightness temperature T_b . Brightness temperature is a proxy for specific intensity and is measured in Kelvin. With the exception of observations comprising of a very low source temperature (<10 Kelvin) and a very high observing frequency ($\nu > 100$ GHz), radio telescopes operate in the Rayleigh-Jeans limit $h\nu \ll kT$ (Gray, 2012); therefore, using the Rayleigh-Jeans approximation the spectral brightness of a source can be related to the brightness temperature as follows,

$$B_{\text{RJ}}(\nu, T) = \frac{2\nu^2}{c^2} kT, \quad (4.9)$$

and consequently the brightness temperature can be written as,

$$T_b = \frac{I_\nu c^2}{2k\nu^2}. \quad (4.10)$$

In the above equations, brightness temperature T_b has been defined as the temperature a black-body source would need to generate the intensity I_ν (Gray, 2012).

A single-dish radio telescope consists of a large dish that intercepts radio waves from astronomical sources for scientific study. The primary components of a radio telescope include:

- The telescope dish which intercepts and focuses the radio waves from astronomical sources. Numerous different telescope designs exist and are used in radio astronomy.
- Radio telescopes make use of reflectors, primary and secondary, to intercept and focus radiation onto focal points where small feed antennas, such as waveguide horns, transfer the signals into a receiver system.
- The receiver system is an electronic system which amplifies and processes received signals into usable signals. A radiometer is a receiver which measures the average power of the antenna noise over a well-defined radio frequency range, which can be written as,

$$\nu_{\text{RF}} - \frac{\Delta\nu}{2} \quad \text{to} \quad \nu_{\text{RF}} + \frac{\Delta\nu}{2}, \quad (4.11)$$

where $\Delta\nu$ is the receiver bandwidth and ν_{RF} is the centre of the radio frequency range.

- A simple radiometer contains a bandpass filter, a square-law detector, an integrator, and a voltmeter.
 - The bandpass filter exclusively allows the throughfare of noise within the desired frequency range, $\nu_{\text{min}} < \nu < \nu_{\text{max}}$.

- The square-law detector outputs signal $y(t)$ proportional to the square of its input signal $v(t)$, i.e, $y(t) = av^2(t)$.
- The integrator, smoothing filter, or averager smooths the rapidly fluctuating detector output.
- The voltmeter measures and records the smoothed voltage.
- The control system manages the telescope movement, pointing and tracking.
- A spectrometer is on the back-end of observations and divides the passband into N frequency channels of width $\delta\nu \leq \Delta\nu/N$; the spectrometer allows for spectral features to be resolved by measuring the power in all N channels.

4.2.1 Beam pattern of radio telescope

The following section draws from discussions in [Burke et al. \(2019\)](#), [Wilson et al. \(2009\)](#), [Condon and Ransom \(2016\)](#), and [Kraus et al. \(1966\)](#). The beam pattern of a radio telescope is the three-dimensional pattern of sensitivity of the telescope, relevant when performing observations. The shape and the size of the telescope’s primary reflector determines the beam pattern and any other design choices, such as secondary reflectors or feed horns, which focus the radio waves onto the receiver. The beam pattern of a parabolic dish radio telescope is shown in figure 4.3. The half-power beam width (HPBW) is the angle between points of the main beam where the normalised power pattern is half the maximum. The main lobe of the beam pattern is typically well-characterised and has the highest sensitivity; it is the region within the beam where astronomers prefer to observe their sources. The width and the shape of the main lobe depend on the primary reflector’s size and geometry as well as the frequency of the observed radio waves.

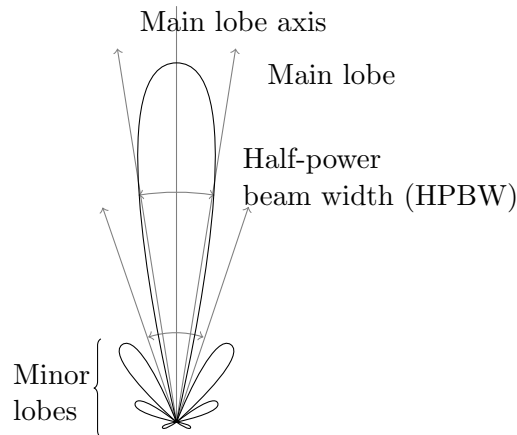


Figure 4.3: The beam pattern of a radio telescope. The main lobe concentrates the majority of the energy and is centered on the telescope’s target direction. The sidelobes, or minor lobes, receive power from offset directions; sources of power detected by sidelobes include other astronomical sources, the atmosphere, ground-based, or telescope noise. In practice, beams are made nearly Gaussian using apparatus such as corrugated horns.

Sidelobes are regions of the beam pattern with lower sensitivity than the main lobe. They occur due to diffraction and reflection of radio waves from the edges of the primary reflector and any secondary reflectors or feed horns. Sidelobes can be significant for radio telescopes

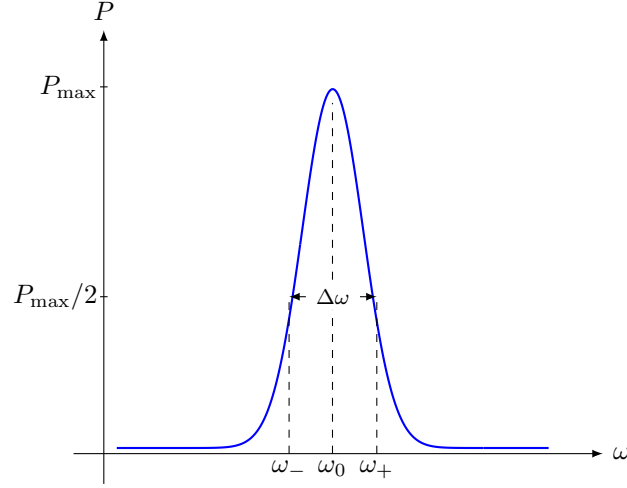


Figure 4.4: Illustration of the full width at half maximum.

with large primary reflectors or observations at high frequencies. Sidelobes can have several effects on radio observations; they can produce spurious signals which can be mistaken for real astrophysical signals, contaminate the data, and reduce the signal-to-noise ratio. Contamination can result from sidelobes detecting signals from other areas of the sky, ground, or from the telescope. Sidelobes may also introduce systematic measurement errors, such as variations in the gain of the telescope. In order to minimise the effects of sidelobes a number of techniques may be employed, such as designing the primary reflector to reduce the amount of diffraction, using secondary reflectors or feed horns to focus the radio waves more precisely, and using digital signal processing techniques to identify and correct for spurious signals in the data. The resolving ability of a radio telescope is often characterised by the full-width at half maximum (FWHM) which is the width of the beam where the power pattern has dropped to one half of the peak value, this is schematically shown in figure 4.4.

In a typical single-dish telescope a good approximation of the FWHM or angular resolution in radians Θ is given by,

$$\Theta_{(\text{FWHM})} = 1.22 \frac{\lambda}{D} \sim \frac{\lambda}{D} \quad (4.12)$$

where, λ is the observing wavelength and D is the diameter of the telescope's primary dish. The angular resolution of a radio telescope is typically worse than λ/D since almost no radio telescope provides uniform illumination of the primary dish. Aside from the FWHM another important and significant way in which the beam is described is in terms of solid angle. The beam solid angle written as,

$$\Omega_A = \int \int_{4\pi} P_n(\theta, \phi) d\Omega, \quad (4.13)$$

is the angle through which all power from a transmitting antenna would stream if the power were constant over the angle and equal to the maximum value (Kraus et al., 1966). If the integration is restricted to the main lobe, the main-beam solid angle is written as,

$$\Omega_M = \int \int_{\text{main lobe}} P_n(\theta, \phi) d\Omega. \quad (4.14)$$

4.2.2 Telescope gain and effective area

The following discussion draws from [Burke et al. \(2019\)](#), [Condon and Ransom \(2016\)](#), and [Wilson et al. \(2009\)](#). The telescope gain can be thought of in two fundamental ways. Firstly, the gain G is the ability of the telescope to amplify and focus incoming radiation and can be defined as the ratio of the output power to the input power written as,

$$G(\text{dB}) = 10 \log_{10}(P_{\text{out}}/P_{\text{in}}). \quad (4.15)$$

Where G is the gain measured in decibels, P_{out} is the output power of the telescope, and P_{in} is the input power from the astrophysical source of interest. The second way of thinking about antenna gain is in the context of a transmitting antenna which defines a direction dependant power gain. The power gain $G(\theta, \phi)$ is the power transmitted per unit solid angle in a direction defined by (θ, ϕ) relative to an isotropic antenna which will transmit evenly in all directions. Therefore the power gain can be expressed as,

$$G(\theta, \phi) = \frac{4\pi}{\Omega_A} \quad (4.16)$$

where Ω_A is the beam solid angle which includes the main lobe and the sidelobes. From equation 4.16 it can be seen that the gain can be intuitively thought of as the number of times the telescope beam can fit into the 4π steradians of a sphere and the higher the gain value the smaller the beam solid angle. The effective area of a telescope A_{eff} is a product of the physical surface area of the primary dish, A_g , and the apperture efficiency η_A which is a combination of several potential losses; effective area of the telescope can be written mathematically as,

$$A_{\text{eff}} = \eta_A A_g. \quad (4.17)$$

The effective area of a telescope can also be described by means of a constant proportionality which relates telescope gain G to the effective area of a telescope. The effective area of the telescope can be written as follows,

$$A_{\text{eff}} = \frac{G\lambda^2}{4\pi}. \quad (4.18)$$

4.2.3 Antenna temperature

The following section follows discussions in [Wilson et al. \(2009\)](#), [Gray \(2012\)](#), [Condon and Ransom \(2016\)](#), and [Nyquist \(1928\)](#). A commonly used measurement in radio astronomy is that of antenna temperature, T_A ; which is the total receiving antenna noise, or power output per unit frequency from the antenna, presented to the radiometer during observation. The concept of antenna temperature arises when electrical power and temperature are related to one another; the definition of antenna temperature relates the antenna output to the power of a resistor at a specific temperature. The theory of noise voltage generated by a resistor was developed by [Nyquist \(1928\)](#) following experimental measurements by [Johnson \(1928\)](#). Consider a simple circuit where a resistor R is connected in series with a linear amplifier. Due to the thermal motion of electrons, a fluctuating potential will be present. The current in the circuit averaged over a suitable period will be zero; however, the power in the circuit will be non-zero since $\langle i^2 \rangle \neq 0$. Therefore, the resistor provides a power input to the amplifier, and in thermal equilibrium, this power is determined by the physical temperature of the resistor. This phenomenon is caused by Johnson-Nyquist noise, where electronic noise is generated by the thermal agitation of electrons in a conductor; this thermal agitation occurs regardless of any applied voltage to the circuit. In conclusion, antenna temperature relates the antenna output to the power of a matched resistor at a specific temperature. The antenna temperature is therefore given by,

$$T_A \equiv P_\nu/k, \quad (4.19)$$

where P_ν is noise power density, k is the Boltzman constant, and T_A is the antenna temperature. Since in the limit of $h\nu \ll kT$ the power per unit bandwidth at a temperature T is,

$$P_\nu = kT, \quad (4.20)$$

as defined by the Johnson-Nyquist theorem. Alternatively, if the power received from the resistor over the bandwidth $\Delta\nu$ is equal to $kT_A\Delta\nu$ where T_A is the antenna temperature, the effective area can be related to the equivalent antenna temperature for a point source of known flux density which is written as follows,

$$A_{\text{eff}} = \frac{2kT_A}{S(\nu)} \sim \eta_A A_g. \quad (4.21)$$

The sensitivity or minimum detectable flux density of a telescope depends on several factors, the two principal factors in sensitivity are effective aperture and system temperature ([Kraus et al., 1966](#)). The minimum detectable flux density of a radio telescope is given by,

$$S_{\text{min}} = \frac{2kK_s T_{\text{sys}}}{A_{\text{eff}} \sqrt{\Delta\nu t}}, \quad (4.22)$$

where, k is the Boltzmann constant, K_s is a receiver constant, T_{sys} is the system temperature, A_{eff} is the effective area of the aperture, $\Delta\nu$ is the bandwidth, and t is the time constant (Kraus et al., 1966).

4.2.4 System temperature

When conducting observations using a radio telescope or antenna, the line radiation from the source of interest is a small portion of the total measured power. There are several contributing sources of noise from the source, atmosphere, ground, and receiver; these contributions, T_i , are always additive $T_{\text{sys}} = \sum T_i$ (Burke et al., 2019; Wilson et al., 2009) and can be summarised as follows,

$$T_A = T_s + T_{\text{cmb}} + T_{\text{gal}} + T_{\text{atm}} + T_{\text{sl}} + T_{\text{loss}}. \quad (4.23)$$

The antenna temperature consists of radiation from the source or region of interest T_s , noise originating from the cosmic microwave background (CMB) and the Milky Way galaxy T_{cmb} and T_{gal} , noise from the Earth's atmosphere T_{atm} , ground radiation detected in the beam sidelobes T_{sl} , and thermal noise associated with antenna losses T_{loss} (Burke et al., 2019). If the measured signal is compared to a measurement which differs from it only by containing no line radiation, i.e., having no T_s contribution, pure line emission can be approximated as the difference between these two observations (Wilson et al., 2009). It is an important distinction between antenna temperature and system temperature, antenna temperature is a measure of the received power from an astronomical source as it would be for an idealised antenna, whilst system temperature accounts for the additional noise contributions which may be present (Condon and Ransom, 2016; Burke et al., 2019; Wilson et al., 2009). The system temperature,

$$T_{\text{sys}} = T_A + T_R, \quad (4.24)$$

is comprised of the antenna temperature T_A and the receiver temperature T_R .

4.2.5 Observed signal

The following section on observed signal draws from discussions in Burke et al. (2019). All signals in radio astronomy contain a stochastic component we refer to as *noise*; noise limits telescope sensitivity and sets a minimum value to the integration time. The noise received by radio telescopes have the characteristics of Gaussian noise meaning that the probability density function $\mathcal{P}(V)$ follows a normal, or Gaussian, distribution. Gaussian noise results from numerous independent oscillations of a continuous physical process and is the most common form of noise seen in practice in radio astronomy. Since stochastic processes have generated all natural signals with which we work they will consequently exhibit random variations in amplitude and phase. The probability density function for Gaussian random

noise, $\mathcal{P}(V)$ is given by,

$$\mathcal{P}(V) = \frac{1}{\sigma_t \sqrt{2\pi}} \exp \left\langle -\frac{V(t)^2}{2\sigma_t^2} \right\rangle, \quad (4.25)$$

where $V(t)$ is the voltage amplitude and σ_t is the standard deviation of the voltage.

4.2.6 Observations of Masers

The following section draws from discussions in [Gray \(2012\)](#). Astrophysical masers result from electric-dipole-allowed transitions between the internal energy levels of maser molecules. An electric-dipole-allowed transition occurs when a molecule changes its energy state by either absorbing or emitting a photon. The electric dipole-allowed transitions are typically observed in maser sources as they are strong and easy to observe. The radiation is emitted in spectral lines, representing emission and absorption features of gaseous and ionised sources, with a width significantly smaller than the observing line frequency provided by the telescope, $\Delta\nu \ll \nu$. The spectral linewidth is a measure of the spread of the line profile and indicates the saturation and velocity distribution of the masing molecules. When observing masers, spectral linewidth can provide information regarding physical conditions in the masing region; a narrow spectral linewidth may indicate a well-defined velocity structure of the masing gas, while a broad spectral linewidth may indicate a more complex velocity structure, potentially resulting from turbulence or outflows.

The spectral linewidth is typically set by inhomogeneous Doppler broadening, dependent on kinetic temperature with a common addition of microturbulence. The thermal and microturbulent contributions add in quadrature to give a full linewidth at half maximum value (FWHM), written as,

$$\Delta\nu = \frac{\nu_0}{c} \left[\frac{(8 \ln 2)kT}{m} + v_T^2 \right]^{1/2}. \quad (4.26)$$

The first term in the square brackets of equation 4.26 is the Doppler contribution from molecules of mass m with kinetic temperature T ; the second term is the microturbulence contribution with a characteristic speed v_T ². The laboratory line-centre transition frequency is ν_0 ; ν_0 is modified by the source's Doppler motions relative to the local-standard of rest, as well as the motions of the telescope relative to the local-standard of rest.

Masers are observed in the radio, millimetre, and sub-millimetre ranges; before any observations of maser sources can begin, the line frequency and suitable observation bandwidth are selected. The bandwidth $\Delta\nu_{\text{obs}}$ is subdivided into channels, each with a width of $\delta\nu$; the greater the number of channels, the smaller the velocity or frequency coverage of an individual channel, and consequently the greater the frequency or velocity resolution. Wider channels

²Note that describing microturbulent action using only one characteristic speed is a very simplistic representation; microturbulence usually consists of a range of characteristic speeds which vary over a range of distance scales ([Gray, 2012](#))

reduce thermal noise; increasing channel size results in a reduced signal-to-noise ratio. Optimising spectral line observations, therefore, involves reducing channel width regardless of the increasing noise fluctuations in the individual channels. In practice the minimum width of a receiving channel is set by the onsite correlator hardware and larger widths are simply multiples of this lower range. The signal received from a single spectral line observation is given by (Burke et al., 2019),

$$T_{\text{line}} = \frac{P_{\text{tot}} A_{\text{eff}}}{2k\delta\nu}. \quad (4.27)$$

Where P_{tot} is the total power observed from a line with centre frequency ν_0 , A_{eff} is the effective area of the telescope, and $\delta\nu$ is the channel width with respect to frequency. There are also noise fluctuations associated with T_{sys} , rms noise in each channel over a finite integration time $\mathcal{T}$ is given by the radiometer equation, one of the most important equations in radio astronomy (Sutton, 2011; Burke et al., 2019),

$$\Delta T_A = \frac{T_{\text{sys}}}{\sqrt{\delta\nu\mathcal{T}}} = \Delta T_{\text{RMS}}. \quad (4.28)$$

In Gaussian statistics the Root Mean Square (RMS) noise is determined by dividing the mean value of the data by the square root of the number of samples $\sqrt{n}$. In radio astronomy it is assumed that the number of samples is equal to the product of the receiver bandwidth $\delta\nu$ and the integration time $\mathcal{T}$ (Wilson et al., 2009). The signal-to-noise ratio is given by,

$$\text{SNR} = \frac{T_A}{\Delta T_A} = \frac{T_A}{\Delta T_{\text{sys}}} \sqrt{\delta\nu\mathcal{T}}. \quad (4.29)$$

Equation 4.28 is the idealised and fundamental relation between system noise, bandwidth, integration time, and rms fluctuations (Wilson et al., 2009). ΔT_A is the rms noise in an observation (Wilson et al., 2009). The topic of velocity resolution is of significant importance particularly when velocity drifts in maser sources are investigated in later chapters. Maser observations require the frequency resolution to be sufficient to resolve the thermal linewidth; therefore, a channel width of $\delta\nu \sim 0.1 \text{ km.s}^{-1}$ or smaller is required for sufficient line resolution. The probability distribution function of noise has a zero mean, standard deviation σ_t which is proportional to the rms noise level.

Table 4.1: Technical Parameters of the 26 m HartRAO Telescope (Nickola et al., 2013)

Owner and operating agency	HartRAO
Construction year	1961
Telescope mount	Offset equatorial
Receiving feed	Cassegrain
Diameter of primary reflector d	25.914 m
Focal length f	10.886 m
Focal ratio f/d	0.424
Slew rate on each axis	0.5 deg/s

4.3 Observations done using the 26m HartRAO radio telescope

The 26-metre radio telescope at Hartebeesthoek Radio Astronomy Observatory (HartRAO) is an equatorially mounted Cassegrain design radio telescope with a focal length of ~ 10.9 metres and a focal ratio of ~ 0.424 . A Cassegrain design telescope consists of a large parabolic main dish and a secondary reflector. Radiation is intercepted by the main dish, which then reflects the radiation onto the secondary reflector, which focuses the radiation into the receiver located in the centre of the main dish, see figure 4.5 (Burke et al., 2019; Wilson et al., 2009). An equatorial mount is a telescope mount which allows for tracking of celestial objects across the sky and compensating for the apparent motion of astronomical objects as a result of the Earth's rotation (Sutton, 2011; Burke et al., 2019). The equatorial mount allows for this compensation as the the telescope is mounted in alignment with the Earth's rotational axis (Burke et al., 2019; Wilson et al., 2009). The focal length, f , is the distance between the telescope's primary reflector and the focus point of the telescope (Gallaway, 2016). The focal length determines the angular resolution of the telescope, i.e., the telescope's ability to resolve fine details of observed sources; the focal ratio is the ratio of the focal length to the diameter of the telescope's primary reflector (Burke et al., 2019; Wilson et al., 2009). It has receivers at 6.7 GHz, which are dual circularly polarised, allowing for the detection of left- and right-circular polarisation (LCP and RCP); dual polarisation receivers allow for the polarisation of incoming radiation to be fully characterised. The 4.5 cm receiver is cryogenically cooled; a cryogenically cooled receiver reduces thermal noise from the receiver and consequently improves receiver sensitivity and signal-to-noise ratio.

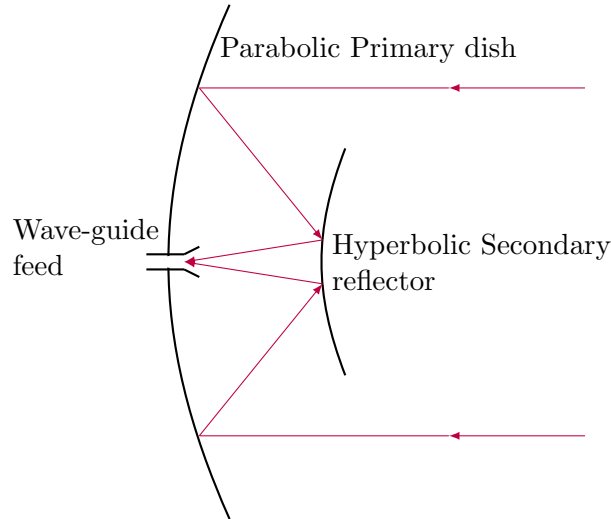


Figure 4.5: Schematic diagram of a Cassegrain telescope. Incoming radiation reflects off the primary dish, which is parabolic in shape, and is redirected into the wave-guide feed by the secondary reflector.

Monitoring of maser source G358.46 - 0.391 was carried out from February 2011 to March 2023; high cadence observations of the maser source was carried out around the dates of the predicted minima during the period of this research project March 2021 to March 2023. All observational data used to study maser source G358.46 - 0.391 in this research project was independently processed and calibrated using a pipeline written in conjunction with the

research project. The data calibration process is discussed in greater detail in section 4.4. Each observation of maser source G358.46 - 0.391 involved an observation at each cardinal point, i.e., North, South, East, and West, two offset central point observations, and two central point observations. The cardinal point observations alongside the two offset central point observations are used to determine the pointing correction. The two non-offset central observations produce the ultimately produce maser spectrum for the observation.

Table 4.2: Observing parameters and receiver characteristics using the 4.5 cm band of the 26m HartRAO telescope. The 4.5 cm receiving band is used for 6.7 GHz maser observations.

Receiver	4.5 cm
Maser transition	$J = 5_1 - 6_0 A^+$
Observing mode	Frequency switching
Rest frequency (MHz)	6668.518
System temperature (K)	57
Polarisation	LCP & RCP
Amplifier	Cryogenic HEMT
Half-Power Beam-width (degrees)	0.116
Number of spectral channels	512
Spectrometer Bandwidth (MHz)	1.000
Velocity range (km.s^{-1})	45.0
Spectrometer resolution (km.s^{-1})	0.044
Monitoring period	February 2011 to March 2023

4.4 Data Calibration

In any branch of observational astronomy, data calibration is essential to yielding accurate results. Calibration sources are astronomical sources with known positions, small angular sizes, known flux density over a wide frequency range, luminous, and relatively stable in luminosity over time (Baars, 1973). No single astrophysical source exhibits all these characteristics; however, a number of sources are sufficiently reliable and can be used in calibration. The calibration sources used to calibrate the G358.460 - 0.391 maser data were 3C123 and Hydra A; they were observed at 6.7 GHz by means of drift scans using the 26 metre HartRAO telescope. A drift scan is an observational technique whereby a source is observed by keeping the telescope stationary and allowing the source to pass overhead (Burke et al., 2019). Calibration flux densities were determined using the flux density standards defined by Ott et al. (1994), see table 4.3. Once the flux density of the calibration sources was determined, the point source sensitivity (PSS) could be determined. Sensitivity defines the minimum detectable signal strength and accuracy of measurements; point-source sensitivity PSS is the approximate flux density corresponding to a point source which will cause the antenna temperature T_A to increase by one Kelvin, PSS is measured in Jansky per Kelvin (Burke et al., 2019; Wilson et al., 2009). PSS provides a conversion factor from the brightness temperature of an observed source, measured in Kelvin, to the flux density, measured in Jansky. The inverse of PSS is known as the gain G and expected range for the PSS accuracy is $\sim 5\%$ (Burke et al., 2019; Wilson et al., 2009).

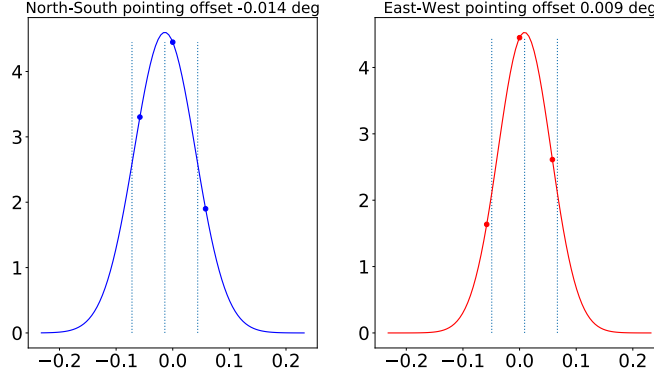


Figure 4.6: North-South pointing offset and East-West pointing offset. The three dotted lines correspond to the centre of the gaussian fit and the centre offset by $\pm$ the halfpower beamwidth.

4.4.1 Flux density calibration

The pointing correction for the calibration sources and PSS values were determined through the following steps. Firstly the calibration sources are observed, and the raw data are collected in the form of counts. The raw count data are converted to Kelvin using the noise calibration value; this value is provided in the observation fits file but can also be calculated using the noise diode data. Since, from an observational point of view, the only temperature values of interest in the observations are those contributed by the calibration source itself, all system contributions must be removed from the scans. System contributions are present in the baseline of the scan, which are flattened using a polynomial fit to the baseline and subsequently subtracting the fit (Wilson et al., 2009). A Gaussian is fitted to the drift scan as a good approximation of the beam (Burke et al., 2019). From the Gaussian fit, the amplitude correction factor due to pointing error is determined using

$$pc = \exp \left[\frac{4 \ln(2)}{(\theta_{1/2})^2} \left([T_A^{NS}]^2 + [T_A^{EW}]^2 \right) \right], \quad (4.30)$$

where components T_A^{NS} and T_A^{EW} are the temperature components determined from the Gaussian fits of different cardinal point drift observations. This pointing error is then multiplied with the measured central temperature of the on source drift scan determining the corrected antenna temperature; this process is completed for both the observed polarisations. Following this, the flux density of the selected calibration source at the centre frequency is determined using the flux density standards defined by Ott et al. (1994). Finally, the PSS of each polarisation channel can be determined using,

$$\begin{aligned} \text{PSS}^{\text{LCP}} &= \frac{S_0}{2 (pc \times T_A^{\text{LCP}})}, \text{ and} \\ \text{PSS}^{\text{RCP}} &= \frac{S_0}{2 (pc \times T_A^{\text{RCP}})}, \end{aligned} \quad (4.31)$$

for the two respective polarisations (Wilson et al., 2009), where S_0 is the flux density determined using the spectral fits defined by Ott et al. (1994), pc is the pointing correction, and T_A is the antenna temperature corresponding to the observation. The PSS values determined for observations of 3C123 and Hydra A can be seen in figure 4.7. The determined PSS values were used to simulate more stable PSS values which can be seen in figure 4.8.

Table 4.3: Spectral fits for calibrator sources 3C123 and Hydra A as defined by Ott et al. (1994).

$$\log S \text{ [Jy]} = a + b * \log \nu \text{ [MHz]} + c * \log^2 \nu \text{ [MHz]}$$

Source	Range [MHz]		a	b	c
	from	to			
3C123	1408	23780	2.525	-0.246	-0.1638
3C218	1408	10550	4.729	-1.025	0.0130

4.4.2 Calibration Sources Hydra A and 3C123

A brief overview of the calibration sources used has been included. The morphology of Hydra A (3C218) includes a central radio galaxy with two symmetrical S-shaped lobes of radio emission and a bright hotspot (Taylor et al., 1990). 3C123 is a radio galaxy approximately 1.1 billion light-years from Earth and is located in the constellation Virgo. It is a relatively compact and symmetrical radio source. 3C123 has two lobes of radio emission on either side of the central galaxy, which take the shape of diffuse twisted plumes (Hardcastle et al., 2001). Hydra A and 3C123 are bright, well-studied radio sources commonly used as calibration sources. They are suitable for calibration as they exhibit stable and well-known flux densities and have compact and symmetrical morphologies, making them relatively simple to observe and interpret (Taylor et al., 1990; Hardcastle et al., 2001; Ott et al., 1994). 3C123 and Hydra A were both used as calibrators in this research. The point source sensitivity (PSS) values derived from these sources are represented in figures 4.7 and 4.8.

4.5 Maser observation and Data Processing

As previously stated, when conducting radio observations the line radiation from the source is a small portion of the total measured power and the system temperature is a sum of several different noise contributions, as summarised in equation 4.23 (Burke et al., 2019; Wilson et al., 2009). If the measured signal is compared to a measurement which differs from it only by containing no line radiation, i.e., having no T_s contribution, pure line emission can be approximated as the difference between these two observations (Burke et al., 2019; Wilson et al., 2009). In the following equation,

$$T_{\text{source}}(\text{K}) = \left[\frac{T_{\text{on}} - T_{\text{off}}}{T_{\text{off}}} \right] T_{\text{off}}, \quad (4.32)$$

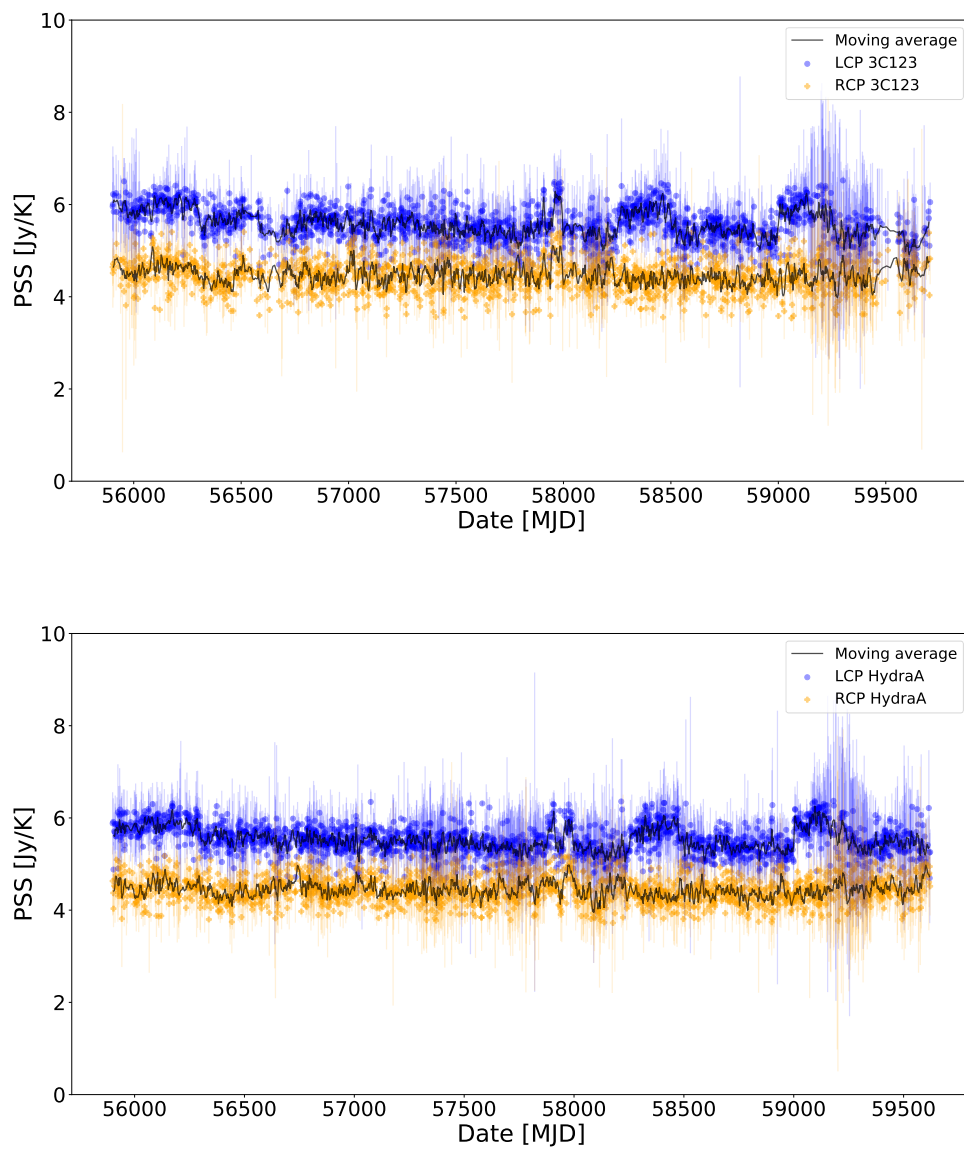


Figure 4.7: The PSS values observed at 6.7 GHz using calibrators Hydra A and 3C123. The figures show only the PSS values observed within two standard deviations of the mean as well as the moving average.

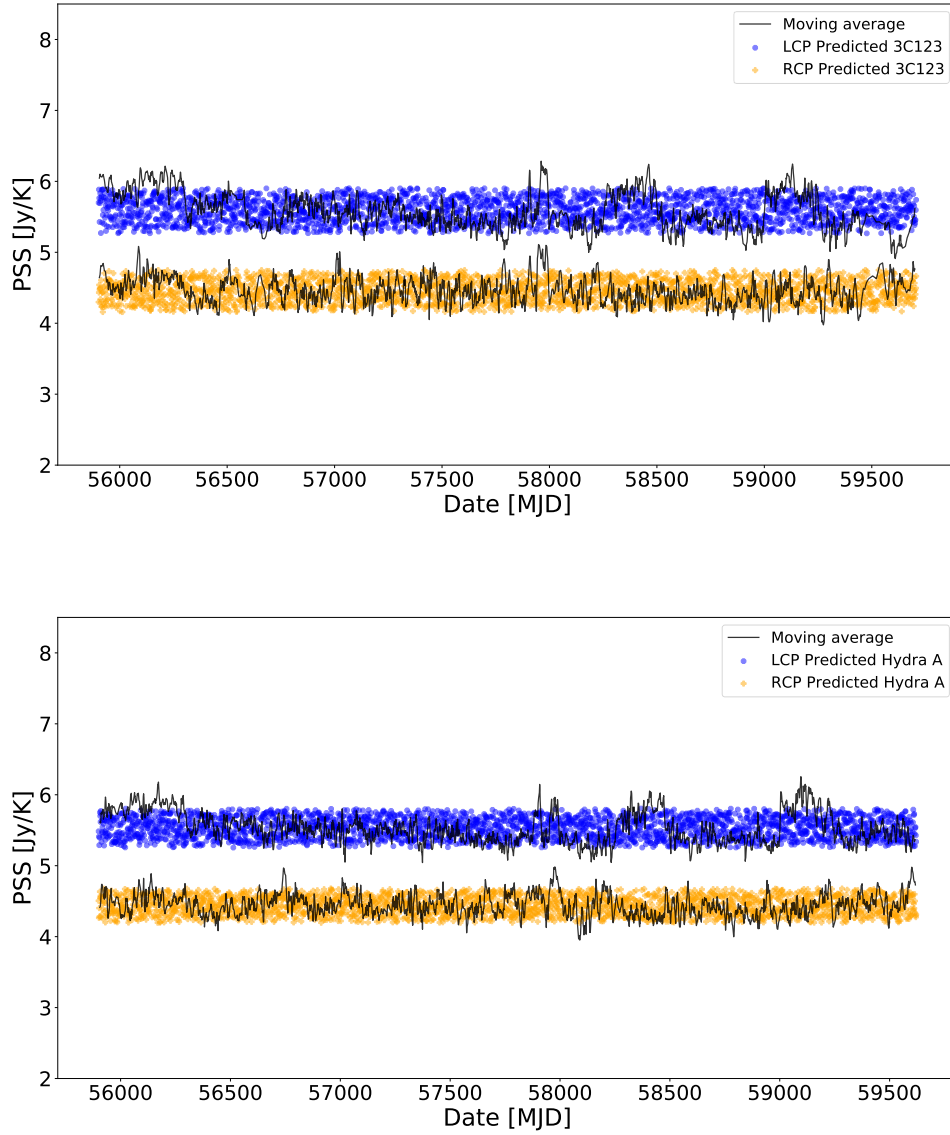


Figure 4.8: Since it can be assumed from previous literature and observations that sources Hydra A and 3C123 are relatively stable sources; the PSS values derived from HartRAO observations can be used to simulate a likely range for PSS values if environmental and instrumental effects were minimised. This simulation is presented by the above figures.

the line emission is determined using the measurements of emission when directed at the source, T_{on} , and when directed at an emission free region, T_{off} .

There are two methods commonly used to approximate the source contribution T_s namely position switching and frequency switching. Position switching involves observing an object of interest for a period of time and then repositioning the telescope to observe a region of the sky which is free of line radiation, i.e., a blank sky observation (Burke et al., 2019; Wilson et al., 2009). Obtaining blank sky observations allows for baseline subtraction. This method is less efficient than frequency switching as it requires more telescope time; however, it has the advantage that no prior knowledge of the observational source is required (Wilson et al., 2009; Rohlfs and Wilson, 2013; O’Neil, 2002).

The frequency switching technique works on similar principles as position switching. In frequency switching, the telescope remains pointed at the object of interest and obtains blank sky measurements by switching the centre frequency of the measurements (Burke et al., 2019; Wilson et al., 2009). Considering a narrow spectral line centred at ν_0 occupying frequency interval $\Delta\nu$ where $\nu_0/\Delta\nu \sim 10^{-6}$, changing the receiver frequency to $10\Delta\nu$ would produce a comparison signal allowing for cancellation of quasi-stationary effects. Since frequency switching does not require repositioning of the telescope, it can be a very efficient method (Wilson et al., 2009; Rohlfs and Wilson, 2013; O’Neil, 2002).

In the observations of maser source G358.46 - 0.391 the frequency switching technique was employed during the data processing, which provided a bandpass-corrected frequency range. The rest frequency used was 6.669 GHz, and the frequency switching offset was 500000 Hz. The spectrometer bandwidth is 1 MHz with 1024 spectrometer channels; each channel has a width or velocity resolution of 0.044 km.s^{-1} . When employing frequency switching 512 channels are saved. The central velocity observed was 1.7 km.s^{-1} . The observation integration time was 30 seconds. The frequency switch is significant enough to produce a reliable comparison signal.

4.5.1 Baseline subtraction

The result of an observing procedure, such as frequency switching, should theoretically result in a spectrum where antenna temperature T_A is zero outside the frequency or velocity range of the line; in practice this is not the case (Wilson et al., 2009). Reflection of radiation is a large contributor of bandpass ripples; reflected radiation can originate from the front end of the receiver where noise power is injected into the antenna, here radiation may be reflected back, alternatively strong continuum radiation from cosmic sources may cause rippling (Wilson et al., 2009). Frequency switching largely removes the instrumental bandpass response; however, the baseline of the total power spectrum still needs to be flattened (O’Neil, 2002). Standard practice involves fitting of a polynomial of second order or higher to the baseline and subtracting it, great care should be taken in this process to prevent additional spurious effects being introduced into the spectrum (Wilson et al., 2009; O’Neil, 2002). The flattening of the baseline was done in a two-step process. Firstly an n th-order polynomial is fitted to the baseline of the power spectrum to flatten it, see figure 4.9. Secondly, for the pur-

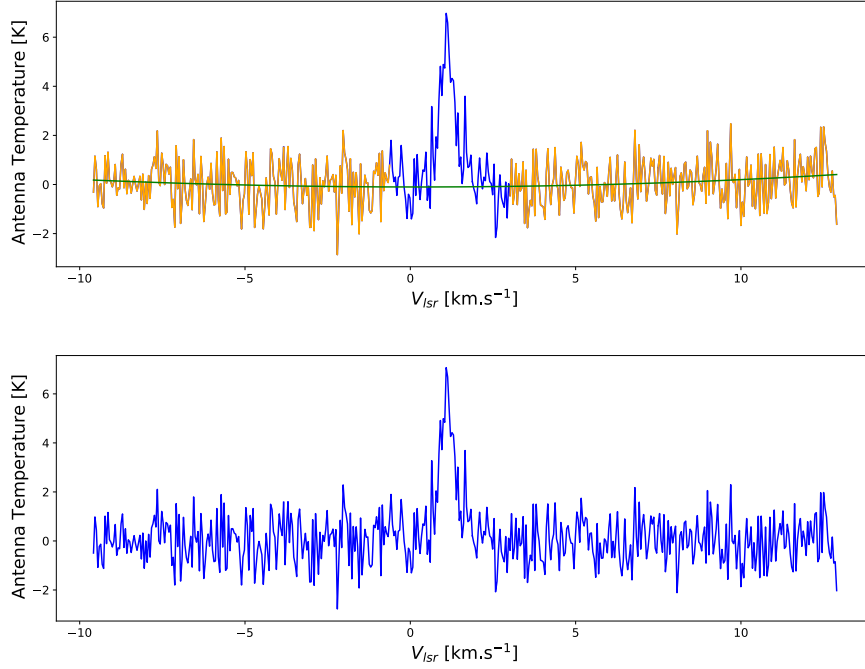


Figure 4.9: Baseline subtraction: The top figure is an example of what an observation on source or at a cardinal point may look like, the main feature (purple) is masked and a third order polynomial (green) is fitted to the unmasked baseline. Below this is the resultant spectrum after baseline subtraction has taken place.

pose of thoroughness, Savitzky-Golay, or ‘savgol’ smoothing, was performed on the power spectrum. Savitzky-Golay smoothing is a commonly used mathematical method in radio astronomy and in processing spectroscopic data (Savitzky and Golay, 1964; Schafer, 2011). The filter effectively reduces high-frequency noise³ whilst preserving the underlying signal (Schafer, 2011). Savitzky-Golay smoothing is particularly useful for smoothing spectroscopic data, where small variations in the signal can make it difficult to accurately identify spectral features.

4.5.2 Combining Spectra

After smoothing has been applied, each polarisation is multiplied by the determined pointing correction determined and the spectra are associated with each polarisation are combined producing a single spectrum, see figure 4.10. Once the final spectrum for an observation has been produced, the RMS noise can be determined.

4.5.3 RMS noise

As previously discussed, in astronomy the term noise refers to any unwanted random fluctuation in signal which may reduce the accuracy of astronomical measurements (Pannuti, 2020; Wilson et al., 2009; Burke et al., 2019). This noise may originate from other celestial objects,

³High-frequency noise refers to random fluctuations in a signal that occur at high frequencies, typically on a scale faster than the underlying signal. High-frequency noise is often characterized by fast, sharp changes in the signal.

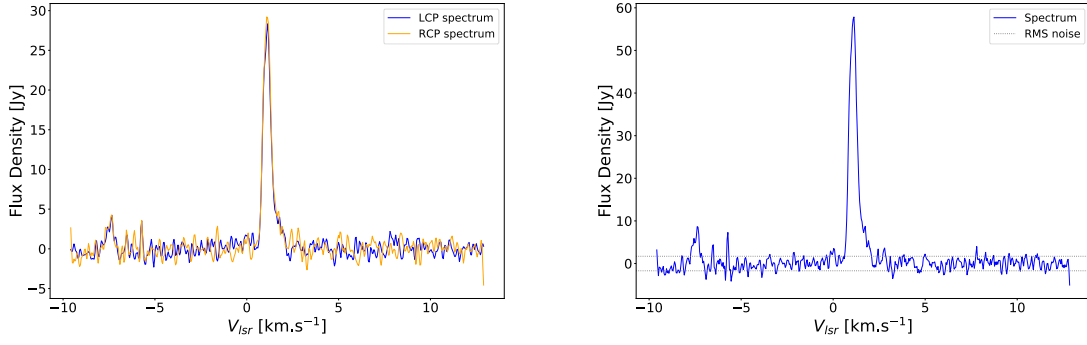


Figure 4.10: The image on the left shows the processed spectra corresponding to the separate polarisation. On the right is the final spectrum, which is the result of the processed data and combined polarisations; two horizontal lines indicate the RMS noise level.

the CMB, ground sources, or instrumental interference to name a few. Root mean square (RMS) noise is the average magnitude of noise fluctuations from the mean value. RMS noise helps quantify the amount of noise present in a signal and provides some indication of data quality. The RMS noise is given by,

$$\Delta T_A = \frac{T_{\text{sys}}}{\sqrt{\delta\nu\mathcal{T}}} = \Delta T_{\text{RMS}}.$$

In order to determine the magnitude of RMS noise in each observation, the main spectral feature was masked, and only fluctuations not associated with the source were considered. The RMS was calculated as the square root of the average noise squared. In a set of n values $\{t_1, t_2, t_3, \dots, t_n\}$ the RMS is determined as follows,

$$\text{RMS} = \sqrt{\frac{1}{n} (t_1^2 + t_2^2 + t_3^2 + \dots + t_n^2)}. \quad (4.33)$$

As can be seen in figure 4.10 (right) the two horizontal dashed lines represent the range of the RMS noise, which does not include the main feature of maser source G358.460 - 0.391.

4.6 Summary of Observations and Data Calibration process

In summary, observational spectra of independent G358.46 - 0.391 maser observations are produced as follows. The observations were completed using the 26 metre HartRAO radio telescope; the 4.5 cm receiver which is composed of dual cryogenically cooled RCP and LCP feeds. Each polarisation was calibrated using Hydra A and 3C123 and the flux density scale defined by Ott et al. (1994); this produced the point source sensitivity (PSS) values. Each observation of the source of interest, i.e., maser source G358.46 - 0.391, consists of cardinal point, central offset, and central on-source observations all of which are frequency switched. Observations were completed with a 1 MHz bandwidth and a 1024-channel spectrometer; in the frequency switching mode 512 channels are recorded. For all epochs, half-power beamwidth

(HPBW) pointing correction observations were carried out. Pointing correction is determined using the cardinal point and central offset observations, also called the HPBW observations; these observations undergo, baseline flattening, averaging of the polarisations, and pointing errors are determined by fitting a Gaussian model of the beam. This produces a pointing correction. Finally the observational spectra are determined using the frequency switched central on source observations. Observations are multiplied by the PSS values for the RCP and LCP channels. The baselines of the spectra are flattened and smoothing is applied. The spectra are then averaged, multiplied by the pointing correction and the polarisations are added together to produce a final spectrum for the observation. Now that a final spectrum has been achieved, determining of the RMS noise value remains. This is achieved by taking the determined spectrum, masking regions of line emission, i.e., regions containing line emission should not be included, and determining the square-root of the average noise squared, $\sqrt{\bar{n}^2}$.

4.7 Time series analysis techniques

The following discussion draws from [VanderPlas \(2018\)](#), [Lomb \(1976\)](#), and [Scargle \(1982\)](#). Time series analysis is a means of extracting information by applying statistical methods to data collected over time, time series analysis allows for better understanding of the intrinsic nature of the source and make predictions about future behaviour of the source. Due to the nature of data collection in observational astronomy, observations of astrophysical sources are unevenly spaced in time; therefore, methods such as classical Fourier spectral analysis cannot be used to determine the periodicity of the data. Algorithms such as Lomb-Scargle, epoch folding using L-statistic, and the Jurkevich method are used in place of classical Fourier spectral analysis to determine periodicity.

The Lomb-Scargle periodogram ([Lomb, 1976](#); [Scargle, 1982](#)) is an algorithm widely used amongst astronomers. The Lomb-Scargle periodogram computes a Fourier-like power spectrum and estimates the power spectral density of the signal, which is a measure of the strength of periodic signals at different frequencies. The Lomb-Scargle periodogram provides an analytic solution for periodicity which is more convenient and efficient than numerical methods ([Zeichmeister and Kürster, 2009](#)). The Lomb-Scargle periodogram is written as,

$$P_{\text{LS}}(\omega) = \frac{1}{2} \left(\frac{[\sum_n g_n \cos \omega(t_n - \tau)]^2}{\sum_n \cos^2 \omega(t_n - \tau)} + \frac{[\sum_n g_n \sin \omega(t_n - \tau)]^2}{\sum_n \sin^2 \omega(t_n - \tau)} \right), \quad (4.34)$$

and the time delay τ which represents the phase shift between the observation times and the assumed period of the sinusoidal model. The time delay is described by the following equation,

$$\tau = \frac{1}{4\pi\omega} \tan^{-1} \left(\frac{\sum_n \sin(4\pi\omega t_n)}{\sum_n \cos(4\pi\omega t_n)} \right). \quad (4.35)$$

In a field such as astronomy where data are sampled at a non-uniform rate, the following can

be applied: signal is sampled a set of N times which is denoted as $\{t_n\}$ and therefore the observing window $W_{[t_n]}(t)$.

$$W_{[t_n]}(t) = \sum_{n=1}^N \delta(t - t_n) \quad (4.36)$$

Applying the observing window $W_{[t_n]}(t)$ to the true underlying signal $g(t)$ the observed signal takes the form of g_{obs} .

$$\begin{aligned} g_{\text{obs}} &= g(t)W_{[t_n]}(t) \\ &= g(t) \sum_{n=1}^N \delta(t - t_n) \end{aligned} \quad (4.37)$$

A periodic signal detected by the Lomb-Scargle method will be presented on the periodogram as a peak with a finite width and height. From a Fourier and Bayesian perspective, the uncertainty of the measurement is directly related to the width of the peak. It is therefore possible to determine an uncertainty in the determined periodicity by fitting a Gaussian function to the peak of the periodogram. Another method in which one can assess the validity of the Lomb-Scargle periodicity measurement is by determining the false-alarm probability or the false-detection peak. False-detection probability determines whether a peak in the power spectrum is a real signal or a false detection by defining a significance threshold. The threshold corresponds to a probability that the peak could have arisen by chance alignment of random errors. If the peak in the power spectrum exceeds the false-alarm probability threshold, it is considered a significant detection and is usually reported as a candidate periodic signal. If the peak does not exceed the threshold, it is considered a false detection and is ignored.

4.7.1 Velocity drifts

Velocity drifting is investigated in both the archival data as well as the observational data for the maser feature associated with G358.46 - 0.391. In order to perform the search for velocity drifts, linear regression fitting was applied to the velocity time-series data of the maser sources over specified velocity ranges where a potential drift was present. A linear regression fitting produced a velocity drift slope, and the goodness of fit, R^2 , was also determined. In order to test the veracity of the velocity drift analysis, Gaussian evaluation was also performed, which produced a Gaussian-fitted velocity drift. Once again, goodness of fit, R^2 , was determined for the Gaussian evaluation. The Gaussian evaluation mentioned here is explained in detail in the proceeding section. The goodness of fit test will briefly be covered in this section. The goodness of fit test or ' R^2 test' measures the variance between a collection of data points and the linear regression model which models the data behaviour (Devore, 2011). Assume a data set which consists of n data points $x_1, x_2, \dots, x_n$; each data point is associated with a modelled data point $f_1, f_2, \dots, f_n$. The residual sum of squares is defined as (Devore, 2011),

$$S_{\text{residual}} = \sum_i (x_i - f_i)^2 = \sum_i e_i^2, \quad (4.38)$$

and the total sum of squares is defined as,

$$S_{\text{total}} = \sum_i (x_i - \bar{x})^2, \quad (4.39)$$

where $\bar{x}$ is the mean of the observed data. The most general definition of the goodness of fit coefficient is,

$$R^2 = 1 - \frac{S_{\text{residual}}}{S_{\text{total}}}. \quad (4.40)$$

A perfect fit of the data to the regression model will yield an R^2 value of one (Devore, 2011).

4.8 Gaussian validation of light curves and Velocity drifts

As stated in the previous section, the veracity of determined velocity drifts can be determined by fitting multiple Gaussian profiles to a maser feature which is suspected of drifting; the Gaussian profiles are fitted to the maser feature over multiple epochs thus determining corresponding velocities, flux densities, and full width at half-maximum (FWHM) line widths. As can be seen in figure 4.11 which, for simplicity, shows three Gaussian fits which would correspond to three spectra observed at three different epochs; each Gaussian fit provides a central velocity value as well as a corresponding flux density measurement. These values can be used for several different purposes throughout the analysis of the maser observations: firstly, to determine the central velocity value of a maser feature, secondly, to test the accuracy and validity of velocity drifts, and finally to produce light curves which graphically show the behaviour of a maser feature over time rather than strictly looking at the flux behaviour within a specified velocity channel or velocity range.

4.9 Statistical analysis

Kernel-density estimations (KDEs) are useful statistical tools for visualising the shape or trends within data (Rosenblatt, 1956; Silverman, 1981; Kim and Scott, 2012). KDEs are a non-parametric method which estimates the probability density function (PDF) of a data point (Feigelson and Babu, 2012). A KDE is therefore able to produce an estimation of the underlying distribution of a dataset without receiving any initial assumptions about the data distribution form (Feigelson and Babu, 2012). A KDE works by placing a kernel, or a smoothing function, at points in the data set, determining an estimate at that point and summing these kernels to form an estimate (Rosenblatt, 1956; Silverman, 1981; Kim and Scott, 2012). Commonly used kernel functions include the Gaussian distribution, the triangular distribu-

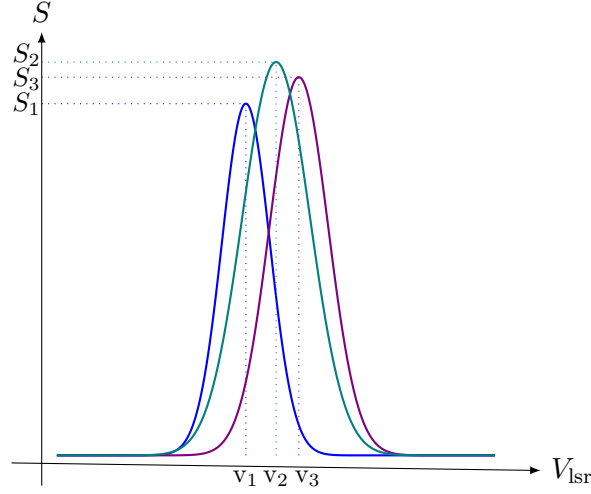


Figure 4.11: Illustration showing a gaussian fit to observations at epochs n_1 , n_2 , and n_3 . These three observations have corresponding central velocities v_1 , v_2 , and v_3 , and maximum flux density values S_1 , S_2 , and S_3 . The illustration has been exaggerated for the purposes of readability; during evaluation of a single source hundreds of gaussians will be fitted to each maser feature over all observed epochs with the Gaussian fits often displaying significant overlap.

tion, and the Epanechnikov distribution. KDEs are used in various applications, such as density estimation, visualising data distributions, and evaluating data which is ineffectively modelled by parametric distributions. In this research, a Gaussian kernel estimator was used alongside a parametric method to visualise the shape and behaviour of maser source G358.460 - 0.391 light curves. One standard deviation is a simple approximation of the uncertainty of a data set; 68% of measurements in a data set will be found within one standard deviation of the mean. The standard deviation, σ , is given by,

$$\sigma = \sqrt{\frac{1}{(N-1)} \sum_{i=1}^N (\mu - x_i)^2}. \quad (4.41)$$

Where N is the size of the data set, μ is the data set mean, and x_i is the value from the data set $(x_1, x_2, \dots, x_N)$. The Gaussian function is given by,

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}; \quad (4.42)$$

the Kernel density estimator (Rosenblatt, 1956) for a window width h based on univariate observations $(x_1, x_2, \dots, x_n)$ is given by,

$$\hat{f}_{\text{KDE}}(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right), \quad (4.43)$$

where K is the chosen kernel function and h is the bandwidth. The bandwidth controls the degree of smoothing and therefore the choice of this parameter predicts the performance of

the KDE ([Feigelson and Babu, 2012](#)). Considering a sample of data $(x_1, x_2, \dots, x_n)$ and a prediction is to be made about the shape of the data at a point, the KDE will make such a prediction using the available data which are within the defined bandwidth and using the chosen kernel function to determine the most likely value of the data at that point.

Chapter 5

Observational results of methanol maser source G358.460 - 0.391

The following chapter presents results on the observations of the periodic maser source G358.460 - 0.391 and maser source G358.460 - 0.393 completed using the 26-metre HartRAO telescope. High cadence observations were specifically conducted around the light curve minima of G358.460 - 0.391 over two years, as investigating the maser source behaviour around the minima may provide some insight into the underlying mechanisms of the observed maser behaviour.

5.1 Introduction

Maser source G358.460 - 0.391 is a known source of 6.7 GHz periodic methanol maser emission. The G358.460 - 0.391 source is likely a HMYSO in its earliest evolutionary stage undergoing rapid accretion and possesses bipolar molecular outflows (Chen et al., 2013; Ugwu et al., 2023). The periodicity associated with G358.460 - 0.391 appeared to be accurately modeled by an absolute cosine function (Maswanganye et al., 2015). This *bunny-hop* behaviour was found in features associated with $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$ by Maswanganye et al. (2015). This maser source warranted further observation to fully characterise the long-term maser behaviour, including periodicity, intrinsic variation, evolution, velocity drifts, and stability. High cadence observations, specifically around the minima, were conducted as Maswanganye et al. (2015) only have one good set of observational data around a single minimum, providing insufficient information to fully characterise the behaviour of this source or make accurate predictions about the underlying cause of the periodicity. Maser source G358.460 - 0.393 coincided with maser observations of G358.460 - 0.391; G358.460 - 0.393 can be seen as a minor feature in the maser spectrum centred around $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$. Table 5.1 presents the coordinates and velocity ranges of maser sources G358.460 - 0.391 and G358.460 - 0.393 as defined by Caswell et al. (2010).

Table 5.1: Maser features G358.460 - 0.391 and G358.460 - 0.393 coordinates and velocity ranges as in [Caswell et al. \(2010\)](#).

Source name	Equatorial coordinates		Velocity range	
	RA (2000)	Dec (2000)	V_L	V_H
	(h m s)	($^{\circ}$ ' ")	(km.s^{-1})	(km.s^{-1})
G358.460 - 0.391	17 43 26.76	-30 27 11.3	-0.5	4.0
G358.460 - 0.393	17 43 27.24	-30 27 14.6	-8.5	6.0

5.2 Spectra and light curves of G358.460 - 0.391

The spectrum of maser source G358.460 - 0.391 is presented in figure 5.1. In figure 5.1, the average spectrum, which is an average of all spectral observations, provides a concise view of the spectral behaviour of the source over the observational period. Figure 5.1 also includes the upper and lower spectral envelope, representing the maximum and minimum flux density measurements per velocity channel over the observational period. [Maswanganye et al. \(2015\)](#) state that the strong main feature is centred around $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$ and the weaker feature at $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$, whilst in this research, the central velocity values were found to be $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ for the main feature and $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$ for the weaker feature. The difference in central velocity values is likely a result of the prolonged observational period and some velocity drifting of the maser features. The weaker feature appears to be partially blended with the primary feature, particularly during early observations. The central velocity of a feature, v_{cen} , describes the location of a feature in the spectrum but contains no information regarding the spatial position of the maser spot if considered without high-resolution interferometric observations.

Light curves were produced corresponding to the following velocity channels: 1.00 km.s^{-1} , 1.129 km.s^{-1} , 1.70 km.s^{-1} , and a light curve which corresponds to peak flux density measurements rather than a specific velocity channel. Two light curves were also produced using the Gaussian-determined values for the main peak and minor peak, which have central velocity values $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ for the main feature and $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$ for the weaker feature. The light curves produced display a periodic *bunny-hop* behaviour. An absolute cosine was used to fit the data with a polynomial which fits the baseline of the data, i.e., the absolute cosine lies on top of a polynomial. The light curves are shown in figures 5.2 to 5.7. Figure 5.8 shows the light curve determined for the maser feature associated with G358.460 - 0.393 at $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$; the maser feature corresponding to $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$ appears to display some variability but no distinct shape or periodicity. The central velocity of the maser feature associated with G358.460 - 0.393 was determined to be $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$ through Gaussian evaluation; this differs slightly from the central velocity $v_{\text{cen}} \sim -7.5 \text{ km.s}^{-1}$ determined by [Maswanganye et al. \(2015\)](#).

5.3 Time-series analysis

Time-series analysis allows time-dependent patterns in astronomical sources to be detected and characterised. The Lomb-Scargle periodogram is a well-established method for deter-

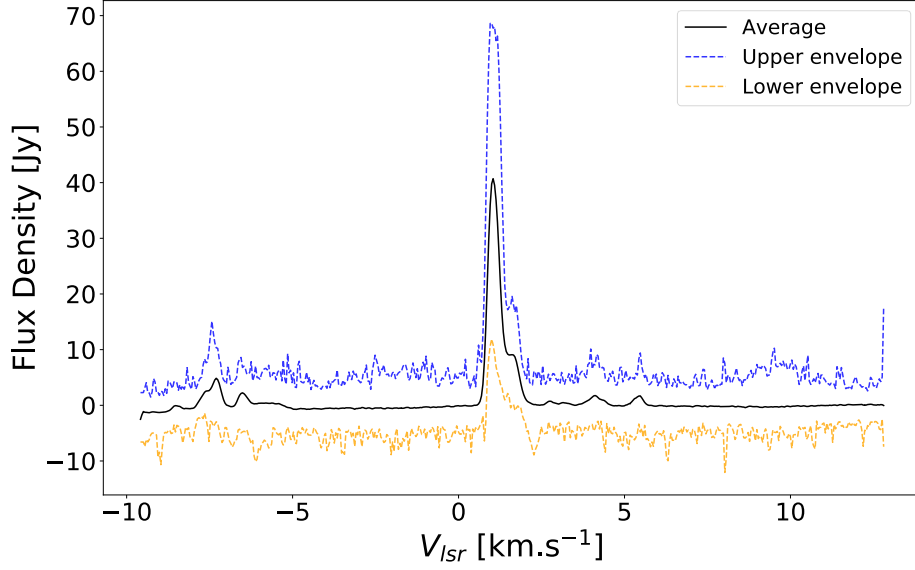


Figure 5.1: Averaged spectra containing maser sources G358.460 - 0.391 and G358.460 - 0.393 with upper and lower envelope; the upper and lower envelope shows the range of flux observations of the source, i.e., the upper envelope represents the maximum flux observations at each velocity while the lower envelope represents the minimum flux observations at each velocity over the entire observing period.

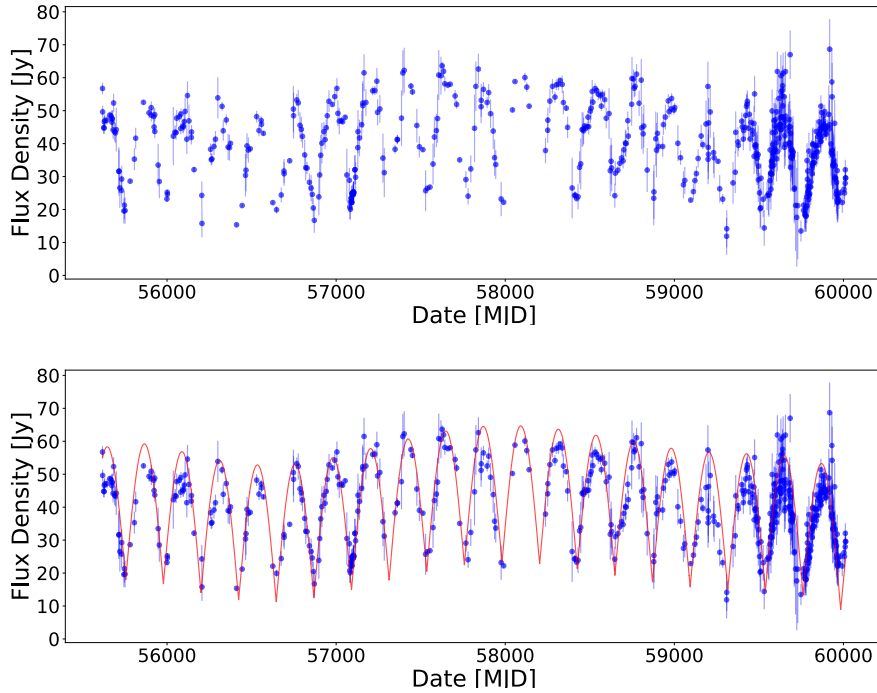


Figure 5.2: Light curves determined from maser observations of G358.460 - 0.391 corresponding to $v_{\text{cen}} \sim 1.00 \text{ km.s}^{-1}$. The top figure shows the data points extracted from spectral observations and the bottom figure shows the data points with estimated fit.

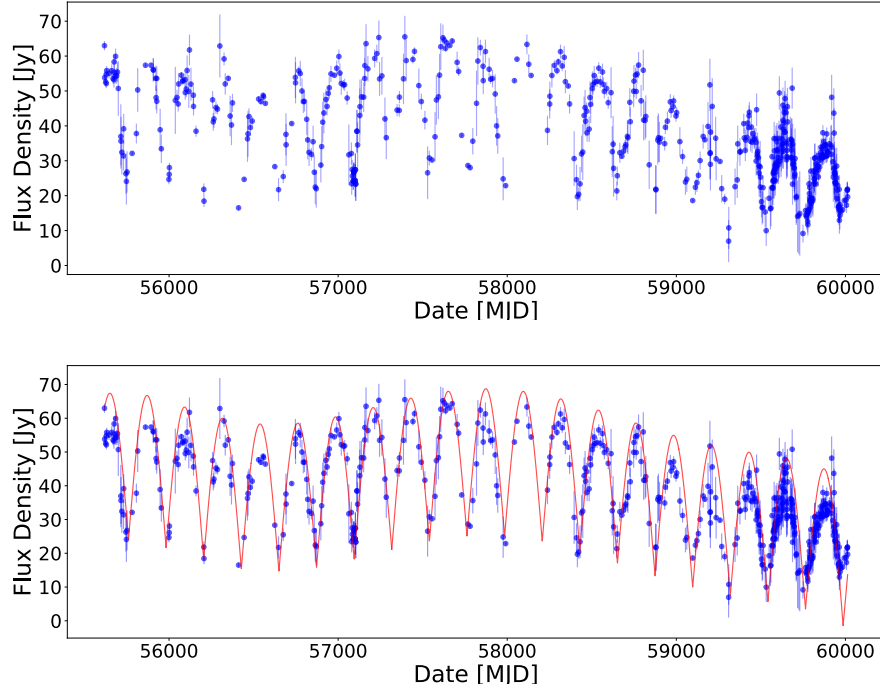


Figure 5.3: Light curves determined from G358.460 - 0.391 maser observations at $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$

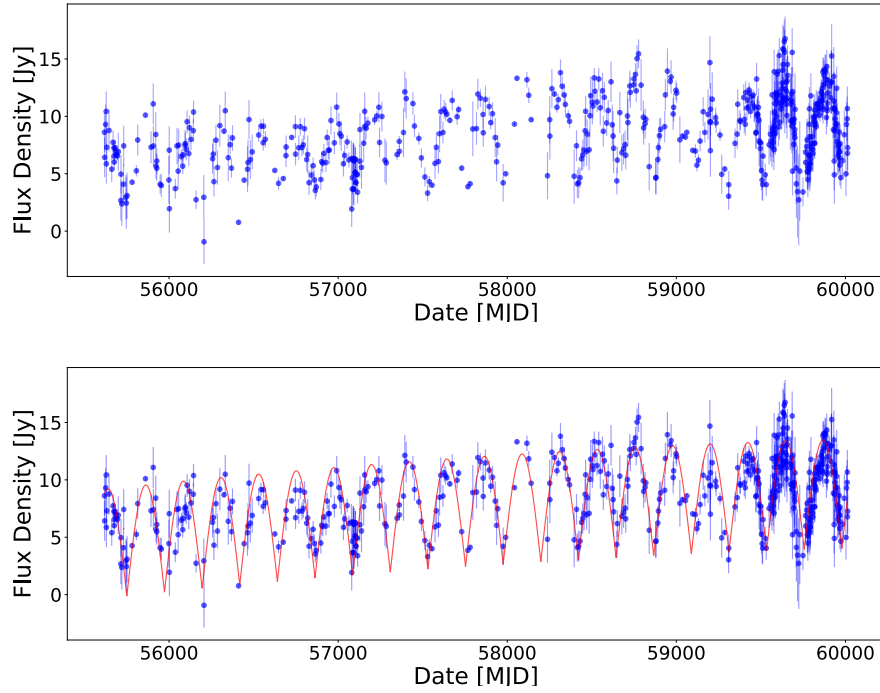


Figure 5.4: Light curves determined from G358.460 - 0.391 maser observations at $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$

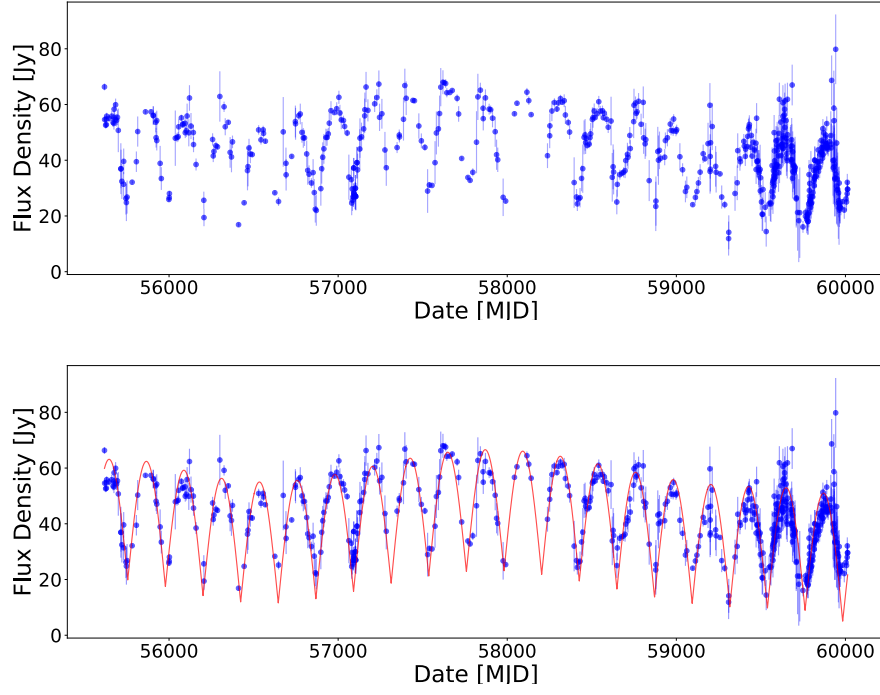


Figure 5.5: Light curves determined from G358.460 - 0.391 maser observations at the peak flux density measurements of each individual observation

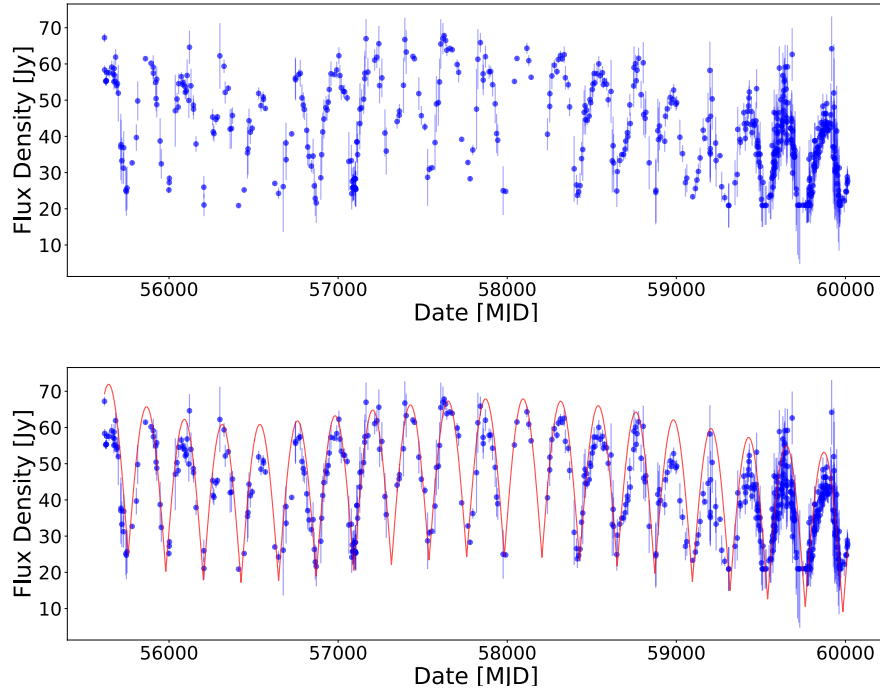


Figure 5.6: Light curves determined from G358.460 - 0.391 maser observations at $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$

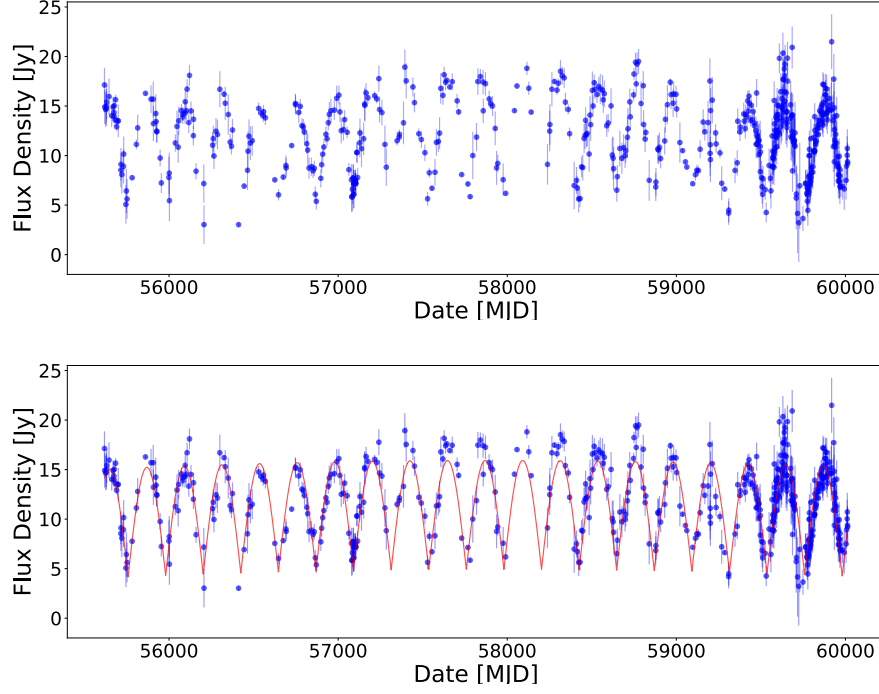


Figure 5.7: Light curves determined from G358.460 - 0.391 maser observations at $v_{\text{cen}} \sim 1.65$ km.s⁻¹ with estimated $|\cosine|$ fit.

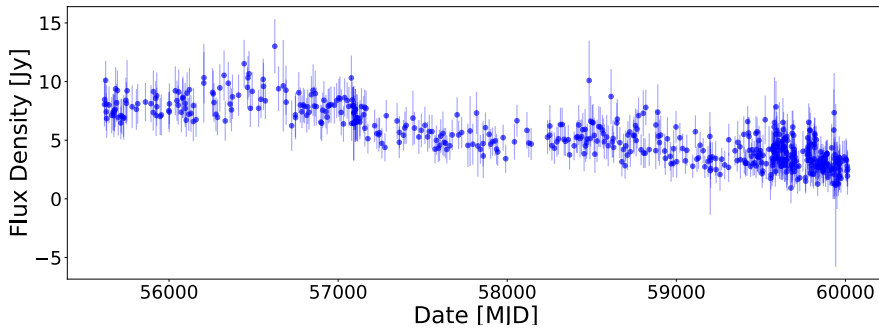


Figure 5.8: Light curves determined from G358.460 - 0.393 maser observations at $v_{\text{cen}} \sim -7.37$ km.s⁻¹

mining periodicity in astrophysical sources, as was discussed in section 4.7. Periodicity was detected in maser source G358.460 - 0.391 using the Lomb-Scargle periodogram, and an uncertainty on the periodicity was determined by fitting a Gaussian function to the prominent peak of the periodogram; the uncertainty was calculated using the FWHM of the Gaussian fit. The false detection peak of the Lomb-Scargle was also determined and is plotted as a horizontal red line on the periodograms, see figures 5.9 and 5.10. The periodicity measurements are presented in table 5.2 alongside periodicity measurements from the absolute cosine fit and previous literature. In addition to the maser features associated with $\sim 1.07 \text{ km.s}^{-1}$ and $\sim 1.65 \text{ km.s}^{-1}$, which were determined in this research using Gaussian fitting, additional velocity ranges were also investigated. These additional velocity ranges were investigated for the purpose of comparison and validation of current findings with previous work completed by Maswanganye et al. (2015).

Table 5.2: Time series analysis of maser feature G358.460-0.391. The periodicity is determined using the Lomb-Scargle periodogram (L-S) with the uncertainty determined from a Gaussian fit, shown in figures 5.9. The periodicity was also determined when fitting an absolute cosine function to the data; those values are presented in the third column. The table also includes in column four a comparison of previous periodicity measurements by Maswanganye et al. (2015).

Velocity channel (v_{cen}) [km.s ⁻¹]	Periodicity (L-S) [days]	Periodicity (cosine) [days]	Periodicity comparison [days]
1.00	222.0 ± 3	222.5	
1.129	222.0 ± 16	222.4	220 ± 14
1.70	222.0 ± 16	222.6	224 ± 18
1.07	222.0 ± 16		
1.65	222.0 ± 3		

5.4 Kernel-Density Estimation

Kernel density estimation (KDE) methods were discussed in section 4.9. A KDE estimation was performed on the determined light curves for maser source G358.460 - 0.391; unlike the absolute cosine fit performed, a KDE does not take a parametric input when predicting the behaviour of data. The KDE uses only the data, a set bandwidth wherein it performs estimations, and the type of kernel used when performing the estimation. A Gaussian kernel was used in the KDE. The KDE estimation of light curves is presented in figures 5.11, 5.12, 5.14, and 5.15. The KDE estimations appear to confirm the periodic bunny-hop shape, which has been consistent over several years. The KDE fit to the high-cadence observations, which can be seen in figures 5.13 and 5.16, clearly show the bunny-hop shape with short minima and a high degree of symmetry.

5.5 Investigation of behaviour around minima

As previously mentioned, high cadence observations were carried out to improve the understanding of the maser features associated with G358.460 - 0.391. Several images have been

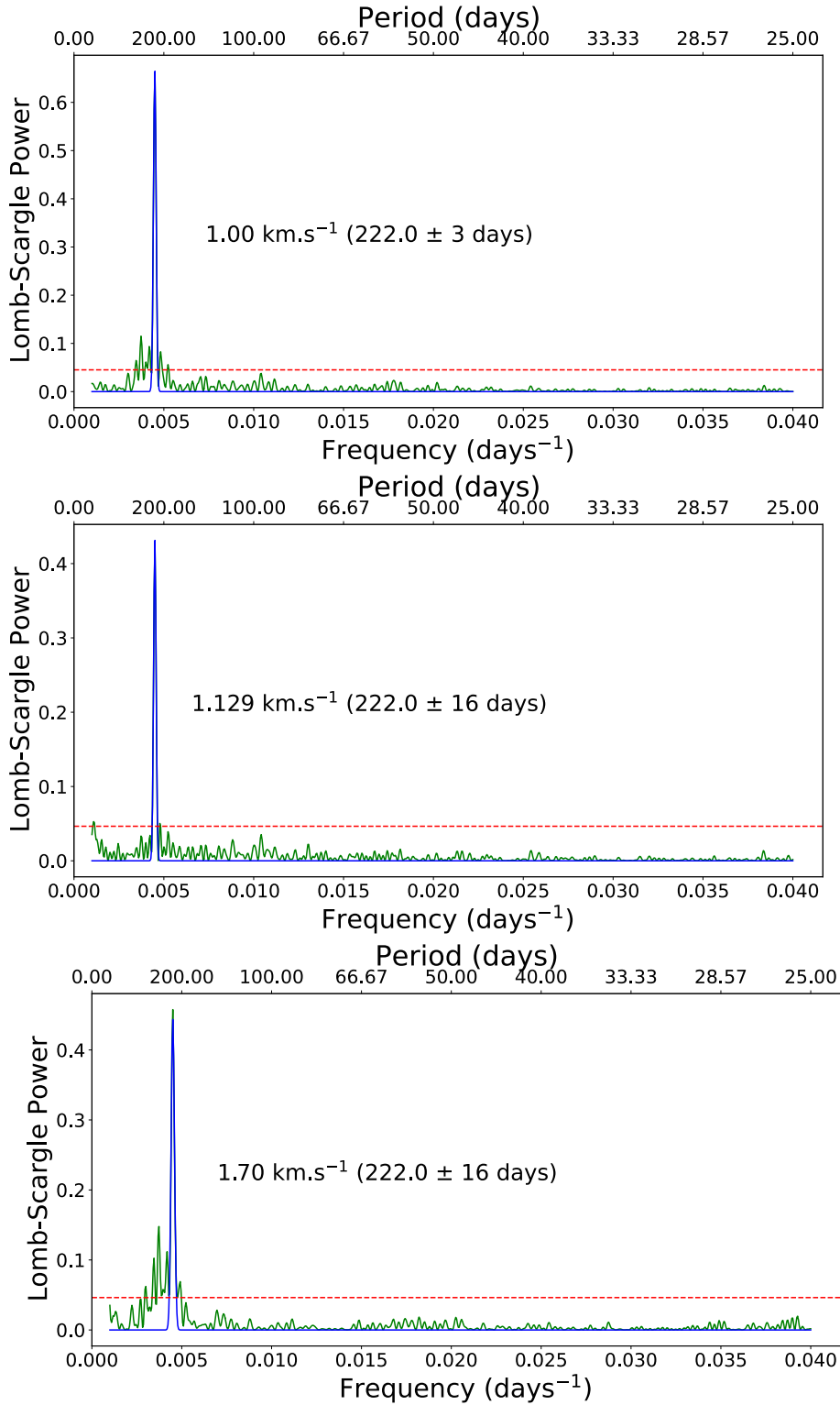


Figure 5.9: Periodicity search of Maser source G358.460 - 0.391 in channels 1.00 km.s⁻¹, 1.129 km.s⁻¹ and 1.70 km.s⁻¹ using the Lomb-Scargle method. A Gaussian function is fitted to the Lomb-Scargle periodogram; the Gaussian fit enables us to determine the error on the predicted periodicity. The green line indicates the Lomb-Scargle periodogram and the blue line indicates the Gaussian fit to the periodogram.

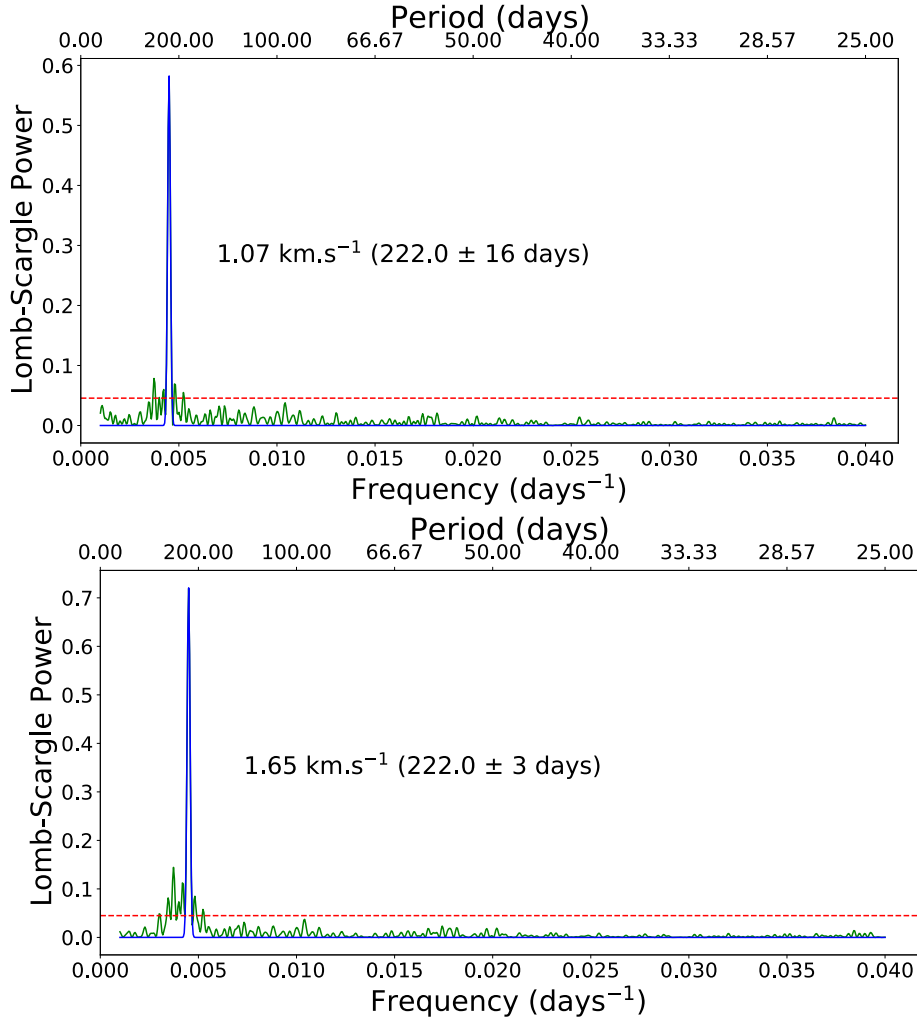


Figure 5.10: Periodicity search of Maser source G358.460 - 0.391 in main feature and weaker spectrally blended feature. Light curves determined from Gaussian fitting. The green line indicates the Lomb-Scargle periodogram and the blue line indicates the Gaussian fit to the periodogram.

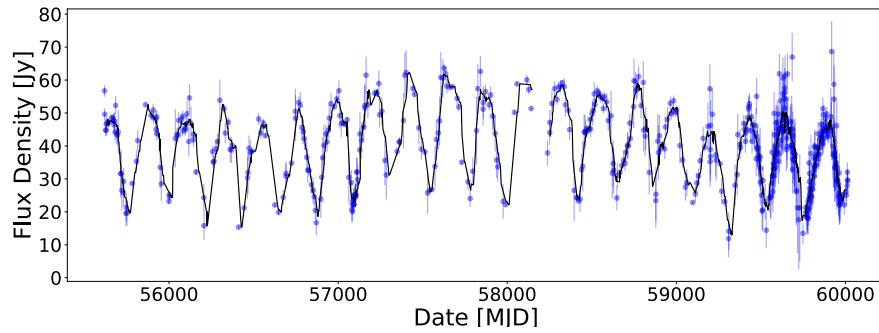


Figure 5.11: Kernel-density estimation of the light curve corresponding to maser source G358.460 - 0.391 at $v_{\text{cen}} \sim 1.00 \text{ km.s}^{-1}$

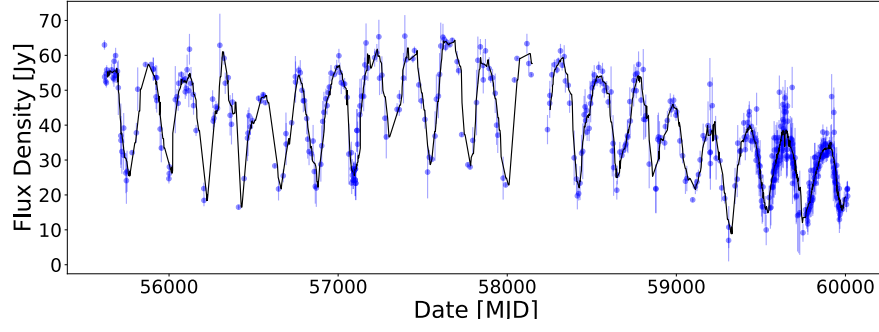


Figure 5.12: Kernel-density estimation of the light curve corresponding to maser source G358.460 - 0.391 at $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$

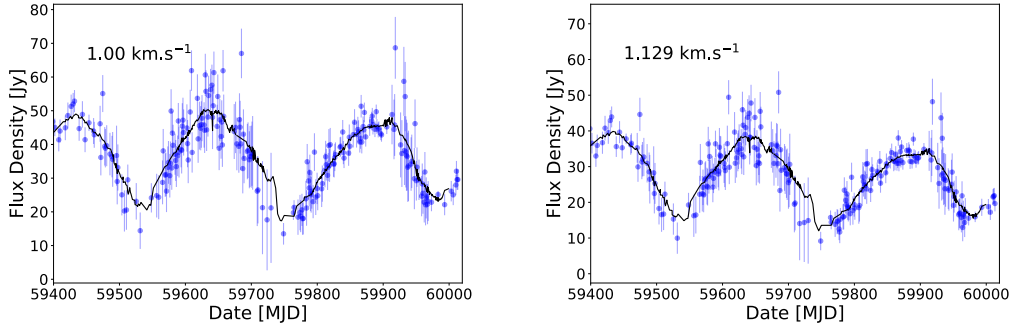


Figure 5.13: High cadence points with KDE fit for $v_{\text{cen}} \sim 1.00 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$

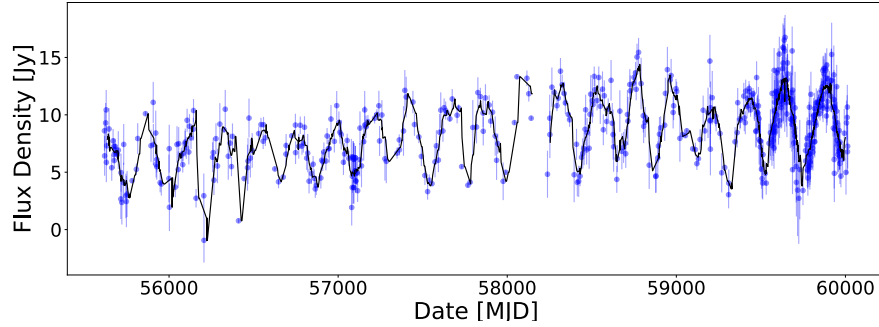


Figure 5.14: Kernel-density estimation of the light curve corresponding to maser source G358.460 - 0.391 at $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$

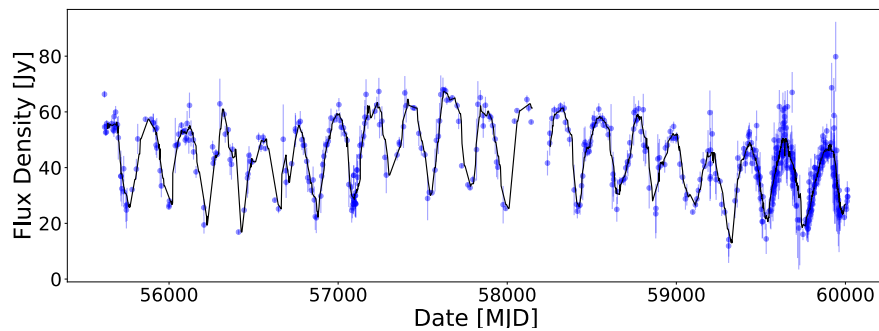


Figure 5.15: Light curve of G358.460-0.391 at $V_{\text{Peak}} \text{ km.s}^{-1}$

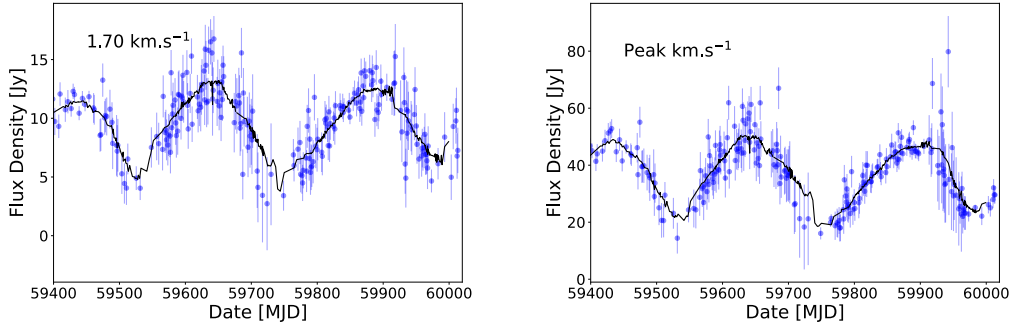


Figure 5.16: High cadence points with KDE fit for $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$ and peak flux density measurements

provided which show only the behaviour of the data around the minima in velocity channels of interest. The behaviour observed around the minima, such as symmetrical or asymmetrical profiles, sharpness of the minima, duration of the minima, and other noteworthy features, may aid in understanding the surrounding environmental conditions and driving mechanisms of maser behaviour.

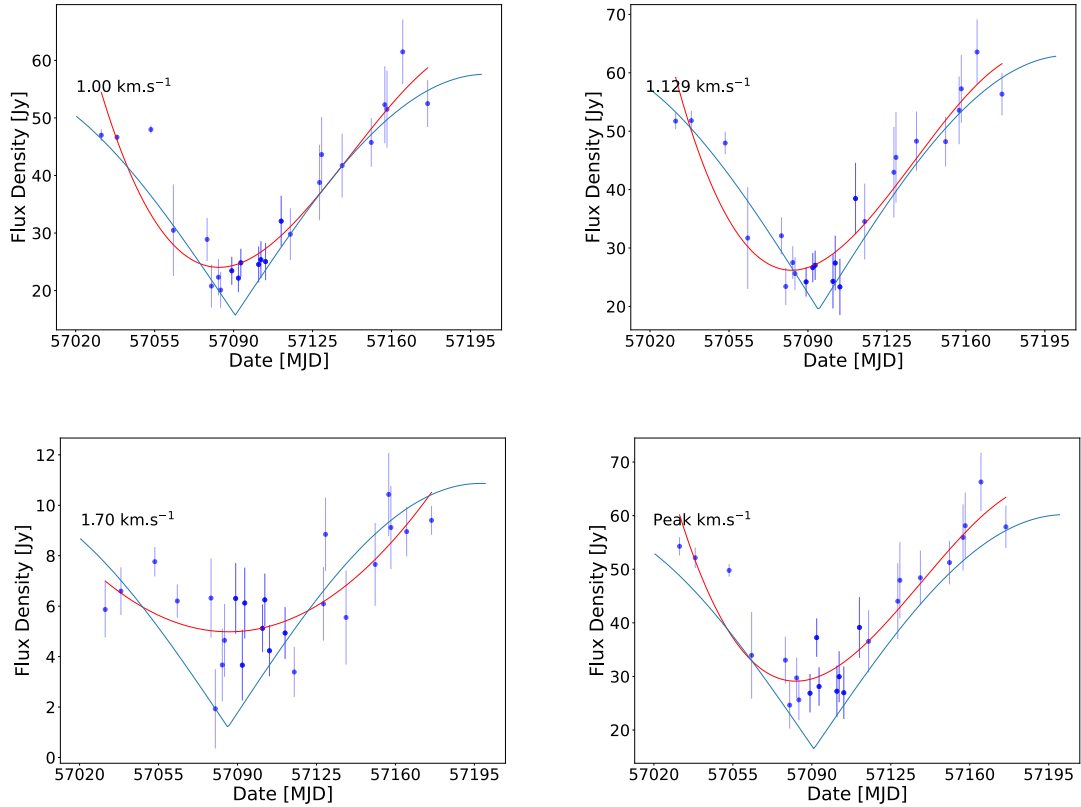


Figure 5.17: Minima zoom in different velocity channels between the dates of 57020 MJD and 57200 MJD. The scatter points represent the observational data with corresponding error bars, the solid blue line represents the absolute cosine fit to the data set, and, the red line represents a polynomial fit to exclusively the minima data shown in each individual figure.

Figures 5.17 to 5.22 show the behaviour of the light curves around selected periods of minima. The blue scatter represents the data points with error bars determined during the Kernel-density estimations of the light curves. The blue line represents the absolute cosine fit to the

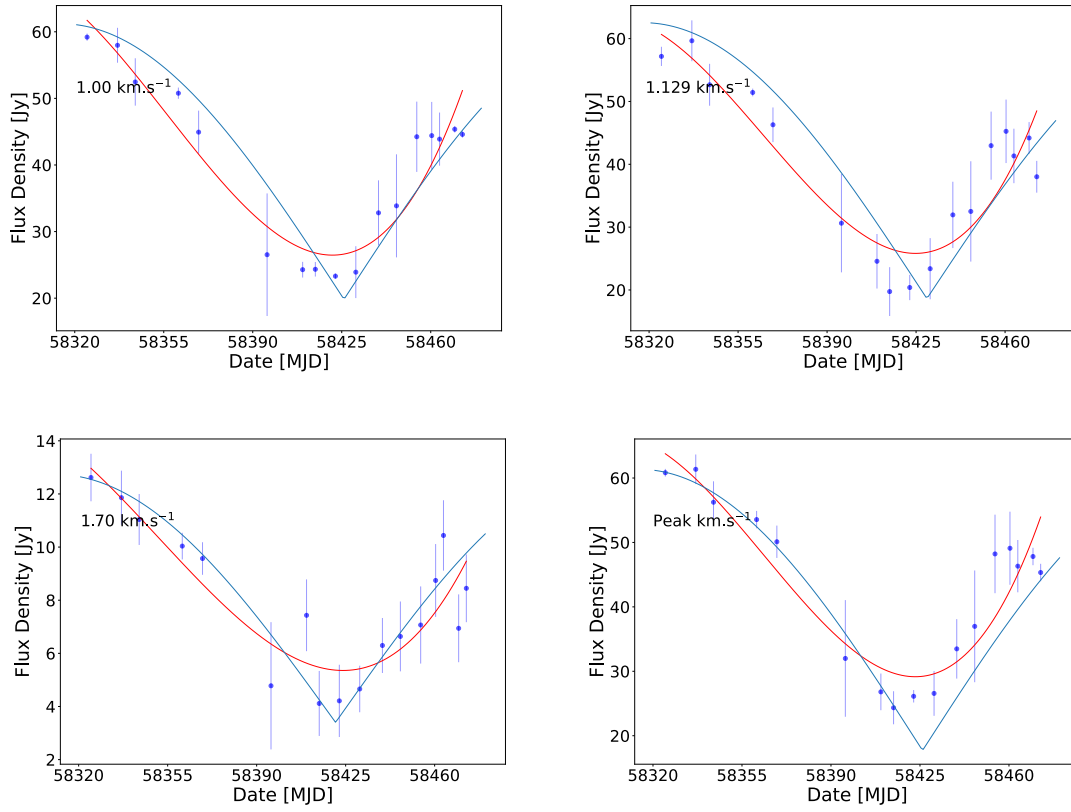


Figure 5.18: Minima zoom in different velocity channels between the dates of 58320 MJD and 58480 MJD

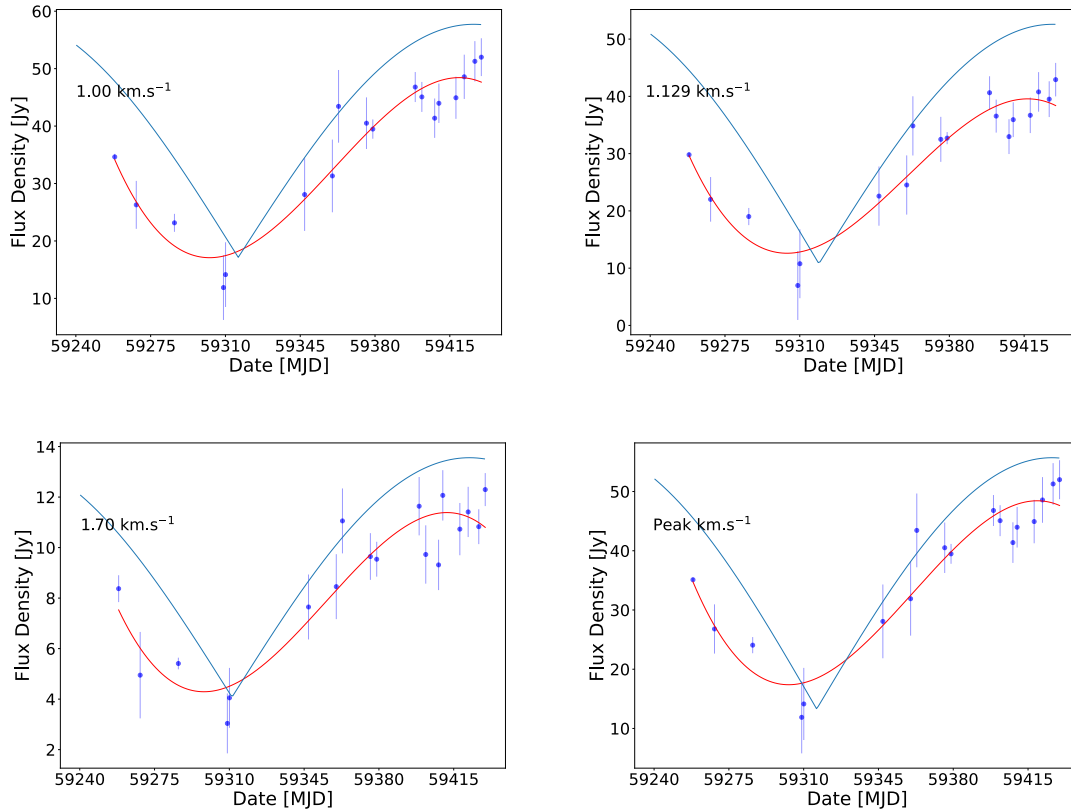


Figure 5.19: Minima zoom in different velocity channels between the dates of 59240 MJD and 59430 MJD

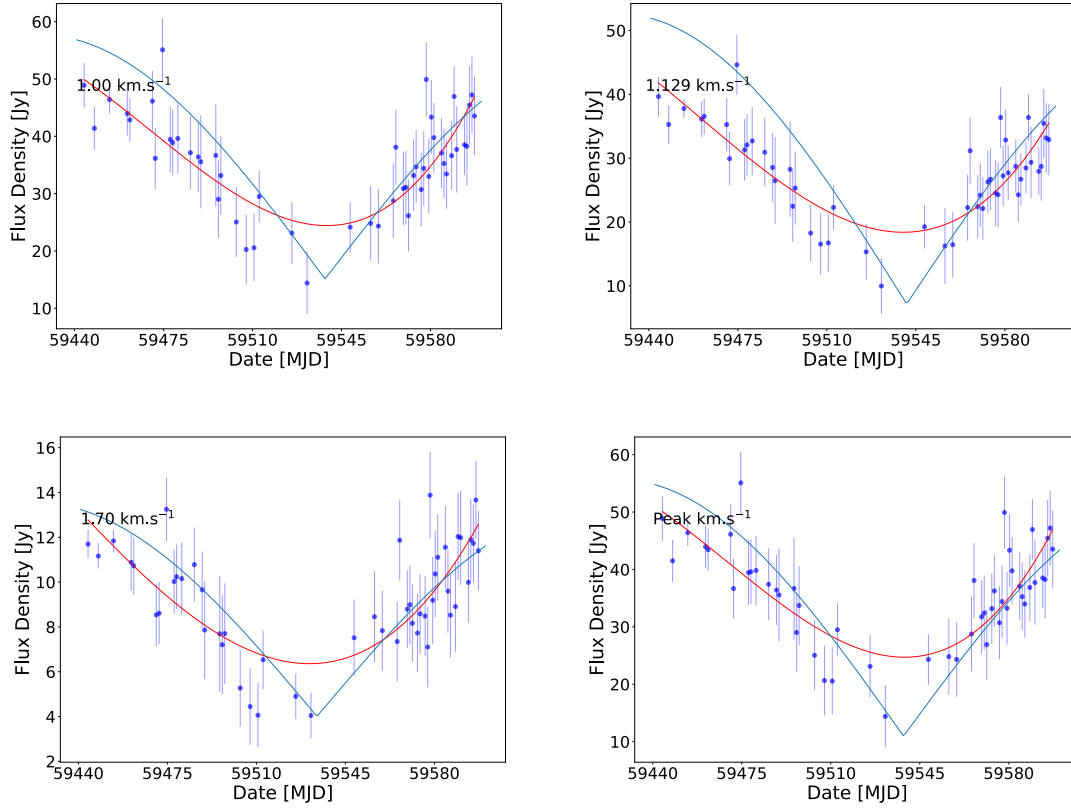


Figure 5.20: Minima zoom in different velocity channels between the dates of 59440 MJD and 59600 MJD.

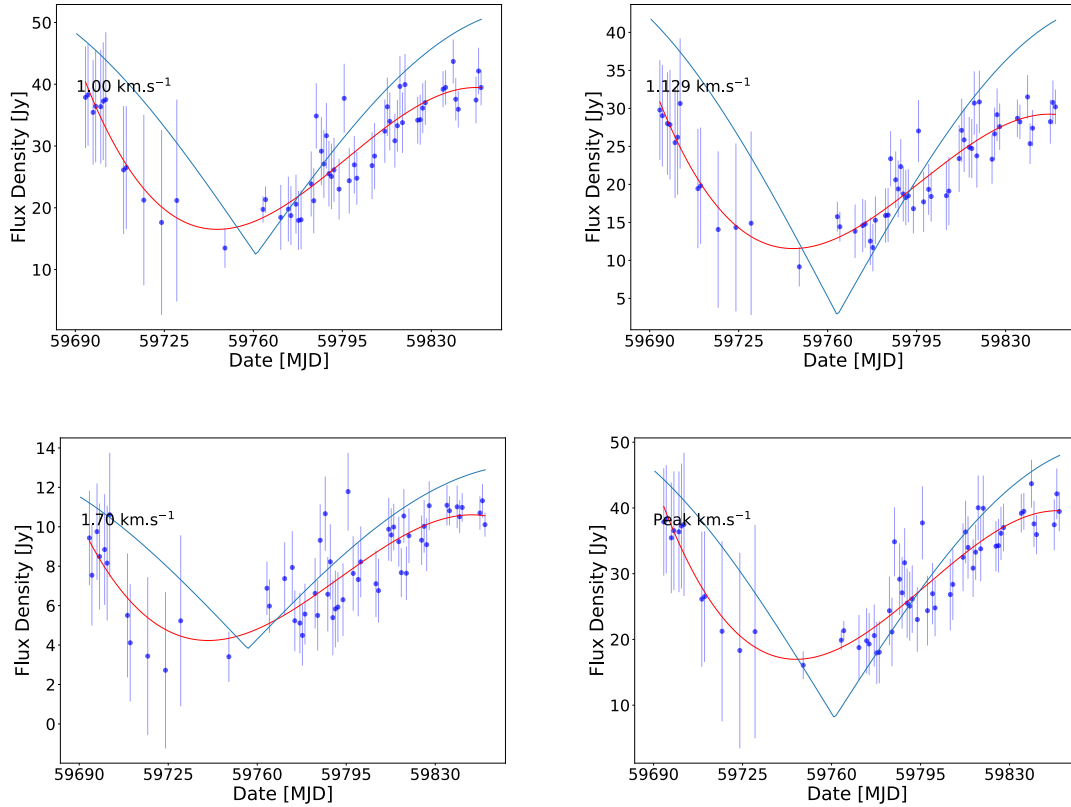


Figure 5.21: Minima zoom in different velocity channels between the dates of 59690 MJD and 59850 MJD

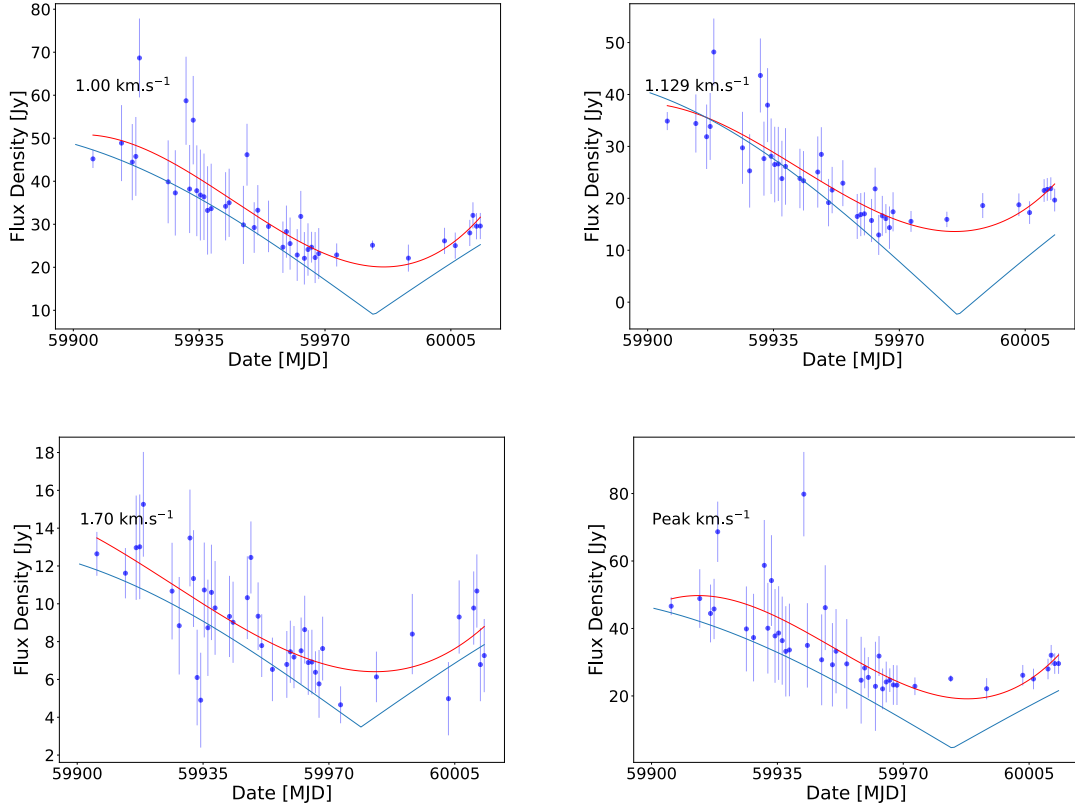


Figure 5.22: Minima zoom in different velocity channels between the dates of 59690 MJD and 59850 MJD with Kernel density estimation

data, and the red line is a polynomial fit to the data points. Figure 5.23 shows the folded light curves of maser source G358.460 - 0.391. Folded light curves are valuable tools in periodic maser sources as they show the long-term behaviour and repeatability of a periodic source over its determined period.

5.6 Gaussian validation, Dynamic Spectra, and Velocity Drifts

Velocity drifts have been observed in both water and methanol masers. Szymczak et al. (2014) and Szymczak et al. (2015) report on maser features associated with Cepheus A and G22.375 + 0.066; these drifts fell within the ranges of $\sim 1 - 3 \times 10^{-4} \text{ km s}^{-1} \text{ d}^{-1}$ and $\sim 6.5 \times 10^{-4} \text{ km s}^{-1} \text{ d}^{-1}$ respectively. These observed velocity drifts may be due to variations of close or line blended features, in-falling gas, or disc precession (Szymczak et al., 2014, 2015; MacLeod et al., 2021). Blended features refer to cases where maser features with similar line-of-sight velocities overlap, resulting in an altered flux or spectral observation. In the analysis of the masers associated with G358.460 - 0.391, velocity drifting was observed as can be seen in figures 5.24, and 5.28. Figure 5.24 shows the determined velocity drift as a dashed line on the dynamic spectra as well as the relatively stable behaviour of the blended feature at $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$. Velocity drifting was observed in the maser source associated with G358.460 - 0.393, as can be seen in figures 5.25 and 5.26. The drift of maser feature associated with G358.460 - 0.393 at $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$ is more significant than the velocity drifts associated

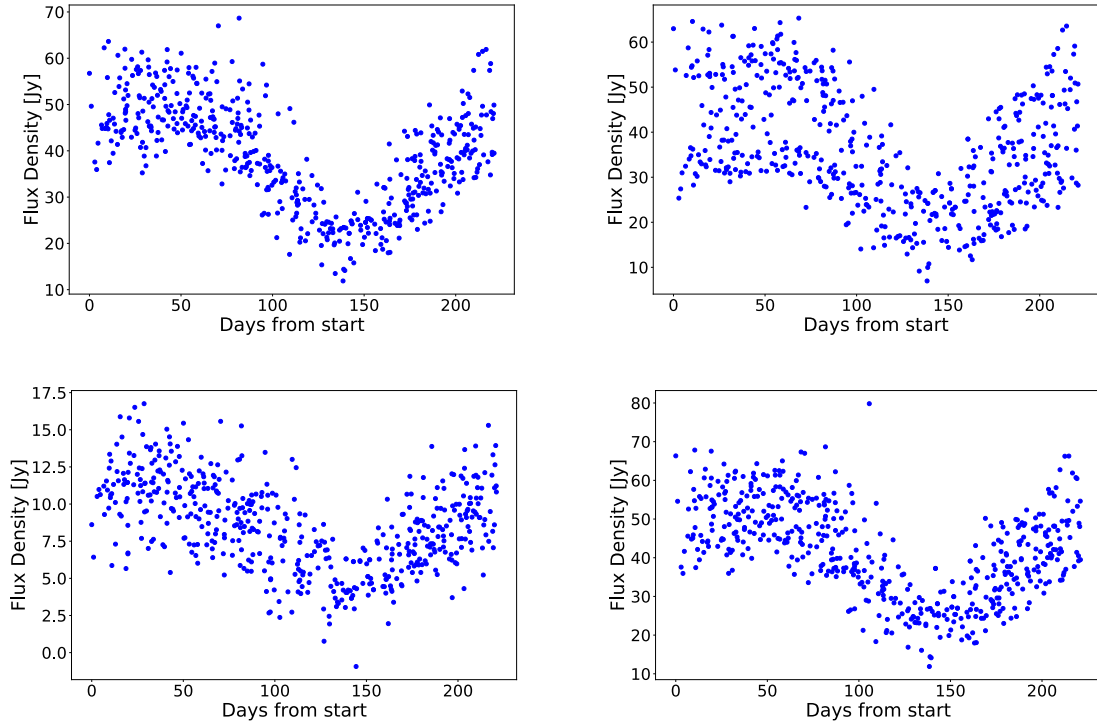


Figure 5.23: Folded light curves. First row: (Left) 1.00 km.s⁻¹ folded modulo 222 days (Right) 1.129 km.s⁻¹ folded modulo 222 days. Second row: (Left) 1.70 km.s⁻¹ folded modulo 222 days (Right) Peak flux density measurements folded modulo 222 days.

with G358.460 - 0.391; however a lower goodness-of-fit, R -squared, value was determined of 0.44 or 44%.

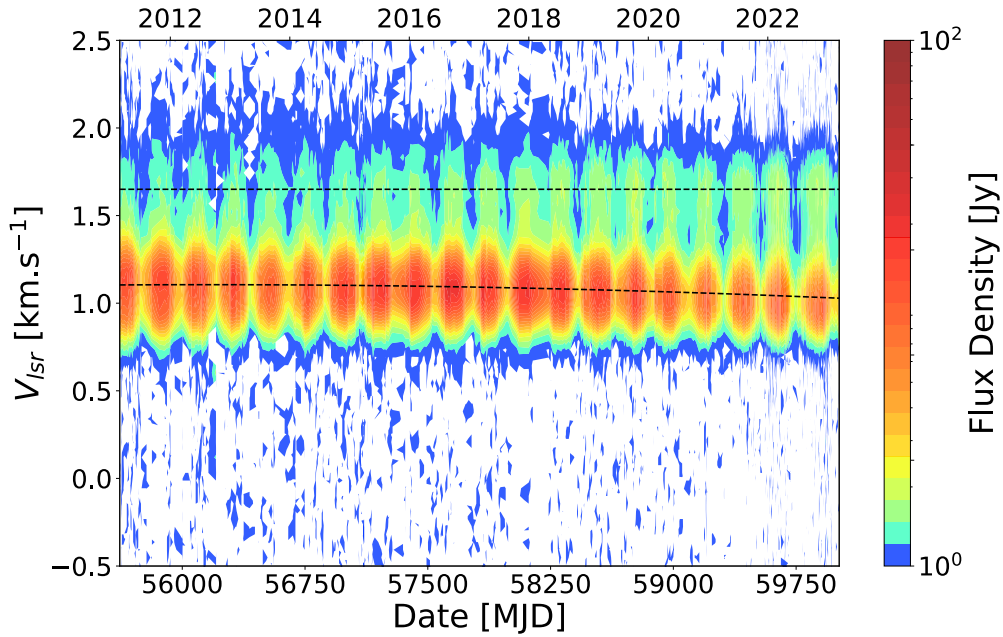


Figure 5.24: Dynamic Spectra of maser source G358.460 - 0.391 with velocity drifts determined from Gaussian fitting displayed on the figure. The Gaussian evaluation of the minor feature, $v_{cen} \sim 1.65$ km.s⁻¹, determined no drift. The drift line at $v_{cen} \sim 1.65$ km.s⁻¹ is approximately horizontal.

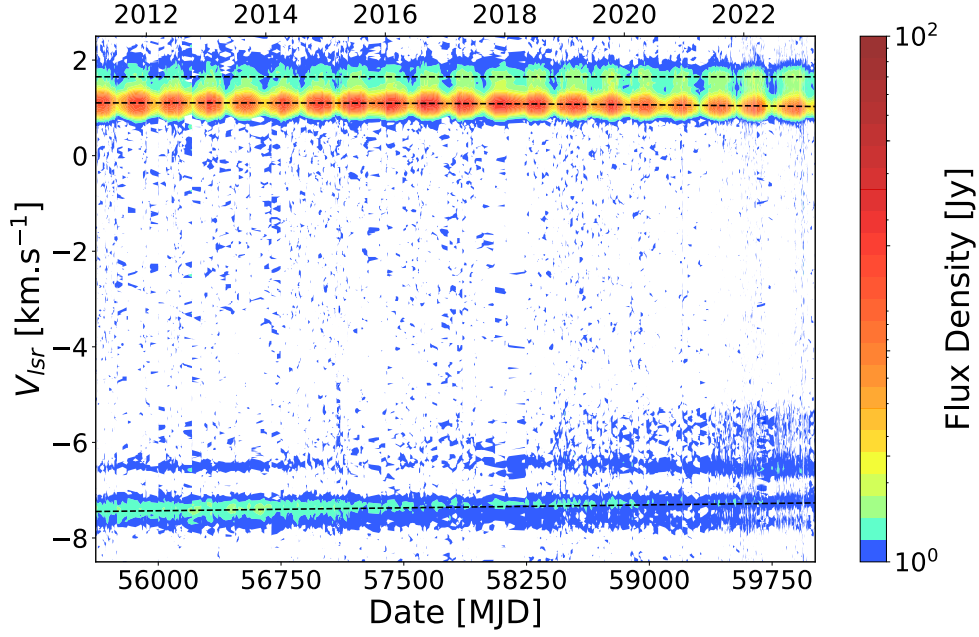


Figure 5.25: Dynamic Spectra of maser source G358.460 - 0.391 and G358.460 - 0.393

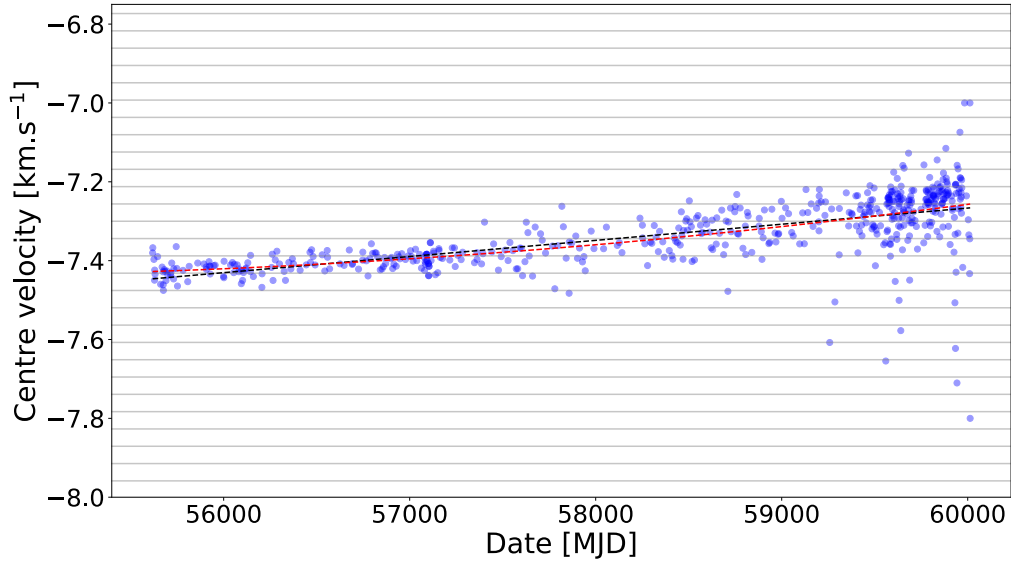


Figure 5.26: Velocity drift of G358.460 - 0.393 determined using Gaussian validation; the linear fit of the drift yields a goodness of fit value of $R^2 \sim 44\%$ and the second order fit to the drift yields a goodness of fit value of $R^2 \sim 44\%$. From the first order fit G358.460 - 0.393 is drifting at approximately $(4.096 \pm 0.79) \times 10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$. The error is determined within a 95% confidence interval.

Figure 5.27 shows a histogram distribution of the central velocity measurements of the main feature as determined by Gaussian evaluation. The histogram distribution shows that the central velocity is not confined to a singular value or within a singular velocity channel throughout the observational period, but rather, the drift results in the central velocity measurements being distributed over three velocity channels with an average central velocity at $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$. Figure 5.28 displays the data points of the central velocity values of the individual observations as well as the linear and second-order fits to the data points. The linear fit to the velocity drift yielded a goodness of fit value of $R^2 \sim 88\%$, and the second-order fit to the drift yielded a goodness of fit value of $R^2 \sim 95\%$; the second-order fit is superior from both visual inspection and R^2 evaluation. There is some data scattering around the regression model fits to the data, therefore, as an additional check the distribution of residuals around the fit was evaluated as can be seen in figure 5.29. In figure 5.29 it can be seen that the residuals around the data fit follow a Gaussian distribution which is the expected result if the fit accurately represents the underlying behaviour of the data.

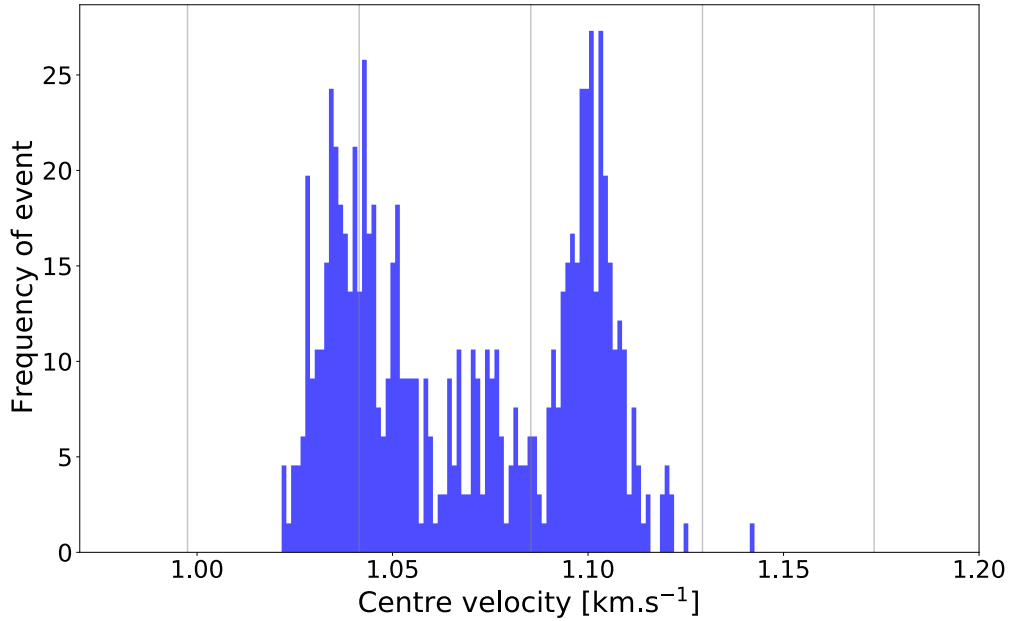


Figure 5.27: Distribution of central velocity measurements, as predicted by Gaussian evaluation, for maser feature G358.460 - 0.391 $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$ plotted in histogram format. The vertical gray lines indicate the velocity channels of the observation.

5.7 Summary

The absolute cosine fit, KDE, evaluation of high-cadence observations, and folded light curves all confirm the bunny-hop behaviour of maser source G358.460 - 0.391. There are spectrally blended features corresponding to $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$; the main feature has an apparent velocity drift while the weaker feature appears to be relatively stable. Maswanganye et al. (2015) report on the two visible features of maser source G358.460 - 0.391 being located at $v_{\text{cen}} \sim 1.129 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.70 \text{ km.s}^{-1}$ however in this research it was

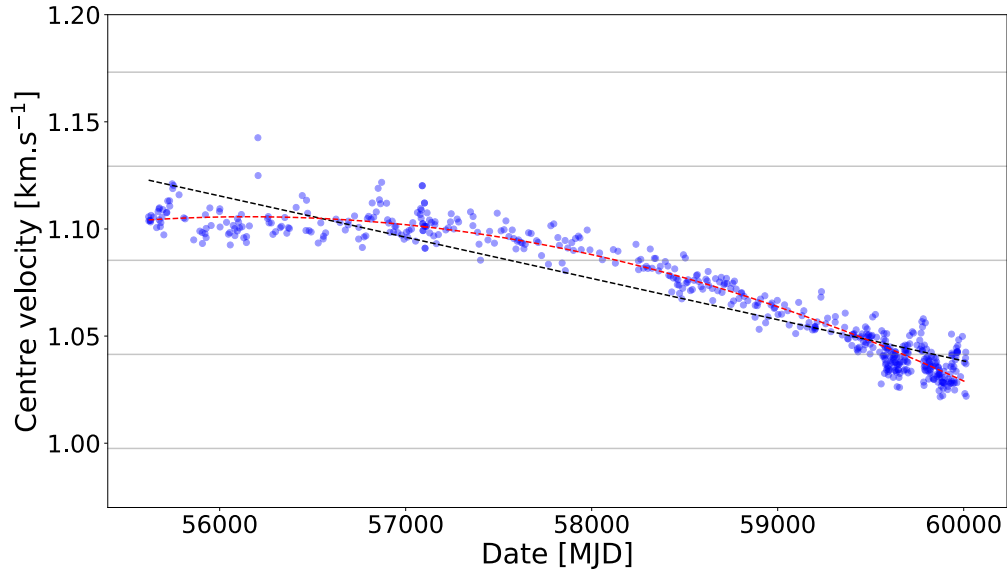


Figure 5.28: Velocity drift of G358.460 -0.391 determined using Gaussian validation; the linear fit yields of the drift yields a goodness of fit value of $R^2 \sim 88\%$ and the second order fit to the drift yields a goodness of fit value of $R^2 \sim 95\%$. The first order prediction of the velocity drift is $\sim (-1.93 \pm 0.12) \times 10^{-5} \text{ km.s}^{-1}\text{d}^{-1}$. The error is determined within a 95% confidence interval.

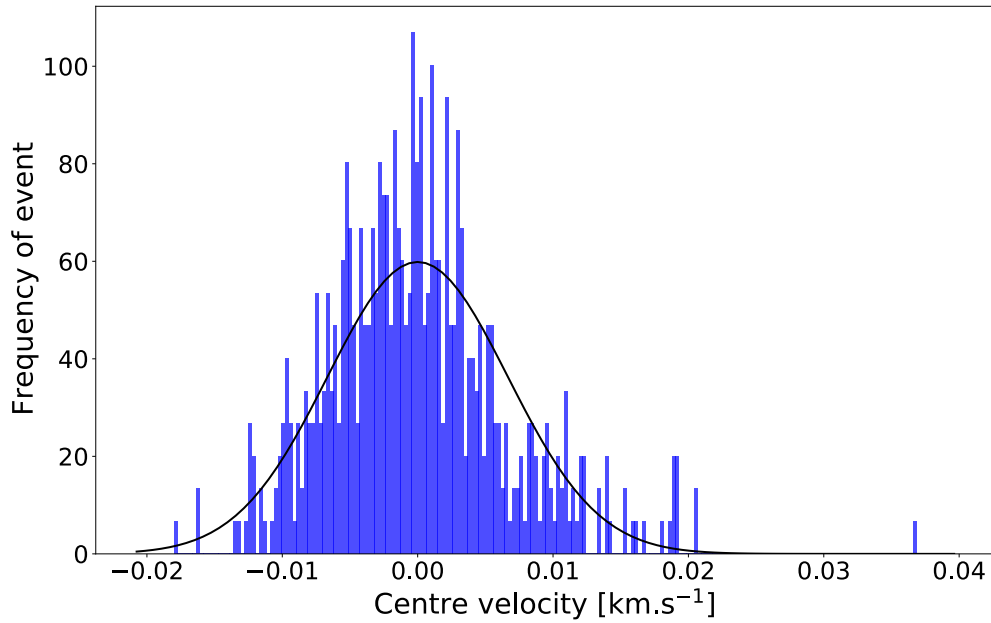


Figure 5.29: The behaviour of the noise is consistent with the Gaussian fit, therefore, the processed data complies with the stochastic behaviour of noise.

found that the two features are more closely associated with $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$. Maser feature associated with G358.460 - 0.393 displays limited variability, however the feature at $v_{\text{cen}} \sim -7.37 \text{ km.s}^{-1}$ appears to display a significant velocity drift over the observational period.

Chapter 6

Survey of Methanol Maser Sources

This chapter presents a thorough dive into archival data of methanol masers observed by the HartRAO 26m telescope. Originally these data were used primarily to search for periodic behaviour in methanol masers. In this research project this data is re-examined for any features or behaviours of interest which may have been previously overlooked. A behaviour which became of interest during the evaluation of these sources was velocity drifting in methanol masers. The data was evaluated using tools such as averaged spectra, dynamic spectra, light curves of individual features, Kernel density estimations to data, Lomb-Scargle periodograms, and folded light curves. Averaged spectra present the average flux density value over observed velocity channels of a maser source. Dynamic spectra presents the behaviour of the maser source over the observation period; where the observation date in Modified Julian Date (MJD) is presented on the x -axis, the LSR (local standard of rest) velocity is presented on the y -axis, and the flux density is given in a heat-map style with a colour-bar corresponding to various flux density values. Dynamic spectra are a very powerful way of representing a large amount of data on a singular plot. Light curves very clearly show the behaviour of the maser source in a constrained velocity region and are helpful in identifying periodicity and flaring behaviour. The Lomb-Scargle periodogram determines periodic behaviour in a source. A Gaussian function is fitted to the main peak of the Lomb-Scargle periodogram allowing for an uncertainty on the periodicity to be determined; the false detection peak is also indicated on the Lomb-Scargle periodograms as a horizontal red dashed line.

6.1 Introduction

A number of methanol masers in high-mass star forming regions have been observed to display variability over various timescales and magnitudes (Goedhart et al., 2004; Szymczak et al., 2018a). The discovery of periodic variability in a number of methanol maser sources was an unexpected result (Goedhart et al., 2003, 2005, 2014; Szymczak et al., 2011; Fujisawa et al., 2014; Maswanganye et al., 2015; Szymczak et al., 2015). Periodic maser sources have been observed to have flux density changes with periods in the range of 24 to 600 days (Goedhart et al., 2004, 2014; Fujisawa et al., 2014; Szymczak et al., 2015). Periodicity can occur in multiple features of a maser source; behaviour in different features of a maser source

can be uncorrelated, correlated, or anti-correlated. Time lags are also sometimes observed in correlated and anticorrelated maser features. This survey is aimed at not only detecting periodicity but also velocity drifts and any other interesting and previously overlooked features. Velocity variations have been detected in water and methanol masers. [Szymczak et al. \(2018a\)](#) measured velocity drifts in methanol maser features associated with four high-mass star forming regions.

Table 6.1: List of the currently known periodic methanol masers

	Source	Frequency (GHz)	Period (days)	Published by
(1)	G9.62+0.19	6.7 & 12.2	243.3	Goedhart et al. (2003)
(2)	G12.681-0.18	6.7	307	Goedhart et al. (2004)
(3)	G12.89+0.49	6.7 & 12.2	29.5	Goedhart et al. (2009)
(4)	G14.23-0.50	6.7	23.9	Sugiyama et al. (2017)
(5)	G22.357+0.066	6.7	178.1	Szymczak et al. (2015)
(6)	G24.148-0.009	6.7	182	Olech et al. (2019)
(7)	G25.411+0.105	6.7	245	Szymczak et al. (2015)
(8)	G30.400-0.296	6.7	222	Olech et al. (2019)
(9)	G33.641-0.228	6.7	540	Olech et al. (2019)
(10)	G36.705+0.096	6.7	53	Sugiyama et al. (2015)
(11)	G37.55+0.20	6.7	237	Araya et al. (2010)
(12)	G45.473+0.134	6.7	195.7	Szymczak et al. (2015)
(13)	G59.633-0.192	6.7	149	Olech et al. (2019)
(14)	G73.06+1.80	6.7	160	Szymczak et al. (2015)
(15)	G75.76+0.34	6.7	119.9	Szymczak et al. (2015)
(16)	G107.298+5.639	6.7	34.6	Fujisawa et al. (2014)
(17)	G108.76-0.99	6.7	163	Olech et al. (2019)
(18)	G188.95+0.89	6.7 & 12.2	395	Goedhart et al. (2014)
(19)	G196.45-1.6	6.7	668	Goedhart et al. (2004)
(20)	G323.46-0.08	6.7	93.5	Proven-Adzri et al. (2019)
(21)	G328.24-0.55	6.7 & 12.2	220.5	Goedhart et al. (2014)
(22)	G331.13-0.24	6.7	509	Goedhart et al. (2014)
(23)	G338.93-0.06	6.7 & 12.2	132.8	Goedhart et al. (2014)
(24)	G339.986-0.425	6.7 & 12.2	246	Maswanganye et al. (2015)
(25)	G339.62-0.12	6.7	200.3	Goedhart et al. (2014)
(26)	G358.460-0.391	6.7	220.0	Maswanganye et al. (2015)
(27)	G45.804-0.356	6.7	416.9	Olech et al. (2022)
(28)	G49.043-1.079	6.7	469.3	Olech et al. (2022)

6.2 Notes on Individual Sources

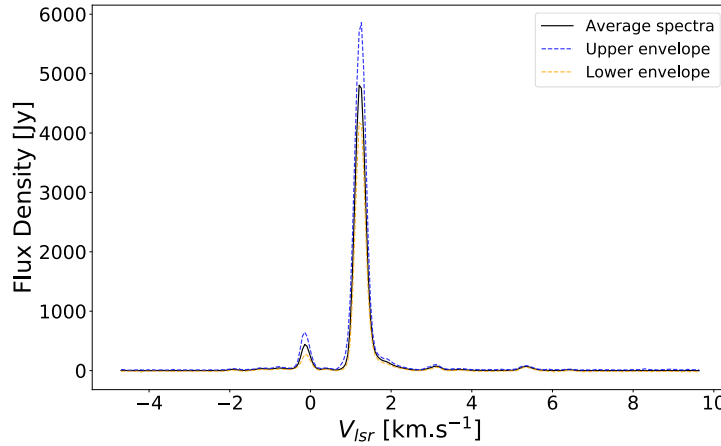
The archival data used in this section to search is from a monitoring programme which spanned from January 1999 to September 2002. The monitoring programme utilised the 26-metre HartRAO telescope with observations occurring in intervals of one to two weeks; the cadence of the observations was increased if rapid variations in the source was detected. Observing parameters for the monitoring programme are summarised in table 6.2. When the monitoring programme was conducted sources were observed either with a bandwidth of 0.32 MHz, which provides good velocity resolution, or with a bandwidth of 0.64 MHz which provides a larger velocity range of observations.

Table 6.2: Observing parameters for archival HartRAO sources

Rest frequency (MHz)	6668.518	
System temperature (K)	50	
Half Power Beamwidth (deg)	0.133	
Number of channels	256	
Bandwidth (MHz)	0.64	0.32
Velocity range (km.s ⁻¹)	28	14
Spectrometer resolution (km.s ⁻¹)	0.112	0.056

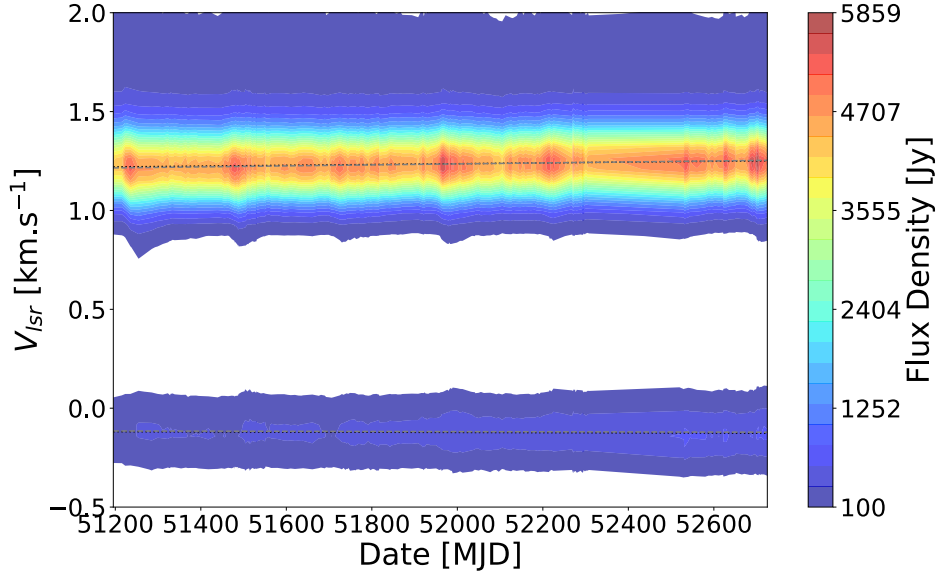
6.2.1 G9.62 + 0.2

Maser feature associated with G9.62 + 0.2 is a complex of HII regions with associated massive young stellar objects (MYSO) and methanol masers (Goedhart, 2004; MacLeod et al., 2021). Observations show that the associated methanol maser features peaks at $\sim 1.26 \text{ km.s}^{-1}$ and $\sim -0.14 \text{ km.s}^{-1}$; the methanol maser features are currently assumed to be associated with an ultra-compact HII-region (UCHII) (Goedhart, 2004; MacLeod et al., 2021). Methanol maser features associated with G9.62 + 0.2 show strong flaring behaviour in investigated channels (Goedhart, 2004; MacLeod et al., 2021).

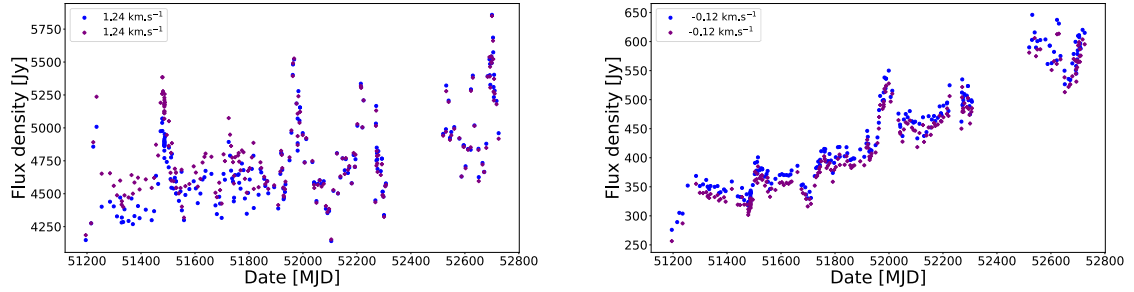


G9.62 + 0.2 averaged spectrum with upper and lower envelope.

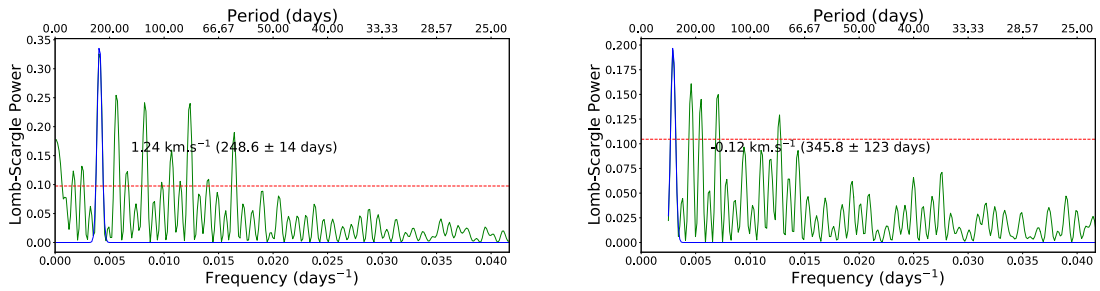
The weak feature at $v_{\text{cen}} \sim -0.12 \text{ km.s}^{-1}$ was determined to have a periodicity of ~ 347 days; the main feature at $v_{\text{cen}} \sim 1.24 \text{ km.s}^{-1}$ was determined to have a periodicity of ~ 246 days, this finding is consistent with previous observations of G9.62 + 0.2 (Goedhart, 2004; Goedhart et al., 2014). There does also seem to be compelling evidence for a velocity drift, particularly in the velocity range surrounding 1.24 km s^{-1} ; visual inspection of the fit as well as a high goodness of fit value on the Gaussian evaluation support the finding of a velocity drift, see following dynamic spectra and associated table. The archival data used in this project have insufficient observation periods and inadequate correlator resolution for hard conclusions to be made; however these results are useful as a reference for future research efforts. Velocity drifts in maser source G9.62 + 0.2 have been observed by other researchers such as MacLeod et al. (2021) who propose that systemic velocity drifts of associated methanol masers may be due to infalling material of the inner radius of the accretion disc; alternatively drifting may be a result of masers in a precessing disc.



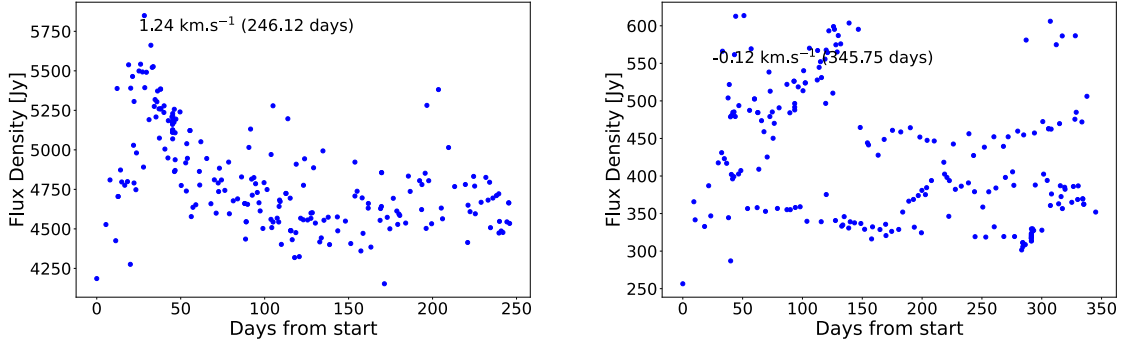
G9.62 + 0.2 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.



G9.62 + 0.2 light curves determined from Gaussian fitting and a channelised approach; the blue dot markers represent the data from the channelised approach and the purple cross markers represent the data from Gaussian fitting.



G9.62 + 0.2 Lomb-Scargle periodograms determined from the Gaussian determined light curves; a Gaussian function to the main peak determines the uncertainty or error on the period and the vertical red line defines the false detection peak.



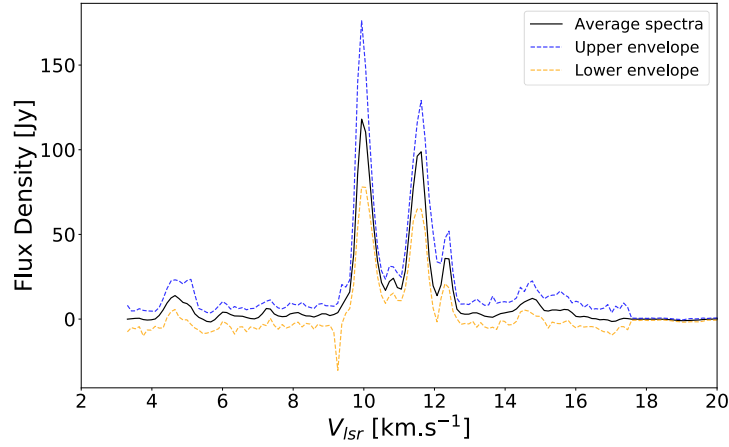
G9.62 + 0.2 folded light curves, maser feature corresponding to 1.24 km.s^{-1} and -0.12 km.s^{-1} folded modulo 246 days and 345 days respectively. The folded light curve for the feature maser at 1.24 km.s^{-1} very clearly shows the sharp rise and slow decay of the periodic behaviour. The folded light curve for the feature at -0.12 km.s^{-1} is less distinct, likely due to the large error on the periodicity estimation.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G9.62 +	1.24	2.52	2	0.312	2.05	79
0.2	-0.12	-0.41	1	0.273	-0.50	23

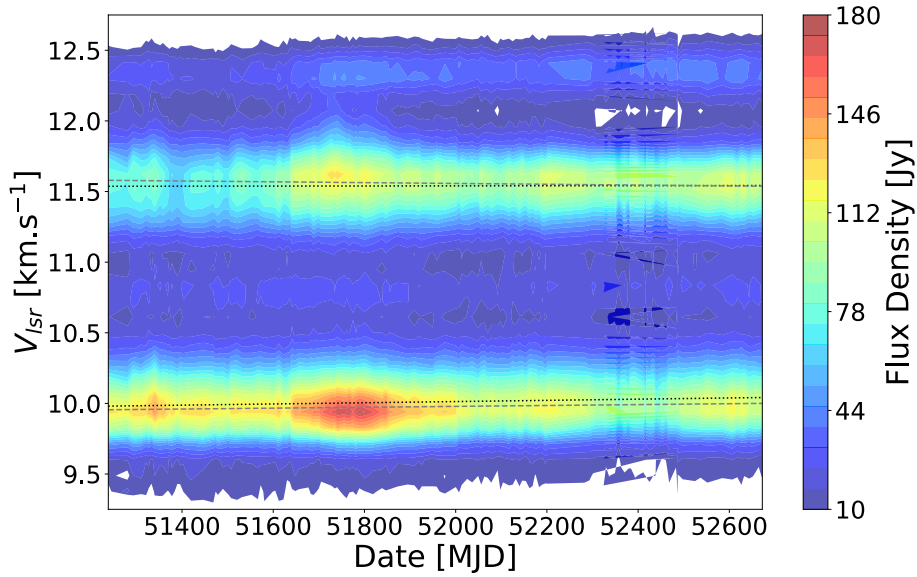
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.2 G10.33 - 0.17



G10.33 - 0.17 averaged spectrum with upper and lower envelope.



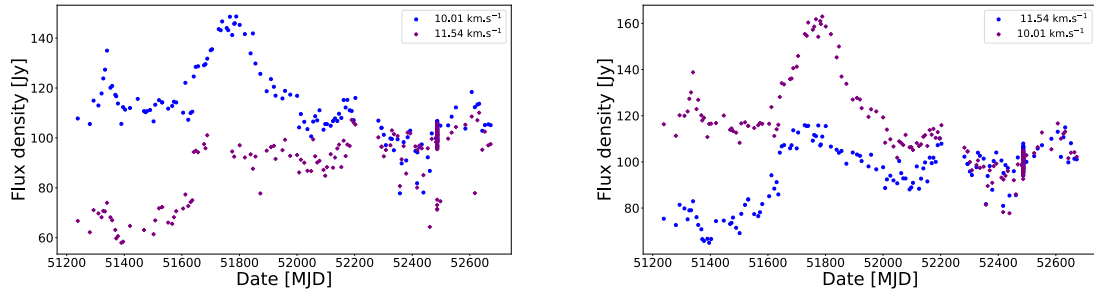
G10.33 - 0.17 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G10.33 -	10.01	3.14	3	0.55	4.25	75
0.17	11.54	-2.90	1	0.70	0.38	1

^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

From visual inspection of the dynamic spectra, the determined velocity drift fits appear to fit the data well. The stronger feature, $v_{\text{cen}} \sim 10.01$ km.s⁻¹, appears to be a promising drift candidate with a high goodness of fit value for the Gaussian evaluation, $R^2 \sim 75\%$.

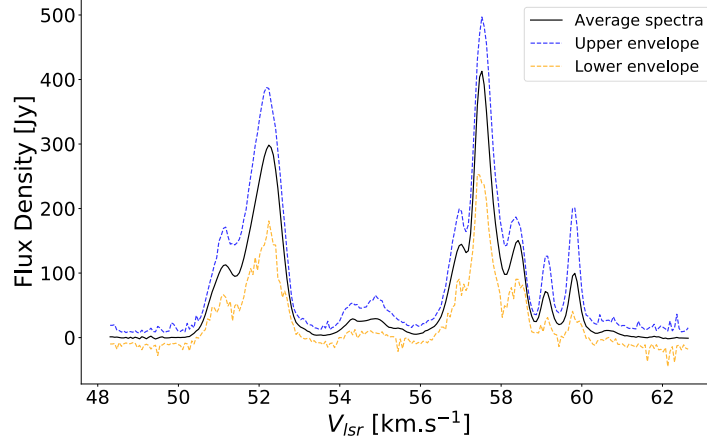


G10.33 - 0.17 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach

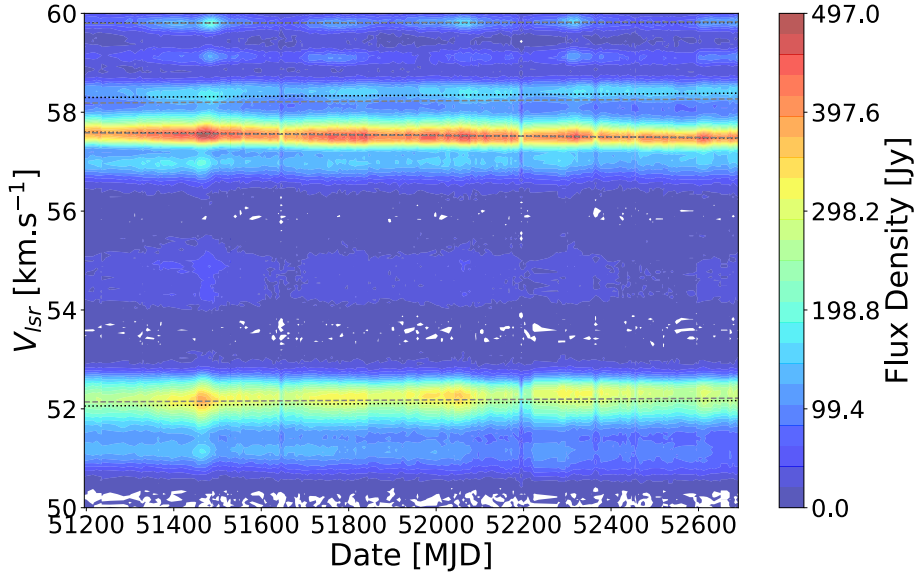
More observations of this source with improved correlator resolution will be beneficial in constraining the drift value and confirming findings in the weaker channel. Poor correlator resolution of 0.112 km.s^{-1} does not lend itself to high levels of confidence in the precise findings of this source.

6.2.3 G12.68 - 0.18 (W33B)

Radio source W33 consists of HII regions G12.80 - 0.20, which is strong and compact, and G12.68 - 0.18, which is fainter with a more extended structure (Colom et al., 2015). This region is a source of strong 6.7 GHz methanol maser emission (Colom et al., 2015).

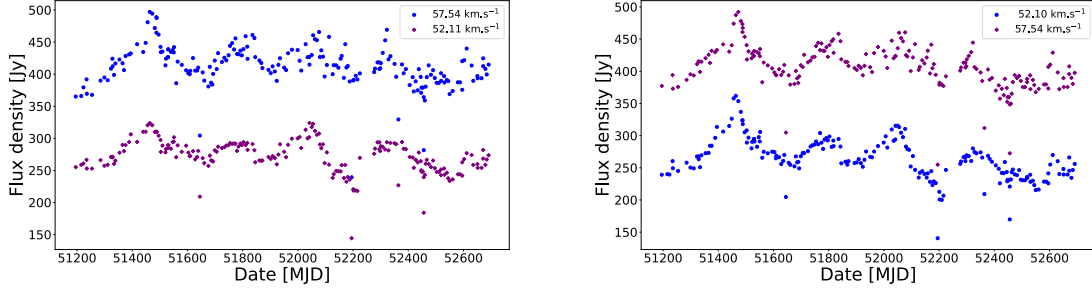


G12.68 - 0.18 averaged spectrum with upper and lower envelope.

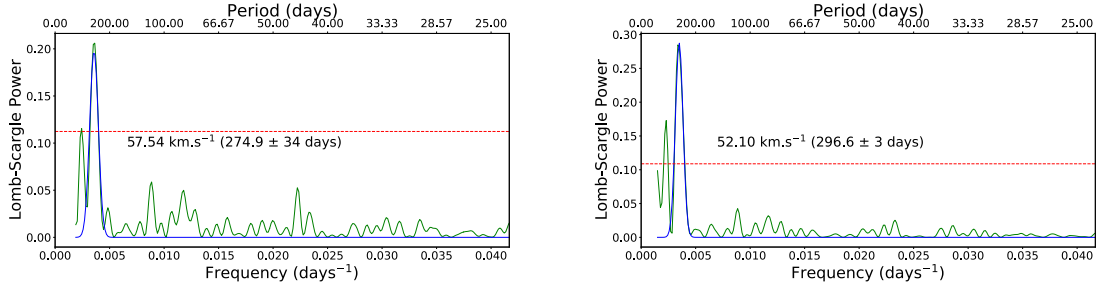


G12.68 - 0.18 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

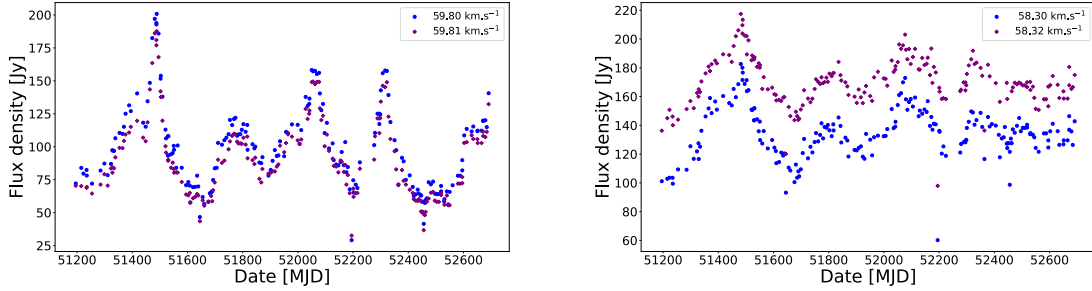
The spectrum associated with G12.68 - 0.18 has several features, many of these features were found to display periodic behaviour and velocity drifting, see associated figures and table. There are several properties observed within this source which offer a high level of confidence that the observed velocity drifts at $v_{\text{cen}} \sim 52.09 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 57.54 \text{ km.s}^{-1}$ are real. Firstly, the features are strong with high flux-density measurements and acceptable noise levels. Secondly, velocity drifts of individual features occur over multiple velocity channels. Additionally, the velocity drifts in the investigated features differ significantly, therefore the



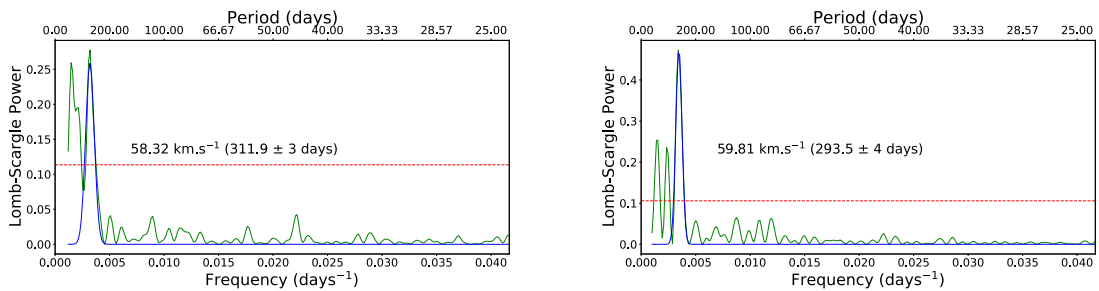
G12.68 - 0.18 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach



G12.68 - 0.18 Lomb-Scargle evaluation for maser features associated with velocity channels 57.54 km.s^{-1} and 52.10 km.s^{-1} respectively.



G12.68 - 0.18 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach



G12.68 - 0.18 Lomb-Scargle maser features associated with velocity channels 58.32 km.s^{-1} and 59.81 km.s^{-1} respectively.

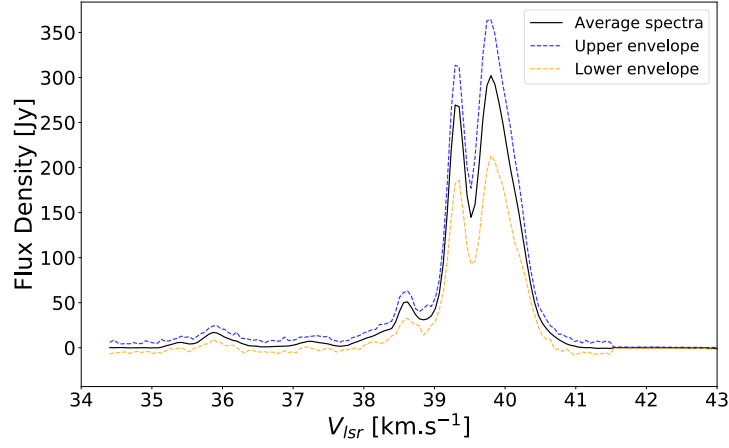
drift is likely not an instrumental artefact of the observation, but rather an intrinsic feature of the maser source. Finally, a high goodness of fit value in the Gaussian evaluation gives an additional layer of confidence that the observed phenomenon is real; both features associated with $v_{\text{cen}} \sim 52.09 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 57.54 \text{ km.s}^{-1}$ have goodness of fit values of 90% and greater. The feature associated with $\sim 58.32 \text{ km.s}^{-1}$ had a goodness of fit value above 50%. The maser source appears to have regular flaring which can be described as cyclical or quasi-periodic; similar claims were made by [Goedhart et al. \(2004\)](#). All investigated features appear to display simultaneous flaring over cyclical timescales of approximately 290 to 310 days. This source is described as quasi-periodic rather than periodic since the shape and magnitude of the flares are inconsistent over the observational period. Lomb-Scargle evaluation of the data revealed periodicity measurements above the false detection peak.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)
G12.68 - 0.18	57.54	-6.88	13	0.57	-7.51	93
	52.09	6.32	2	1.05	7.41	90
	58.32	5.59	4	0.38	5.85	69
	59.81	1.98	2	0.28	0.43	2

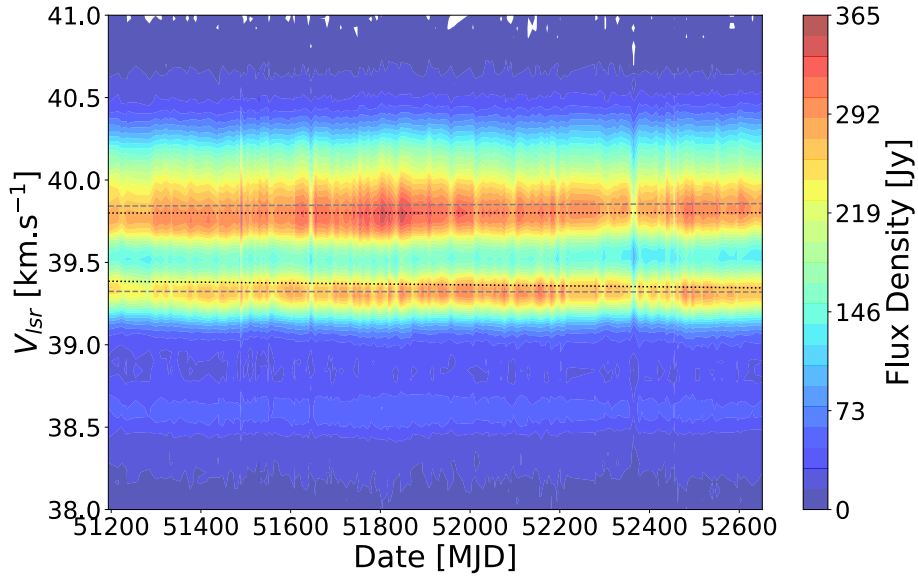
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.4 G12.91 - 0.26 (W33A)

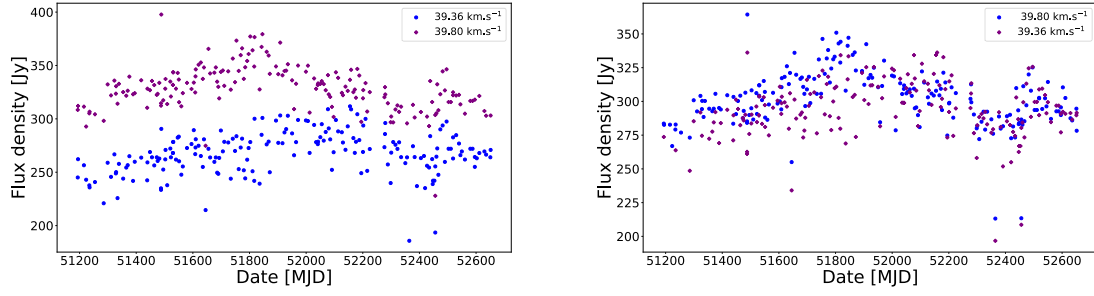


G12.91 - 0.26 averaged spectrum with upper and lower envelope.



G12.91 - 0.26 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

The possibility of maser source G12.91 - 0.26 displaying velocity drifts seems promising based on visual inspection of the velocity drift as well as a reasonable goodness of fit value to the Gaussian evaluation of the main feature, $R^2 > 50\%$. However longer term, high cadence observations will be necessary in confirming this finding. The maser features display moderate variability. The maser spots have previously been found to be distributed in a linear distribution (Goedhart, 2004).



G12.91 - 0.26 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

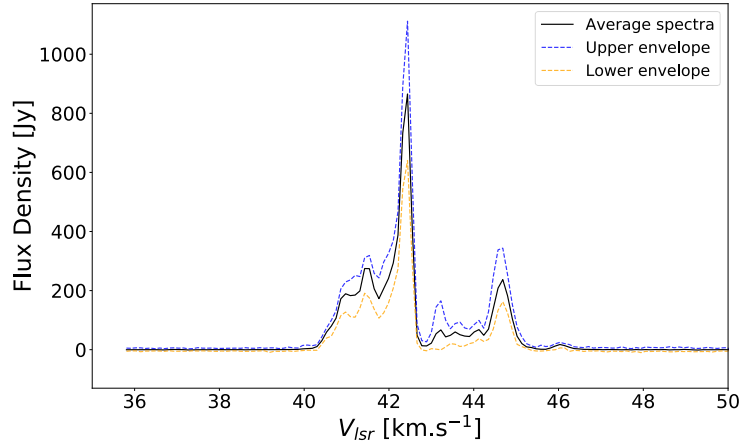
Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G12.91 -	39.36	2.05	1	0.31	0.13	12
0.26	39.81	-0.26	0	0.57	-2.77	74

^a Linear regression fitting to associated velocities of determined flux densities.

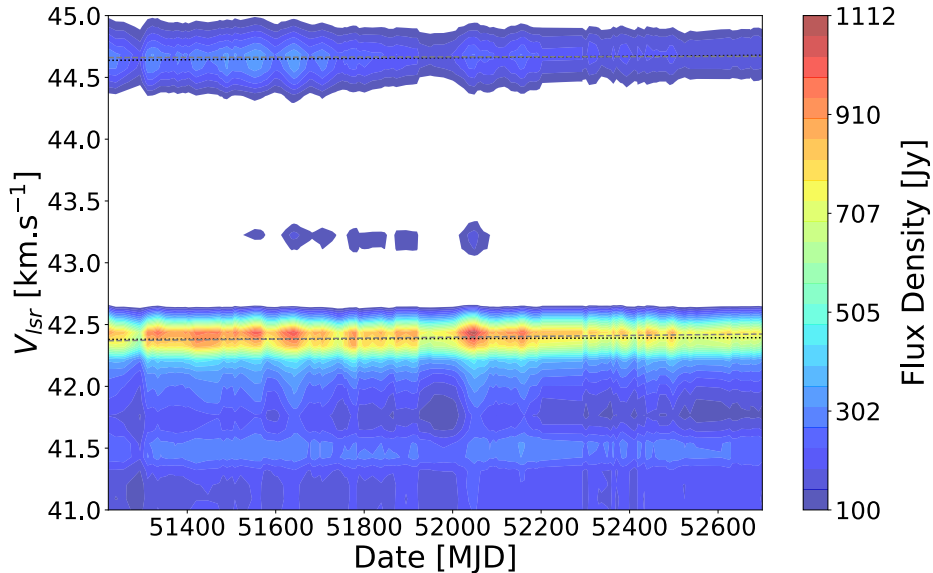
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.5 G35.20 - 1.74

The region W48A is a well known region of massive star formation; W48A is home to numerous high-mass protostellar objects, HII regions, and is associated with photodissociation whereby molecules are broken down by photons (Chibueze et al., 2020). G35.20 - 1.74 is associated with 6.7 GHz methanol maser emission indicating the presence of a high-mass protostellar object. Chibueze et al. (2020) found that G35.20 - 1.74 likely hosts a disc outflow system where 6.7 GHz methanol masers trace the disc and water masers trace a bipolar outflow.

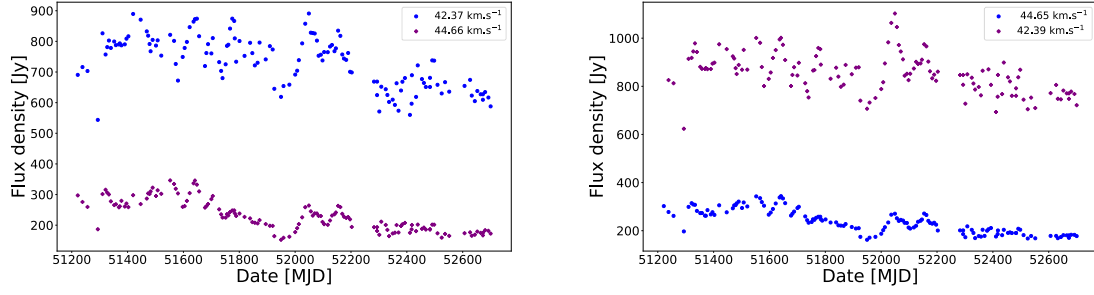


G35.20 - 1.74 averaged spectrum with upper and lower envelope.



G35.20 - 1.74 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G35.20 - 1.74 has one very strong and distinct feature as well as several smaller and more minor features. The strong feature at $v_{\text{cen}} \sim 42.37 \text{ km.s}^{-1}$ did not display adequate evidence of a velocity drift; the weaker feature at $v_{\text{cen}} \sim 44.65 \text{ km.s}^{-1}$ did display evidence



G35.20 - 1.74 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

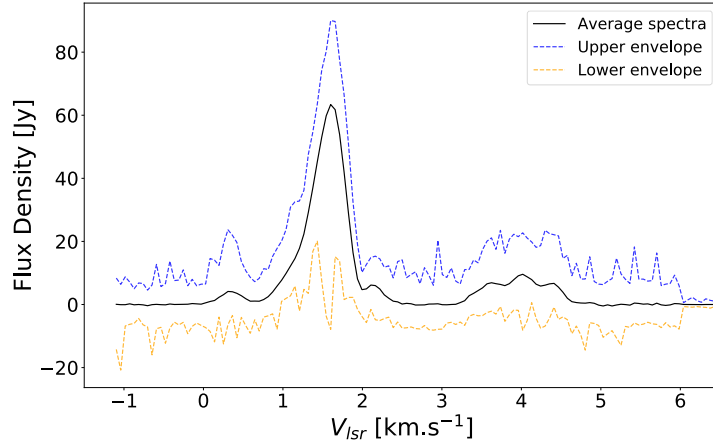
of a velocity drift. The feature at $\sim 44.65 \text{ km.s}^{-1}$ yielded goodness of fit value above 50%; however, the drifts did not cross over multiple velocity channels, the correlator resolution was only 0.112 km.s^{-1} , and the data set consisted of only 138 observations which is not a very high cadence. As a result of insufficient observations and resolution, there is insufficient evidence that the determined velocity drifts are reliable findings. More observations will be necessary with improved resolution and higher cadence would be necessary in order to confirm and constrain these findings. Both maser features displayed moderate variability.

Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)	
G35.20 -	42.37	0.65	0	0.28	0.95	25	
1.74	44.65	3.63	7	0.47	2.74	57	

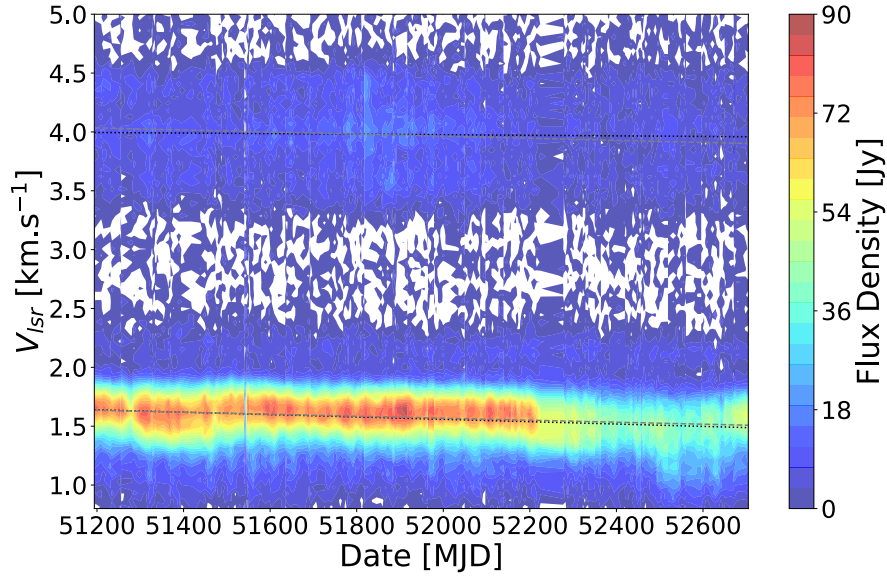
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.6 G174.20 - 0.08

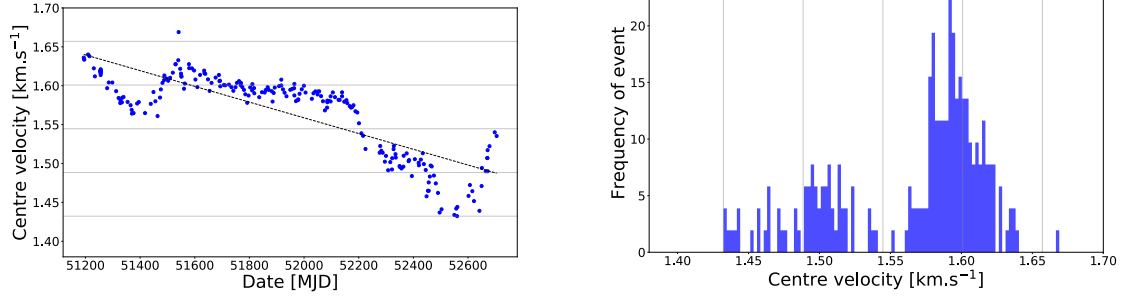


G174.20 - 0.08 averaged spectrum with upper and lower envelope.

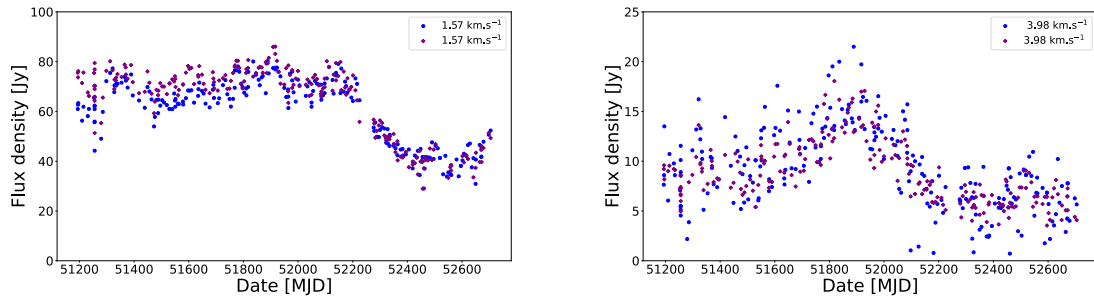


G174.20 - 0.08 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

In maser source G174.20 - 0.08 two velocity drifts have been detected, the drift present in the strongest feature $v_{\text{cen}} \sim 1.57 \text{ km.s}^{-1}$ is of interest as it does not appear to follow a linear drifting behaviour as can be seen in the plot of centre velocity over time. The drifting behaviour measured does seem to be influenced by changes in flux density; longer observational data would be of value in order to accurately define the drifting behaviour.



The above figures (left) show the velocity drift of maser source associated with G174.20 - 0.08 as determined by Gaussian fitting of the channel centred at 1.57 km.s^{-1} and (right) the spread and frequency of central velocity values as determined through Gaussian fitting. The grey lines represent the velocity channels.



G174.20 - 0.08 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

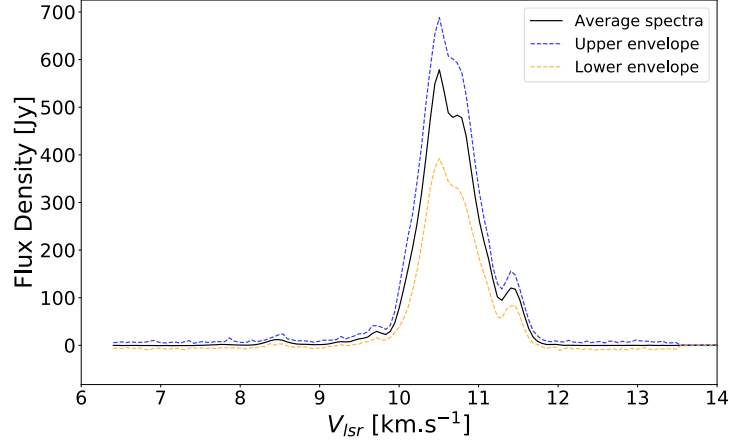
Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)
G174.20	1.57	-8.46	7	0.52	-10.05	69
- 0.08	3.98	-8.80	1	0.93	-2.40	3

^a Linear regression fitting to associated velocities of determined flux densities.

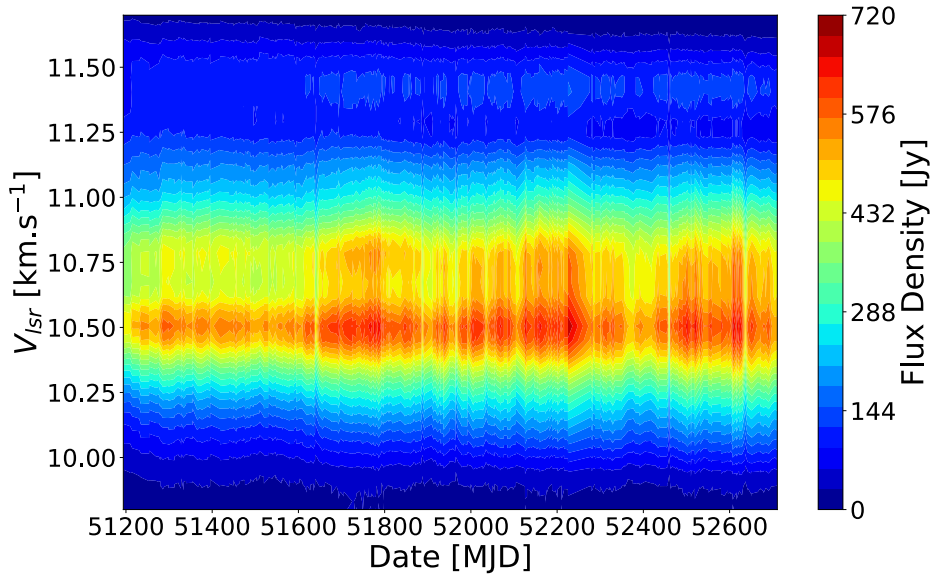
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.7 G188.95 + 0.89

G188.95 + 0.89 is a known source of periodic maser emission; velocity drifting has been observed in this maser source. [Mutie et al. \(2021\)](#) found evidence of a binary system in G188.95 + 0.89 - MM2, evidence supporting the presence of a binary outflow, two measurable velocity drifts in maser source G188.95 + 0.89, and outflows suggesting the presence of an accretion disc.



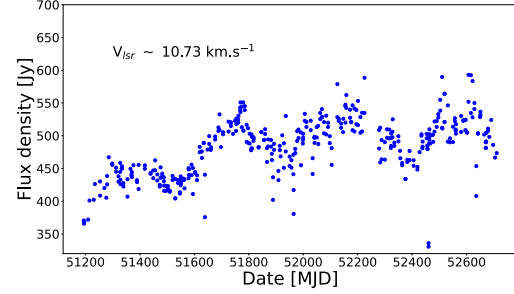
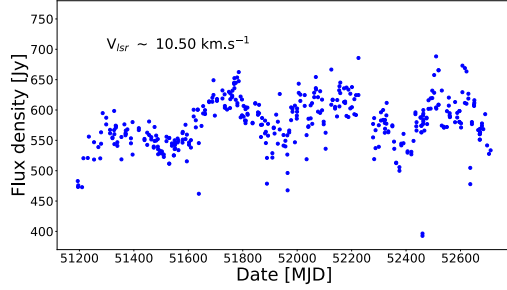
G188.95 + 0.89 averaged spectrum with upper and lower envelope.



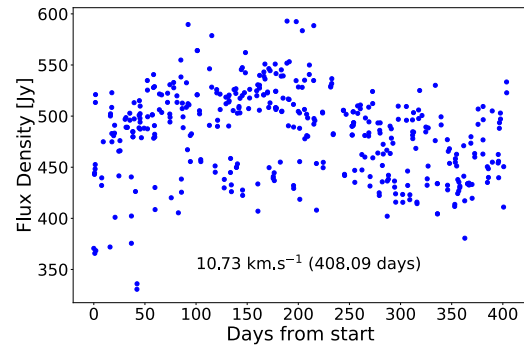
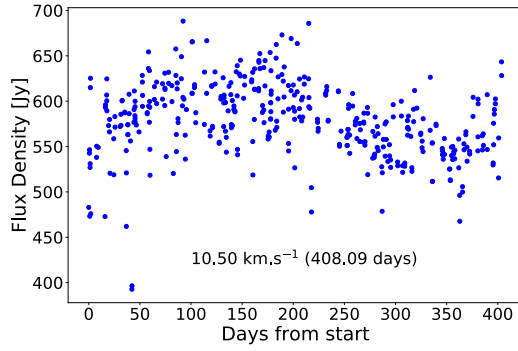
G188.95 + 0.89 Dynamic spectra, heavy line merging can be seen in the velocity regime, this is likely a result of the feature being composed of multiple masers

Velocity drifting has been observed in this source by [Mutie et al. \(2021\)](#); the two velocity drifts with goodness of fit measurements above 50 per cent are $v_{\text{LSR}} = +9.65 \text{ km s}^{-1}$ is blue-shifting at a rate of $-2.38 \pm 0.03 \times 10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$; the other drift $v_{\text{LSR}} = +11.45 \text{ km s}^{-1}$, is red-shifting at a rate of $+1.88 \pm 0.04 \times 10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$ ([Mutie et al., 2021](#)). Additional observations have also constrained the period of the source to be in the range of $397.6 \pm$

0.7 days. The source presents with a bunny hop periodic behaviour with a non horizontal baseline; the minima do not go down to zero or the same minimum value. Investigation into this source did not yield any additional information regarding this source.



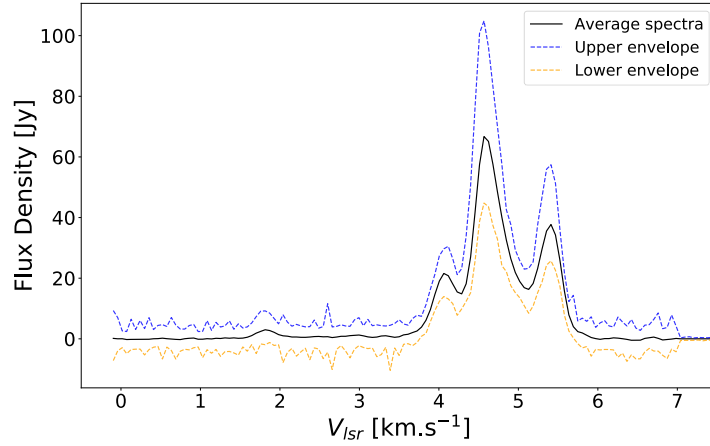
G188.95 + 0.89 light curves determined from Gaussian fitting



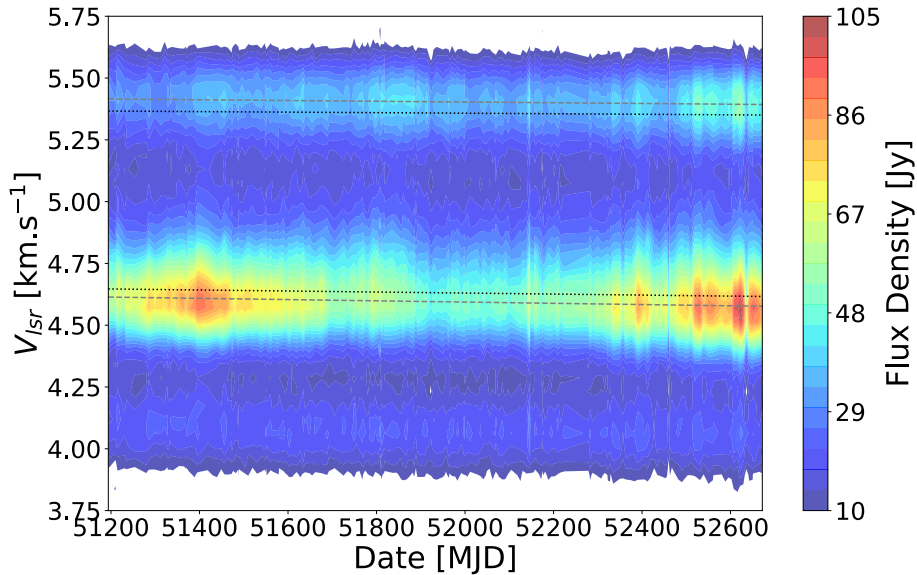
G188.95 + 0.89 folded light curves, maser features corresponding to 10.50 km.s^{-1} and 10.73 km.s^{-1} both folded modulo 408 days. Periodicities were determined by the Lomb-Scargle periodogram.

6.2.8 G192.60 - 0.05 (S255IR-NIRS3)

Maser feature G192.60 - 0.05 (S255IR-NIRS3) is a relatively well studied source; it is associated with a $\sim 20 M_{\odot}$ protostar with a nearly edge-on in rotating disk-like structure (Boley et al., 2013). Maser feature G192.60 - 0.05 has been observed to have an incredibly strong burst after a long quiescent period, ~ 23 years (Szymczak et al., 2018b). The maser luminosity during the burst peak was more than an order of magnitude higher than the luminosity measured during the quiescent period; Szymczak et al. (2018b) proposed that the burst was likely due to an accretion event.

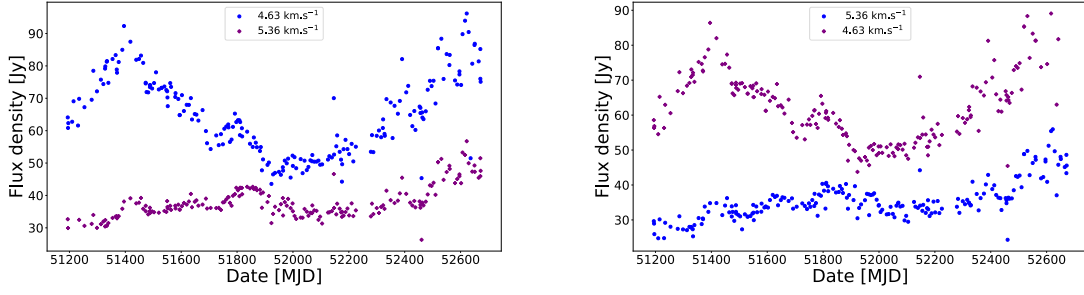


G192.60 - 0.05 averaged spectrum with upper and lower envelope.



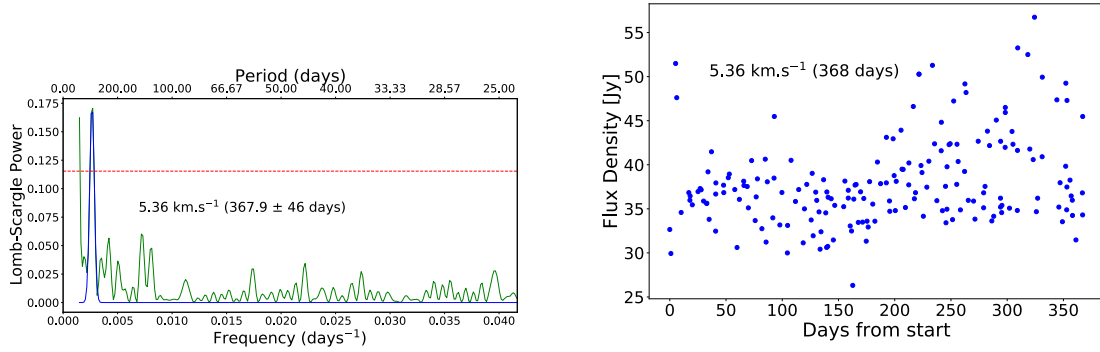
G192.60 - 0.05 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

The averaged spectra of maser source G192.60 - 0.05 (S255IR-NIRS3) has a triple peaked shape often seen in sources residing in discs (Wallin et al., 1998). The light curves of individual features differ from one another in shape; this suggests that the features are either spatially



G192.60 - 0.05 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

separated and their respective regions respond differently to the YSO exciting pulse; or, their physical conditions have significant variations in time. [Szymczak et al. \(2018b\)](#) report on a burst.



G192.60 - 0.05 Lomb-Scargle periodogram and light curve folded modulo 368 days

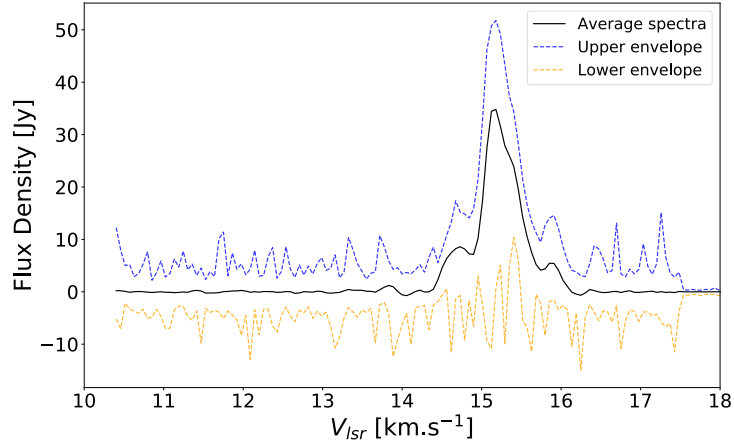
The possibility of velocity drifts being present in this source seems promising; however higher resolution long term monitoring will be necessary to confirm or deny these findings. It is yet to be seen if the velocity drifting behaviour is simply a result of the bursting behaviour of the source. [Szymczak et al. \(2018b\)](#) reported that velocity drifts were observed in peak velocities during the observed burst.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G192.60	4.63	-2.52	4	0.47	-2.06	33
- 0.05	5.36	-1.50	1	0.38	-1.08	30

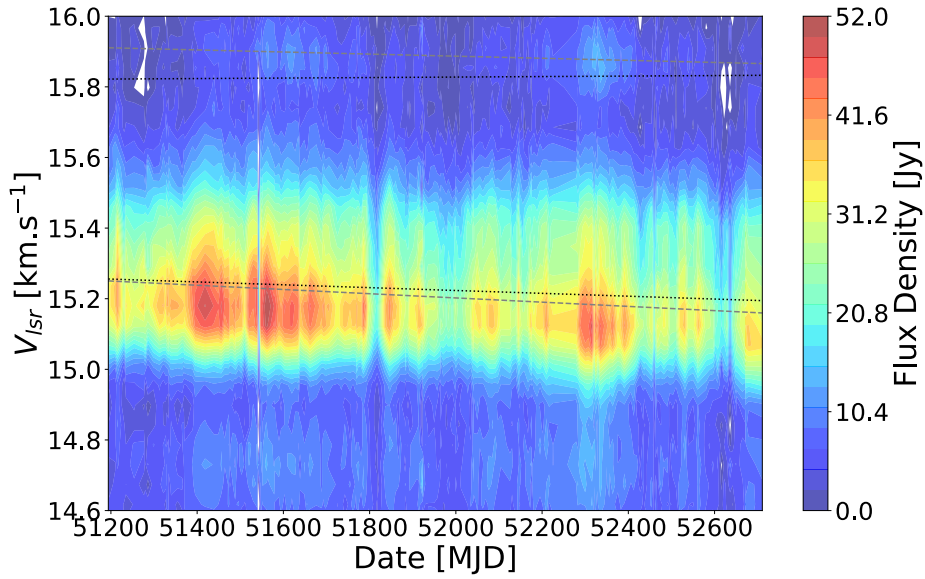
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.9 G196.45 - 1.68

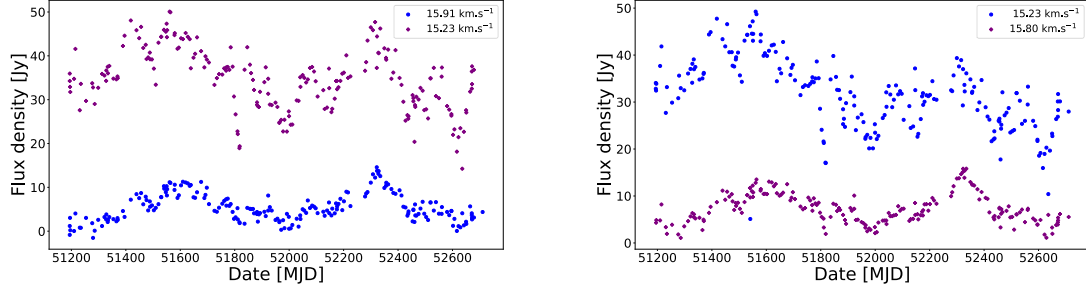


G196.45 - 1.68 averaged spectrum with upper and lower envelope.

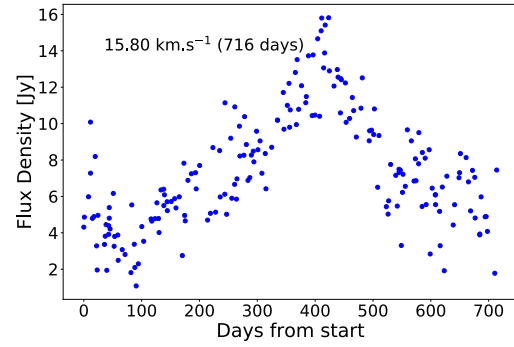
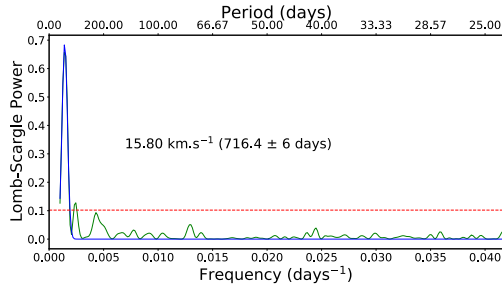


G196.45 - 1.68 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G196.45 - 1.68 has a triple peaked spectral profile which is predicted to indicate masers present in a disc (Wallin et al., 1998); when a disc is viewed face on there tends to be blending of the maser features (Morgan et al., 2021). Since this source contains only one distinct feature it is difficult to determine if the observed velocity drift is valid as a finding with the given data. While a high goodness of fit value on the Gaussian evaluation seems promising, it would be recommended for further, long-term observations, to be completed on this maser source to confirm and constrain the findings. Despite a high R -squared value visual inspection of the fit seems less promising. The velocity drift fit will improve with improved spectral resolution of the data and a longer observational period.



G196.45 - 1.68 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



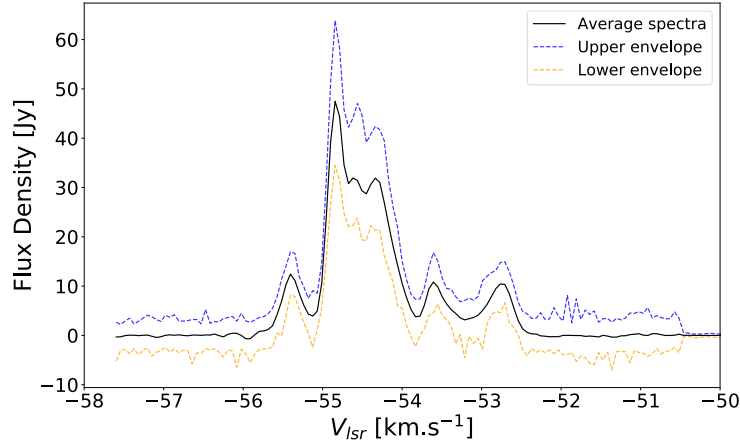
G196.45 - 1.68 Lomb-Scargle periodogram and folded light curve for the feature associated with 15.80 km.s^{-1} .

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a		Gaussian-fitted velocity ^b		
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G196.45	15.22	-5.99	6	0.47	-4.04	79
- 1.68	15.80	-2.96	7	0.20	0.70	0

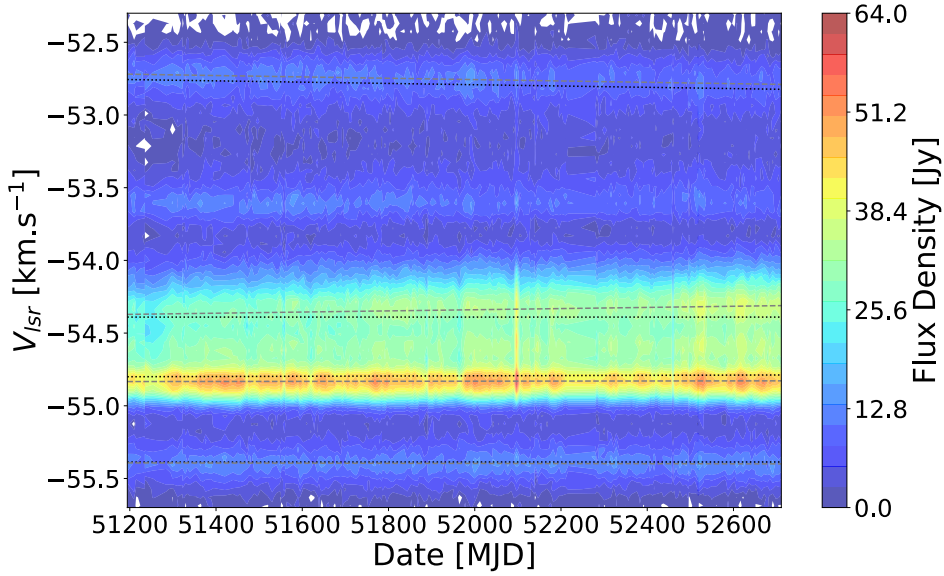
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.10 G308.92 + 0.12

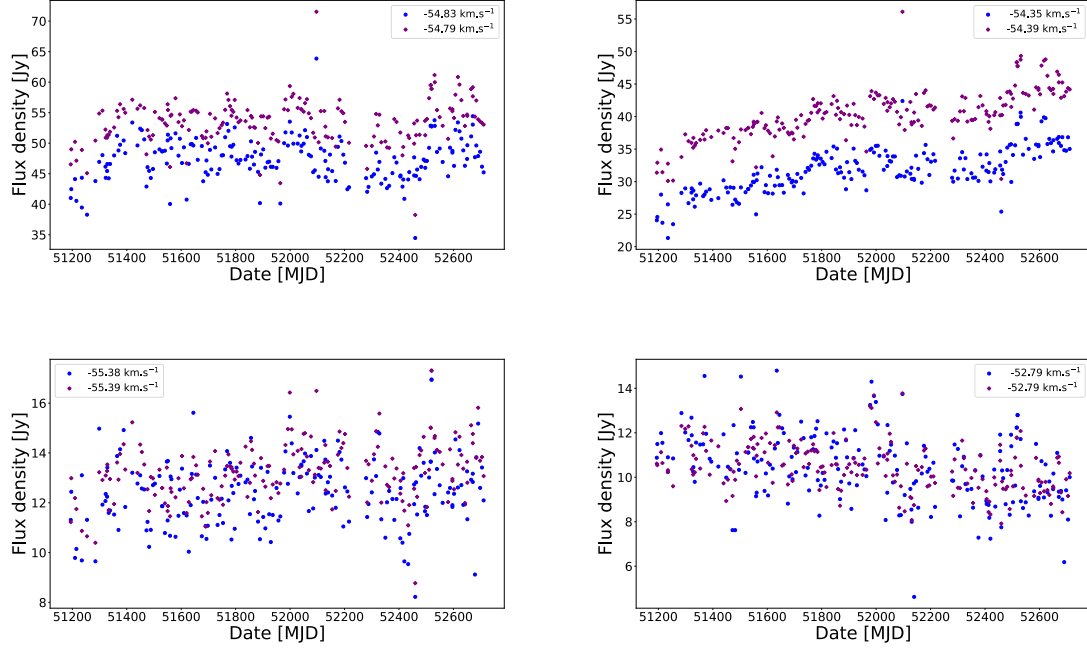


G308.92 + 0.12 averaged spectrum with upper and lower envelope.



G308.92 + 0.12 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Only a single maser feature at $\sim -52.79 \text{ km.s}^{-1}$ appears to have a velocity drift while other evaluated features appear very stable. Maser feature at $\sim -52.79 \text{ km.s}^{-1}$ is a comparably weak feature and is the only feature which displays a meaningful velocity drift. This source does not display significant variability. [Phillips et al. \(1998\)](#) found that the maser components have a linear distribution, although reported no clear velocity gradient; furthermore the shape and size of the HII region suggest more than one embedded stellar object.



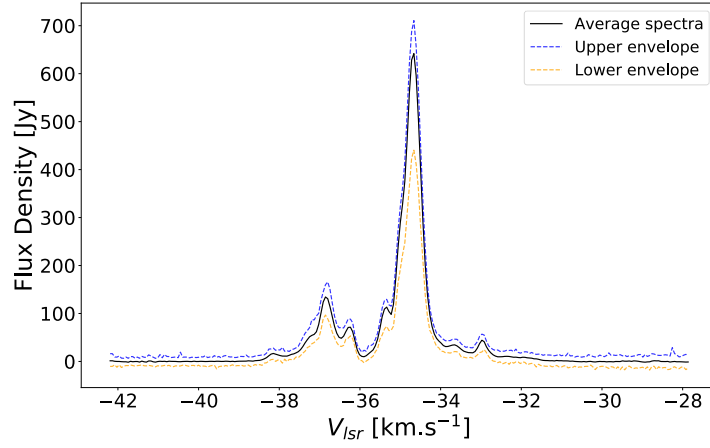
G308.92 + 0.12 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G308.92	-54.79	0.32	0	0.24	0.80	26
+ 0.12	-54.39	3.98	4	0.47	0	0
	-55.39	-4.48	0	0.24	0.04	0
	-52.79	-4.65	10	0.40	-4.43	61

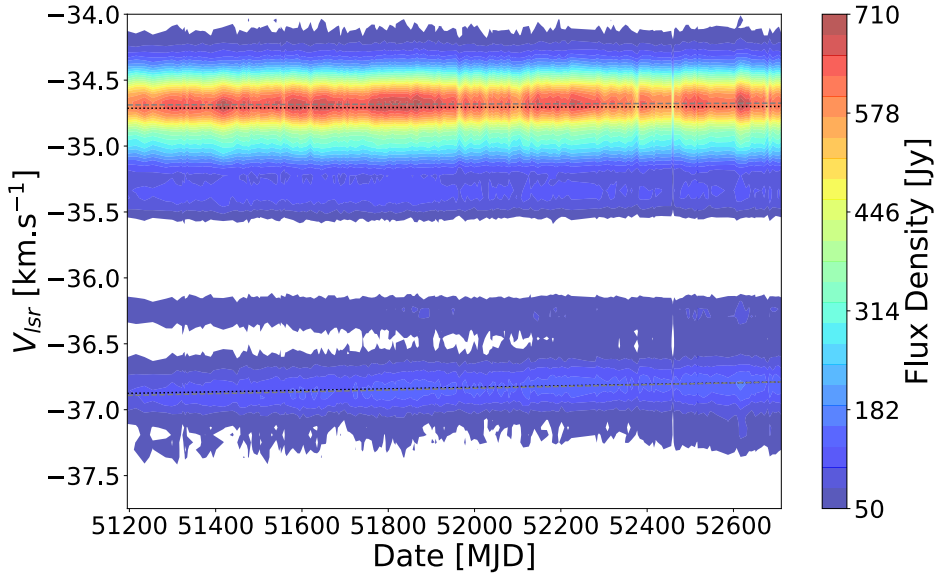
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.11 G318.95 - 0.2

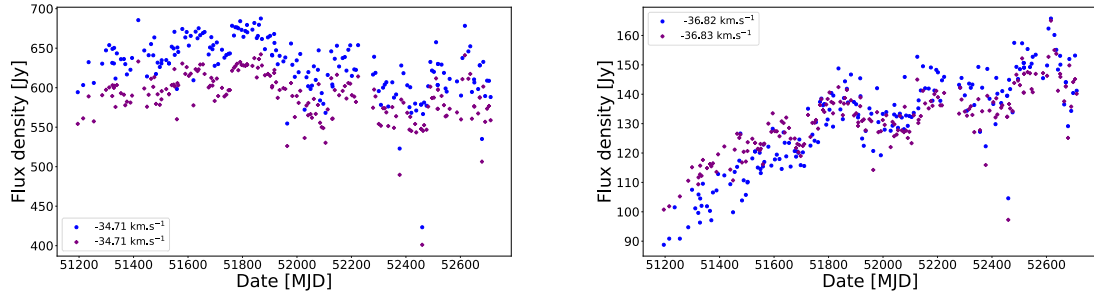


G318.95 - 0.2 averaged spectrum with upper and lower envelope.



G318.95 - 0.2 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Periodicities for maser features at $v_{\text{cen}} \sim -36.82 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim -34.71 \text{ km.s}^{-1}$ are determined to be ~ 372 days and ~ 391 days respectively. These periodicities are consistent with previous findings within a reasonable error. Additional monitoring is needed to confirm the periodicity of this source as the findings are not entirely convincing. A more convincing finding is the velocity drifts. Both velocity drifts yielded goodness of fit values for the Gaussian evaluation above 50% and the maser source associated with $v_{\text{cen}} \sim -36.83 \text{ km.s}^{-1}$ displays a drift which crosses over multiple velocity channels. In addition to the drifts appearing to fit the data very well it seems very likely that the observed drifts are real phenomena and not a result of observational error.



G318.95 - 0.2 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

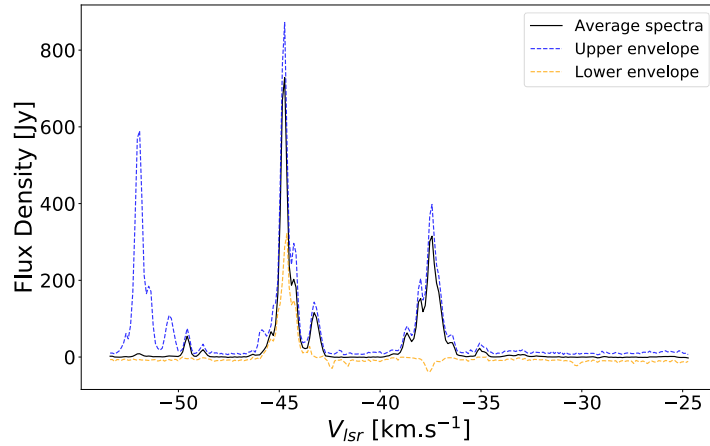
Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G318.95	-34.71	0.88	0	0.58	0.90	57
- 0.2	-36.83	6.77	11	0.52	5.72	74

^a Linear regression fitting to associated velocities of determined flux densities.

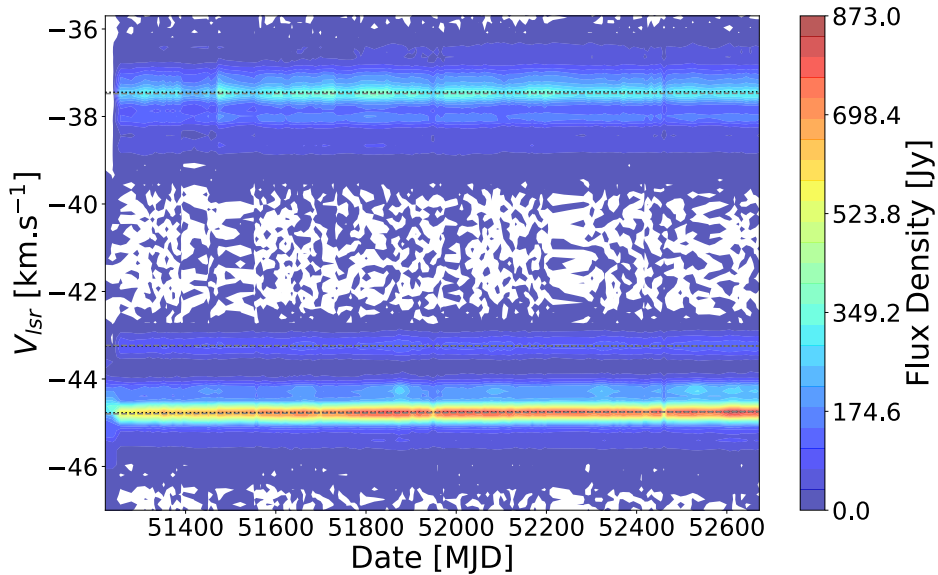
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.12 G328.24 - 0.55

The maser spectrum associated with G328.24 - 0.55 is composed of maser sources G328.24 - 0.55 and G328.25 - 0.53 which form two clusters on opposing sides of an UC HII region (Phillips et al., 1998; Caswell et al., 2010). These maser sources were simultaneously observed by HartRAO. The strong feature found in the velocity range $v_{\text{cen}} \sim -47 \text{ km.s}^{-1}$ to $v_{\text{cen}} \sim -42.25 \text{ km.s}^{-1}$ corresponds to maser source G328.25 - 0.53, and the weaker feature found in the velocity range $v_{\text{cen}} \sim -40 \text{ km.s}^{-1}$ to $v_{\text{cen}} \sim -35 \text{ km.s}^{-1}$ corresponds to maser source G328.24 - 0.55 (Goedhart, 2004).

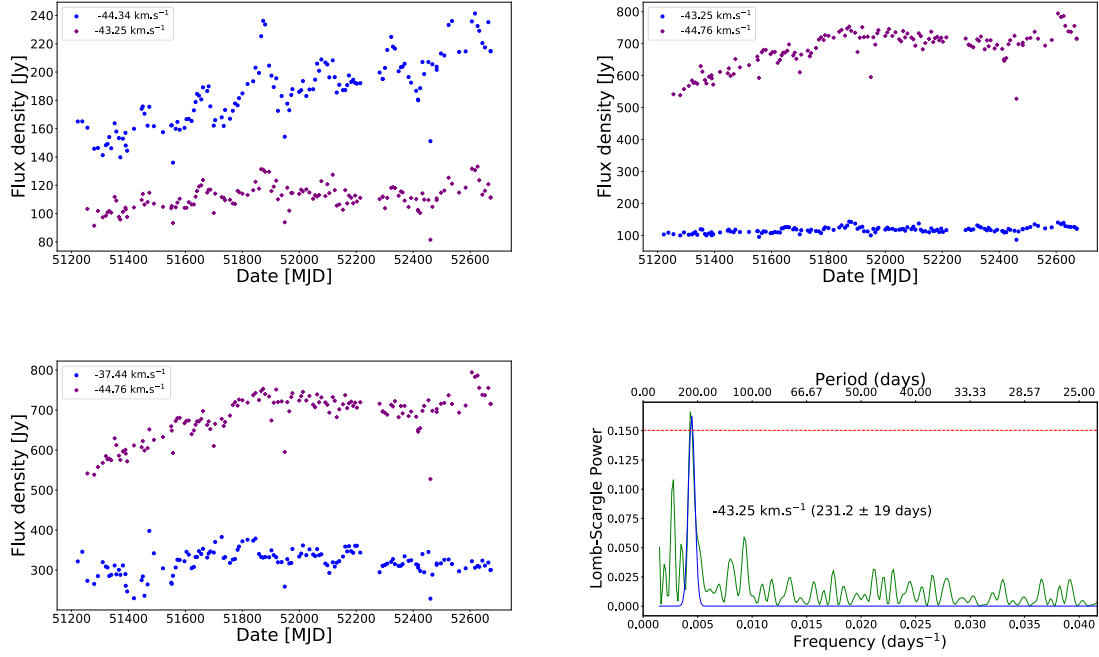


G328.24 - 0.55 averaged spectrum with upper and lower envelope.



G328.24 - 0.55 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G328.24 - 0.55 displays moderate variability. Only the feature associated with $v_{\text{cen}} \sim -43.35 \text{ km.s}^{-1}$ yielded a significant period estimate of 231 ± 19 days. Using longer monitoring Goedhart et al. (2014) found significant periods in several of the maser features.



G328.24 - 0.55 light curves determined from Gaussian fitting and velocity channel inspection. The light curves denoted with blue dots were determined using manual fitting; light curves denoted by purple crosses were determined using Gaussian fitting. Lomb-Scargle for maser feature at -43.25 km.s^{-1} .

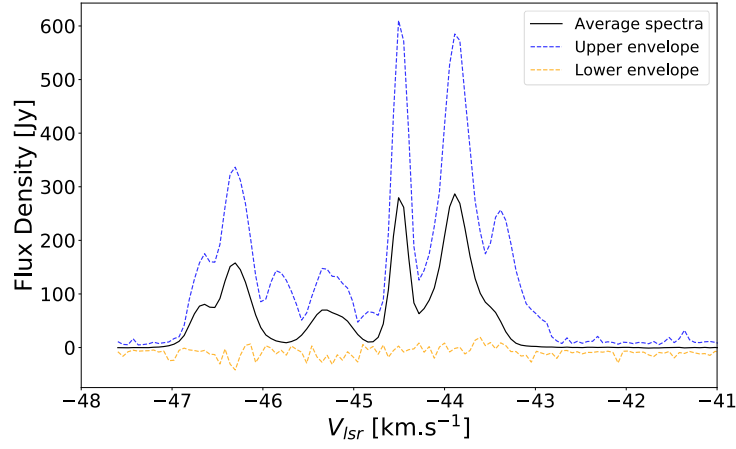
The maser feature associated with $v_{\text{cen}} \sim -44.76 \text{ km.s}^{-1}$ was found to be velocity drifting, however extended observations would be necessary to confirm and constrain this result.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G328.24	-44.76	3.52	4	0.46	2.02	79
- 0.55	-43.25	-0.9	0	0.53	-0.09	0
	-37.44	0.03	0	0.58	0.77	14

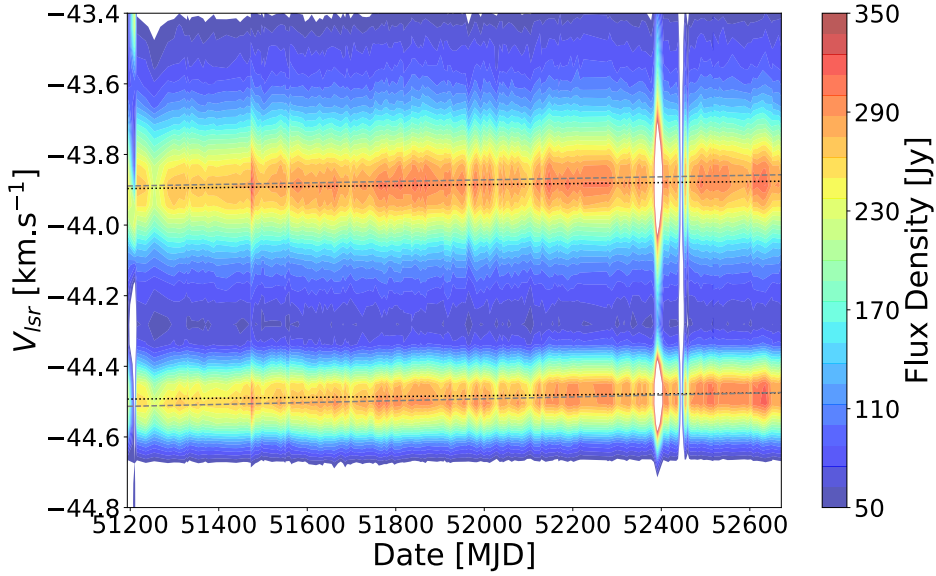
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.13 G328.81 + 0.63



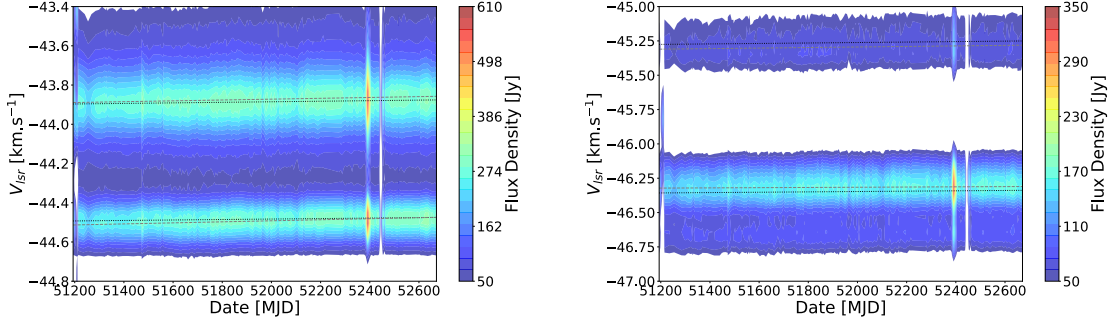
G328.81 + 0.63 averaged spectrum with upper and lower envelope.



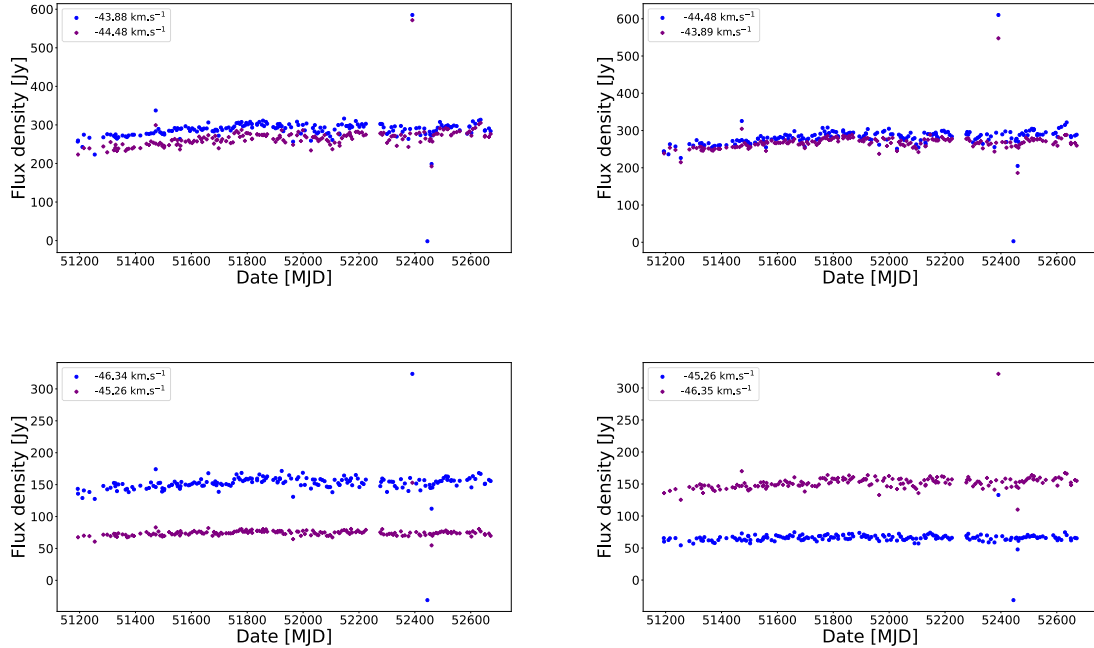
G328.81 + 0.63 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Considering the behaviour of the light curves and dynamic spectra, the maser source associated with G328.81 + 0.63 appears to be relatively stable in flux density. However, there are three observations which yielded outlying points. Firstly, there is an outlier whose flux density is approximately 300 Jy above the majority of other readings. This observation is followed not long after by two observations which drop significantly. It cannot be said with confidence if the outlying observations are due to instrumental or observational error, or a sudden flaring of the maser source; this lack in confidence is primarily due to the low cadence of the observations. It is important to note that there have been observations of maser sources which experience rapid increases in their flux densities relative to their stable states; these events often show up as outliers and corrupted spectral channels in dynamic spectra. This

being said, flaring events should not be ruled out when investigating this source in future. Furthermore it is worth mentioning that there is no measured time delay between the flare in the different velocity channels; this is because the cadence of observations is rather low and so a time delay in a short-lived flare would be impossible to detect. It should also be stated that flaring events in 6.7 GHz methanol masers are rather rare.



G328.81 + 0.63 Dynamic spectra with adjusted scales and velocity ranges. On the left, the dynamic spectra have a larger flux density scale in order to show the flare which is ~ 300 Jy above the average flux density measured. On the right, the dynamic spectra over the velocity range -47.00 km.s^{-1} to -45.00 km.s^{-1} are shown.



G328.81 + 0.63 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach

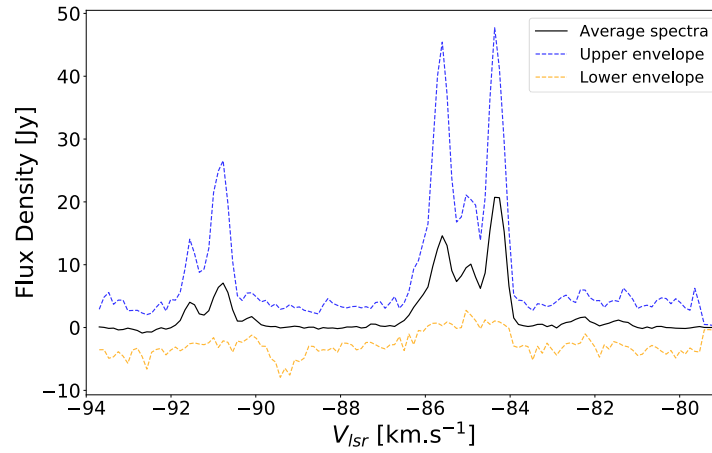
Velocity drifts were detected in all four investigated features; Gaussian evaluation of all four drifts yielded goodness of fit values above 50%. Drifts do not cross over multiple velocity channels. Therefore, due to low cadence of observations and similar drift values determined by the Gaussian evaluation, the source will require longer observations with a higher cadence before the drift can be confirmed despite sufficient goodness of fit values.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G328.81	-43.88	2.15	1	0.47	1.40	71
+ 0.63	-44.48	2.61	4	0.26	1.21	70
	-46.35	0.76	0	0.47	1.29	63
	-45.26	1.97	1	0.47	1.69	52

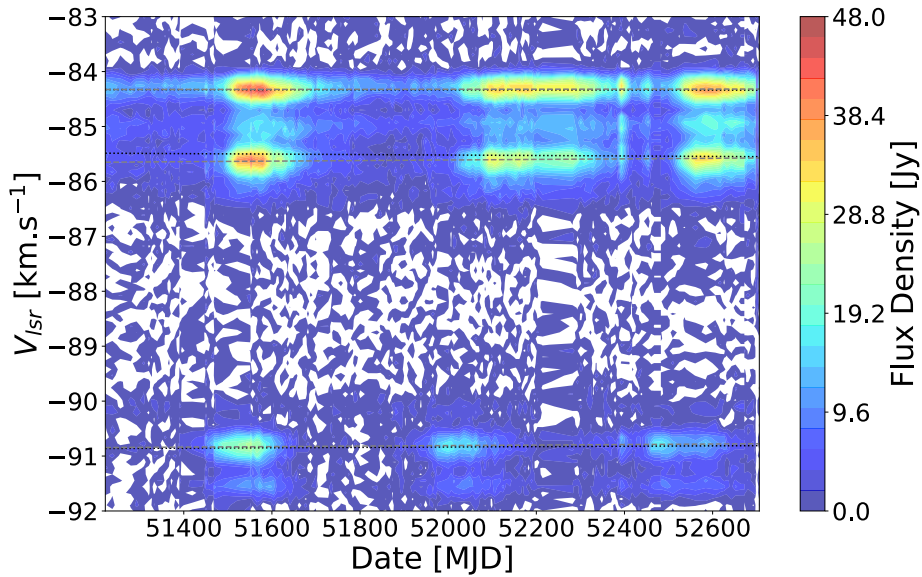
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.14 G331.13 - 0.24



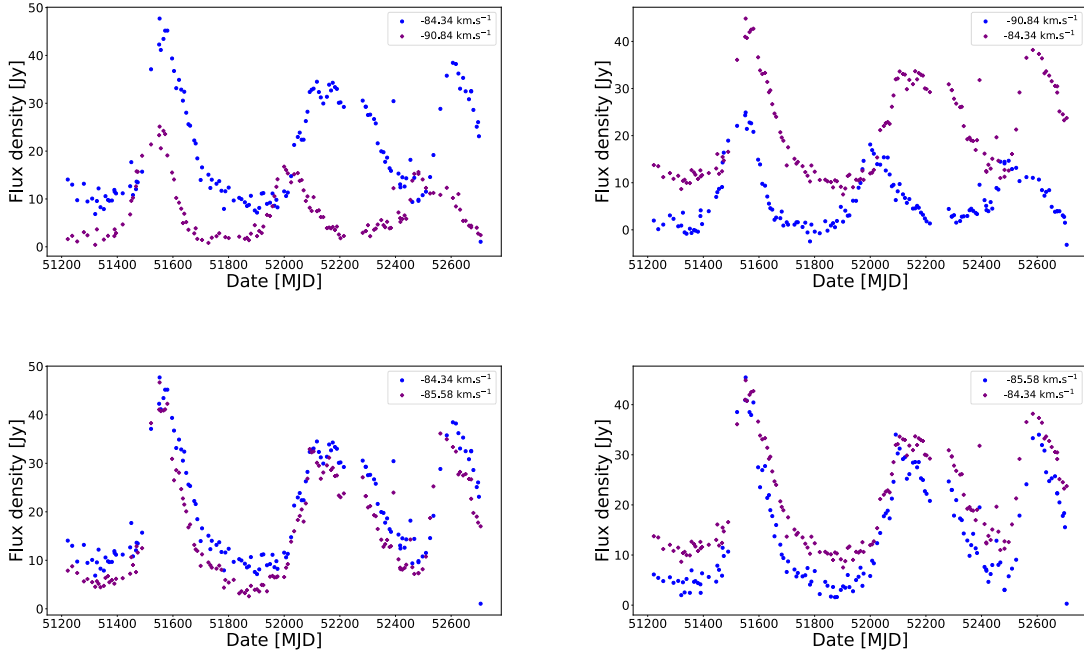
G331.13 - 0.24 averaged spectrum with upper and lower envelope.



G331.13 - 0.24 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G331.13 - 0.24 displays clear periodic behaviour; in this research flares were

determined between 490 and 568 days for different features. Goedhart et al. (2014) used extended monitoring and determined a mean period of 509 ± 10 days. In addition to periodicity, velocity drifting was observed in this source; upon inspection of the dynamic spectra the determined velocity drifts appear to fit the data well. However goodness of fit values were low and insufficient. The low goodness of fit values are due to a high amount of scatter in the central velocity values and poor correlator resolution used when monitoring G331.13 - 0.24; the correlator resolution was $0.11239 \text{ km.s}^{-1}$. G331.13 - 0.24 does appear to be a promising source for velocity drifting, however, more observations with improved correlator resolution are needed. Observed periodicity in this source is very distinct. Maser features at $v_{\text{cen}} \sim -84.34 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim -85.58 \text{ km.s}^{-1}$ appear to be very much in sync, i.e., the light curves of these two features appear to peak and drop around the same times. However, maser feature at $v_{\text{cen}} \sim -90.84 \text{ km.s}^{-1}$ lags behind. Time lags are indicative of the distances between maser features; it is known from spot maps of this source, from Phillips et al. (1998), that there are two linearly distributed groups of spots which correspond to the different periods observed. The time lag between flares of the maser features was also observed by Goedhart et al. (2014).

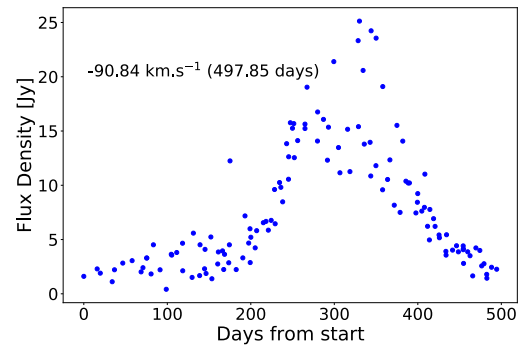
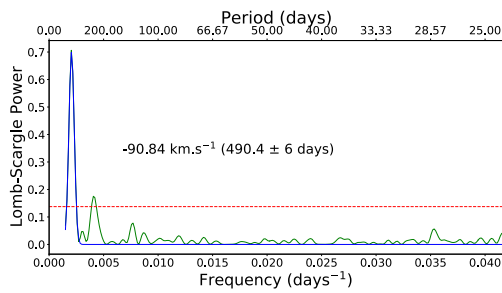
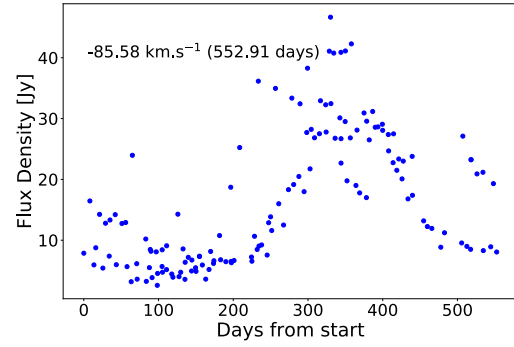
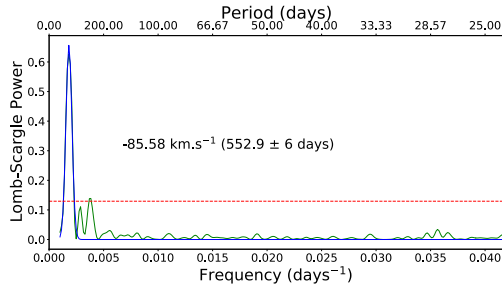
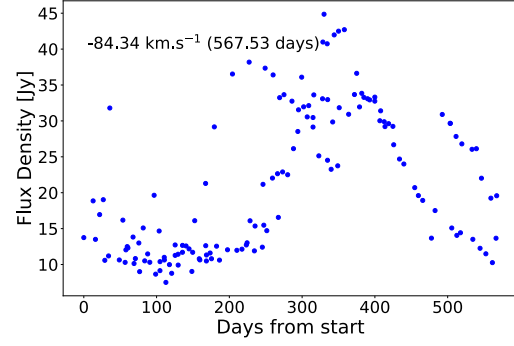
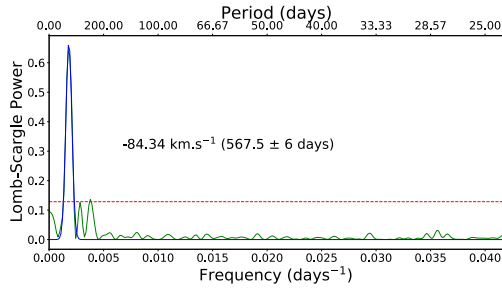


G331.13 - 0.24 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach

Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)	
G331.13	-84.34	0.59	0	0.50	-0.66	2	
- 0.24	-85.58	5.16	5	0.49	-5.08	2	
	-90.84	4.61	2	0.49	3.48	1	

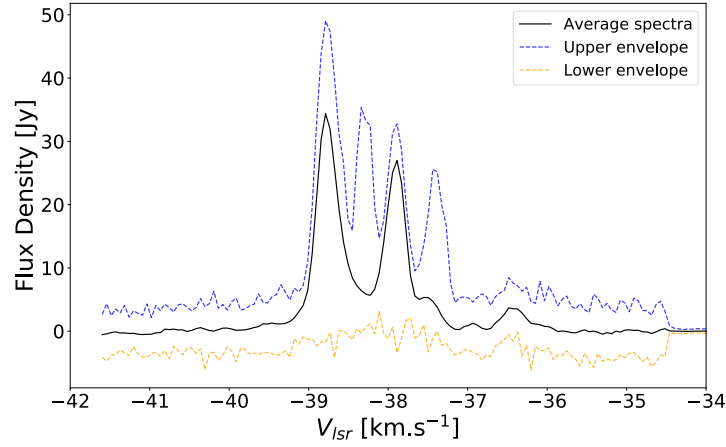
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

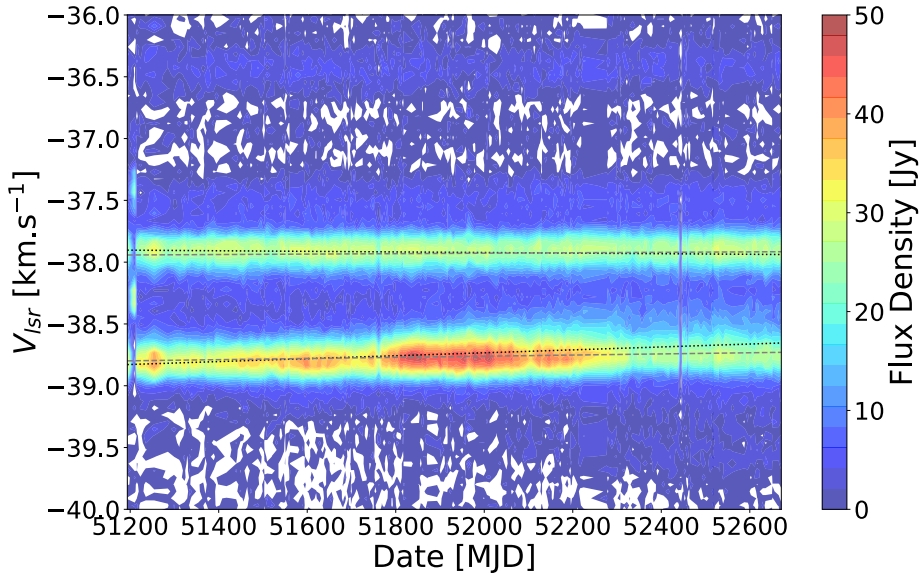


G331.13 - 0.24 Lomb-Scargle periodograms and corresponding folded light curves for maser features at -84.34 km.s^{-1} , 85.58 km.s^{-1} , and -90.84 km.s^{-1} .

6.2.15 G337.92 - 0.46



G337.92 - 0.46 averaged spectrum with upper and lower envelope.



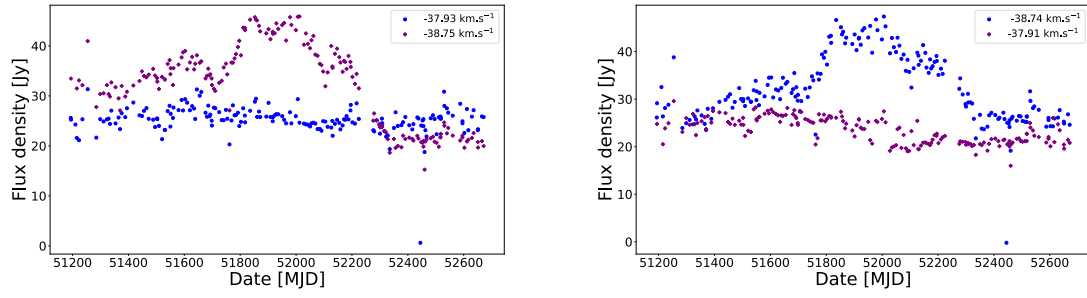
G337.92 - 0.46 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G337.92	-37.93	1.80	0	43	-2.38	50
- 0.46	-38.74	4.65	4	44	11.8	88

^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

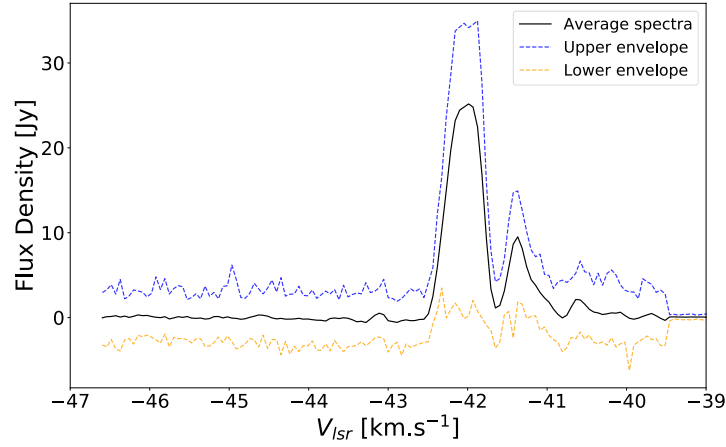
Maser feature associated with G337.92 - 0.46 has several characteristics which make it a promising velocity drift candidate. Firstly, velocity drift of two prominent features can be visually identified on the dynamic spectra. Secondly, velocity drifts are not consistent over



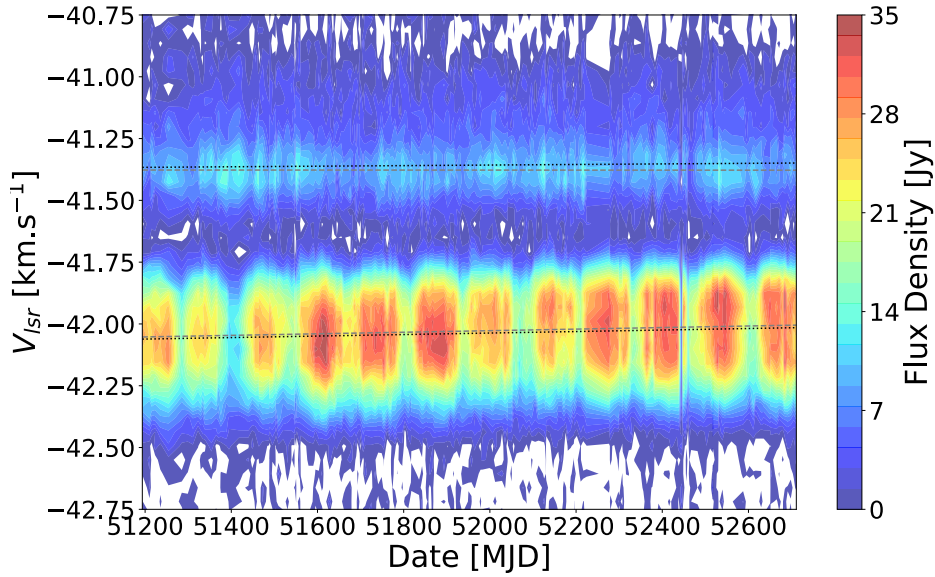
G337.92 - 0.46 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

multiple features or channels, therefore, it is likely the drifting is intrinsic to the source and not an instrumental effect. Thirdly, the drifts, particularly those of the strongest feature, occur over multiple velocity channels. Finally, a high correlation coefficient of the Gaussian test was determined.

6.2.16 G338.93 - 0.06



G338.93 - 0.06 averaged spectrum with upper and lower envelope.



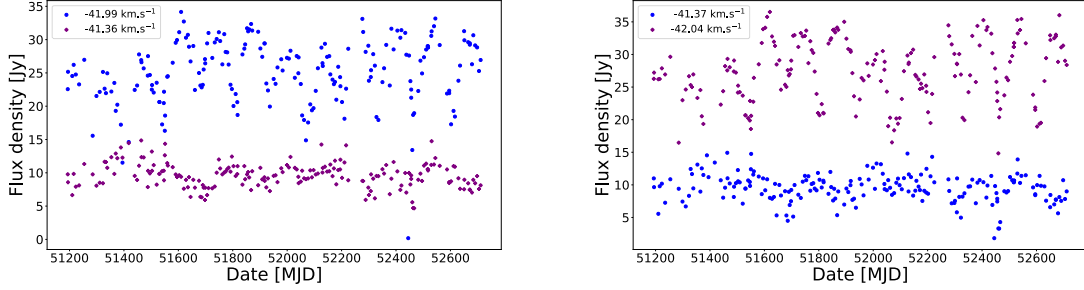
G338.93 - 0.06 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)
G338.93	-42.04	3.16	2	0.49	3.05	61
- 0.06	-41.36	0	0	0.28	1.15	8

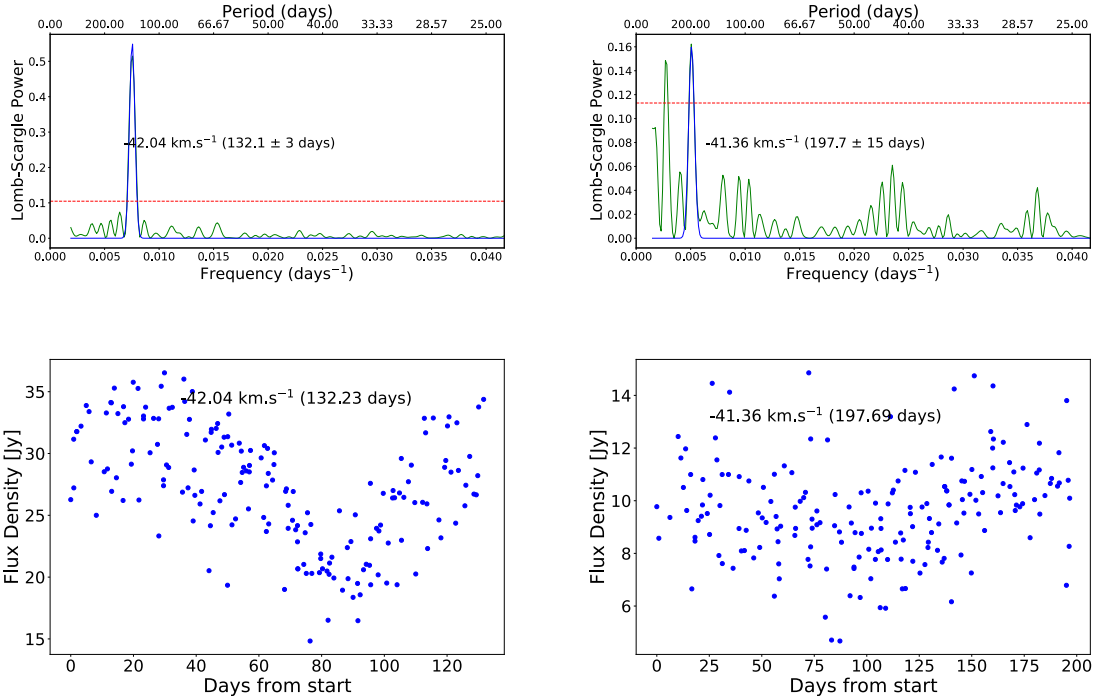
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

Velocity drifting and periodicity are observed in G338.93 - 0.06. Periodicity was observed in velocity channels $v_{\text{cen}} \sim -42.04$ km.s⁻¹ and $v_{\text{cen}} \sim -41.36$ km.s⁻¹; the Lomb-Scargle periodograms determined the periodicities to be ~ 132 days and ~ 197 days respectively, both



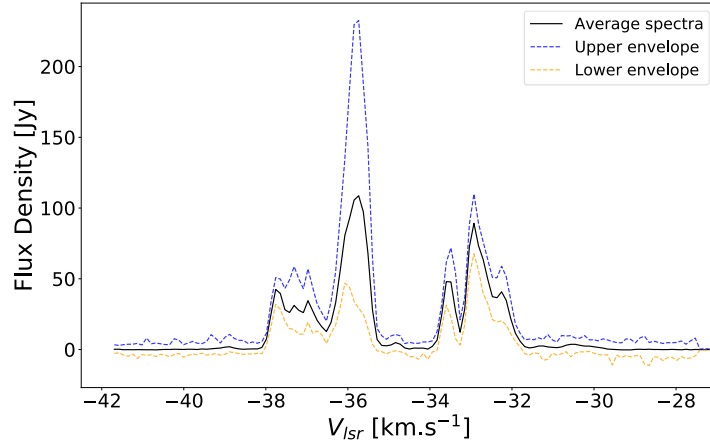
G338.93-0.06 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



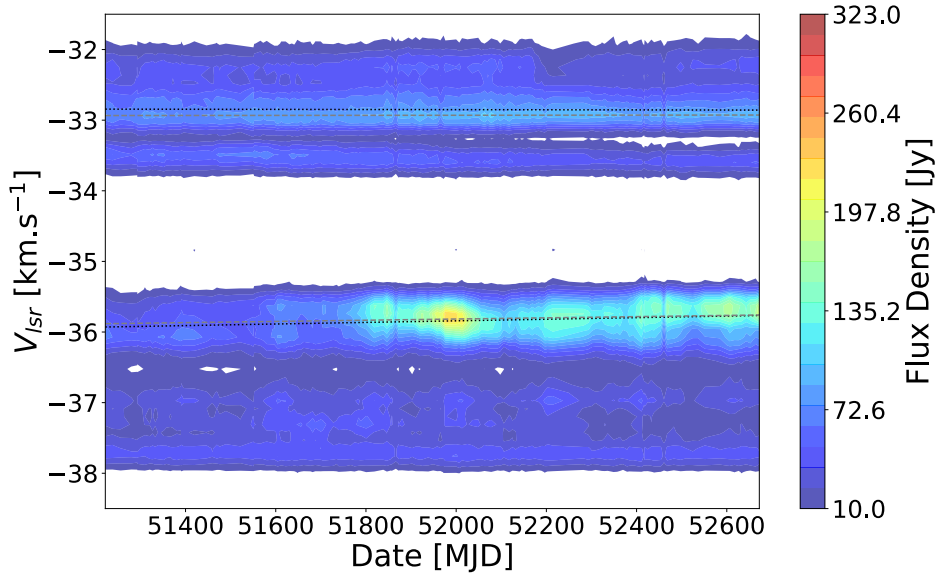
G338.93-0.06 Lomb-Scargle periodograms of light curves determined from Gaussian fitting and folded light curves. Time series corresponding to features at -42.04 km.s^{-1} and -41.36 km.s^{-1} are folded modulo ~ 132 days and ~ 197 days respectively.

periods determined were above the false detection peak. These periodicities are consistent with previous findings, [Goedhart \(2004\)](#) and [Goedhart et al. \(2014\)](#) found periodicity in the feature at $v_{\text{cen}} \sim -42.04 \text{ km.s}^{-1}$ to be approximately 132 days and the feature at $v_{\text{cen}} \sim -41.36 \text{ km.s}^{-1}$ to be approximately 201 days. The light curve associated with the weaker feature, $v_{\text{cen}} \sim -41.36 \text{ km.s}^{-1}$, appears to display more of a sinusoidal behaviour while the stronger feature appears more consistent with bunny-hop behaviour similar to that seen in G358.460 - 0.391. There are several properties of this observation which suggest the observed velocity drift may indeed be real. Firstly, the velocity drifts measured are not consistent in all features meaning that the drift cannot simply be put down to observational error; if the drift was due to the nature of the observation then it could be expected that the drift would be consistent over all features in the observation. The drifts were determined using a linear regression fit and confirmed using Gaussian fitting. Finally, considering the distribution on the central velocity determined with Gaussian fitting, it was determined that the central velocity measurements lie over two observational channels, in some cases this could be due to a feature bleeding over into a neighbouring channel, however with maser feature G338.93 - 0.06 this does not seem to be the case as the goodness of fit value indicates a high correlation between the velocity drift fit and the velocity measurements.

6.2.17 G339.62 - 0.12

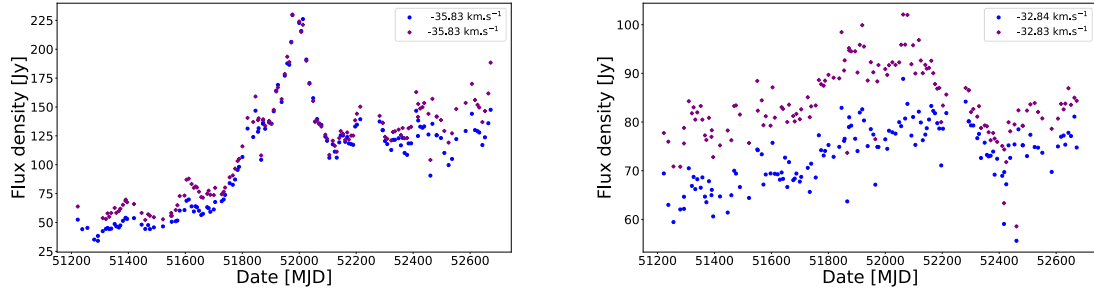


G339.62 - 0.12 averaged spectrum with upper and lower envelope.



G339.62 - 0.12 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Only the strongest feature of this source displays statistical veracity in confirming a velocity drift. The drift corresponding to the feature $v_{\text{cen}} \sim -35.83 \text{ km.s}^{-1}$ crosses over multiple velocity channels and provide a goodness of fit measure in the Gaussian evaluation above 50 per cent. [Goedhart et al. \(2014\)](#) found maser source G339.62 - 0.12 to have several features which display periodic variability; these features are found at $-37.661 \text{ km.s}^{-1}$, $-37.310 \text{ km.s}^{-1}$, $-36.959 \text{ km.s}^{-1}$, and -32.92 km.s^{-1} . The weighted-mean period adopted by [Goedhart et al. \(2014\)](#) is 200.3 ± 1 days.



G339.62 - 0.12 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

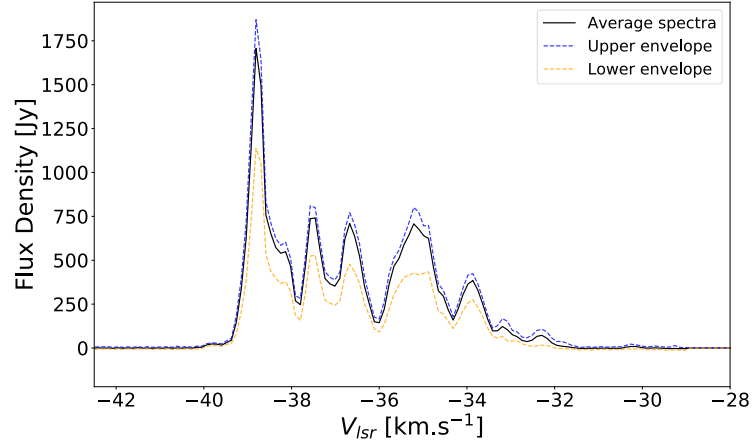
Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G339.62	-32.84	0.48	1	0.47	-0.91	11
- 0.12	-35.83	8.50	2	0.65	11.3	59

^a Linear regression fitting to associated velocities of determined flux densities.

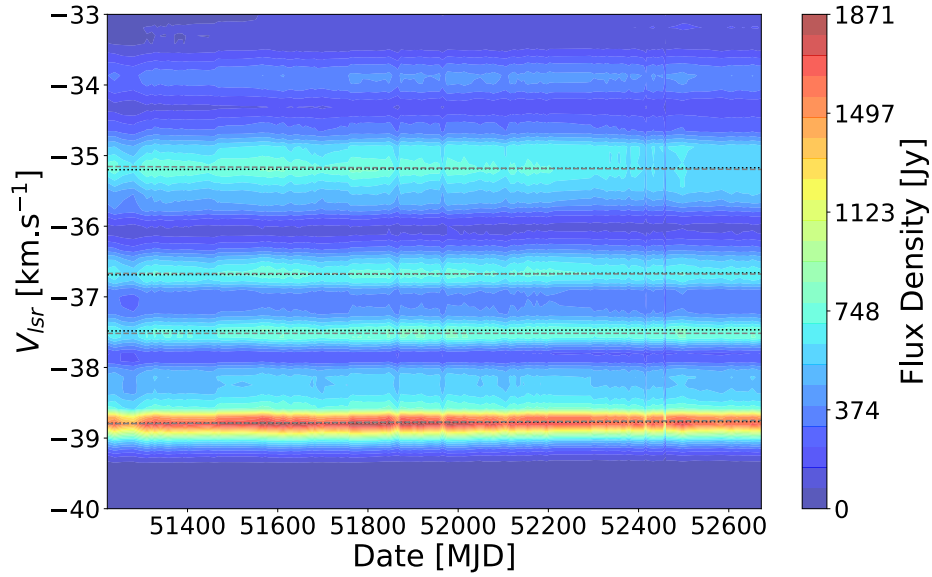
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.18 G339.88 - 1.26

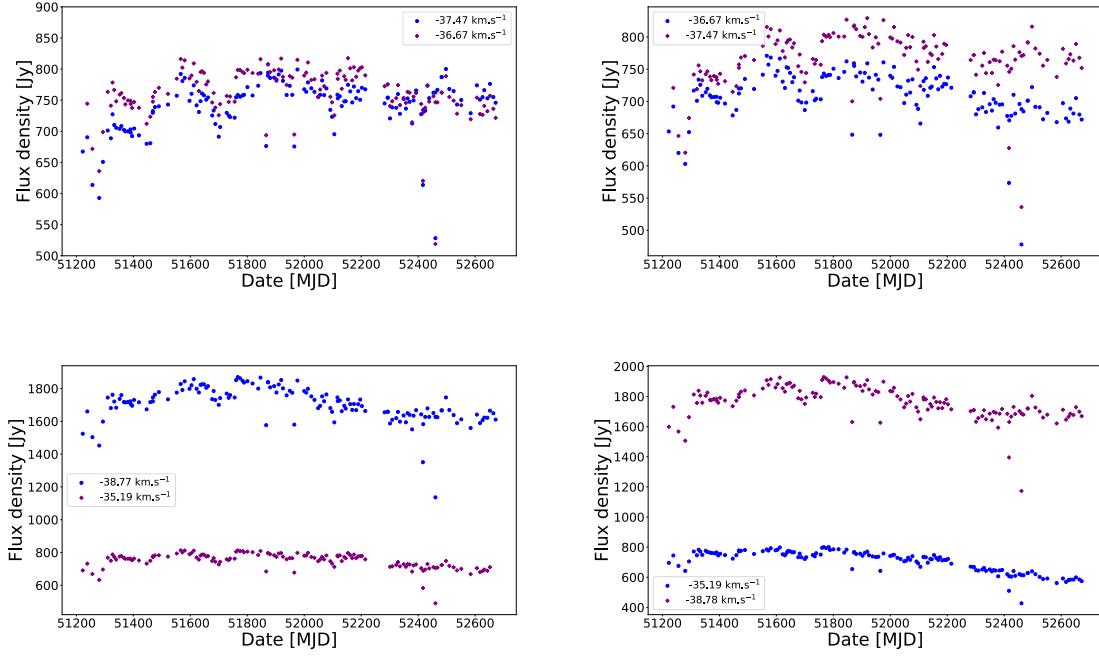
Source G339.88 - 1.26 (IRAS 16484-4603) lies within an extended mid-infrared region with ionised outflows present (Liu et al., 2019).



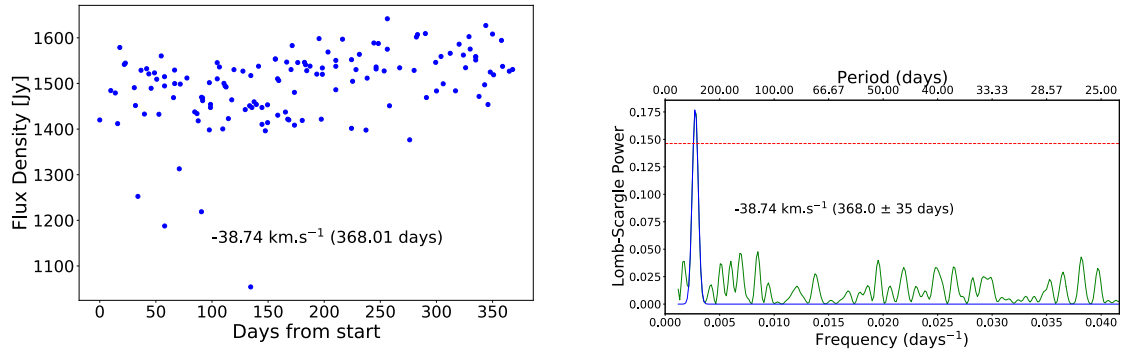
G339.88 - 1.26 averaged spectrum with upper and lower envelope.



G339.88 - 1.26 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.



G339.88 - 1.26 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



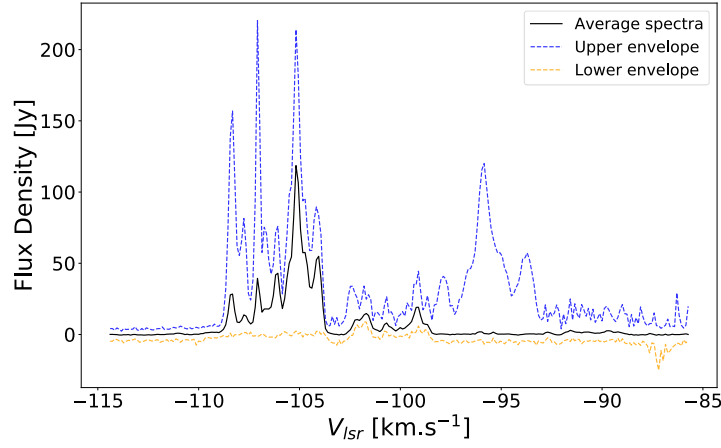
G339.88 - 1.26 folded light curve alongside Lomb-Scargle periodogram for maser feature associated with $v_{\text{cen}} \sim -38.74 \text{ km.s}^{-1}$.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)
G339.88	-38.77	3.14	3	0.35	1.80	66
- 1.26	-35.19	-2.86	2	0.99	1.91	24
	-37.47	0.02	0	0.54	1.09	26
	-36.67	-0.62	2	0.54	1.85	56

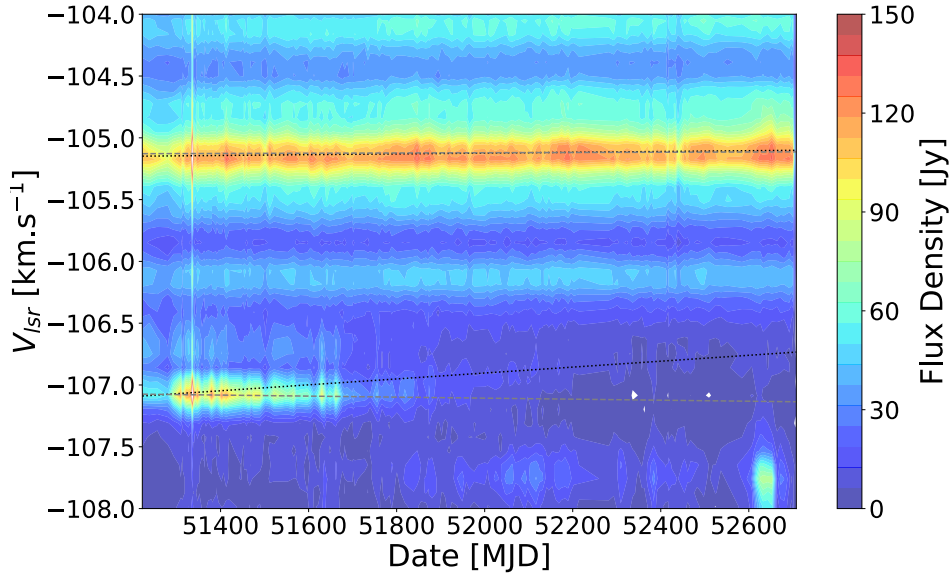
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.19 G340.79 - 0.10

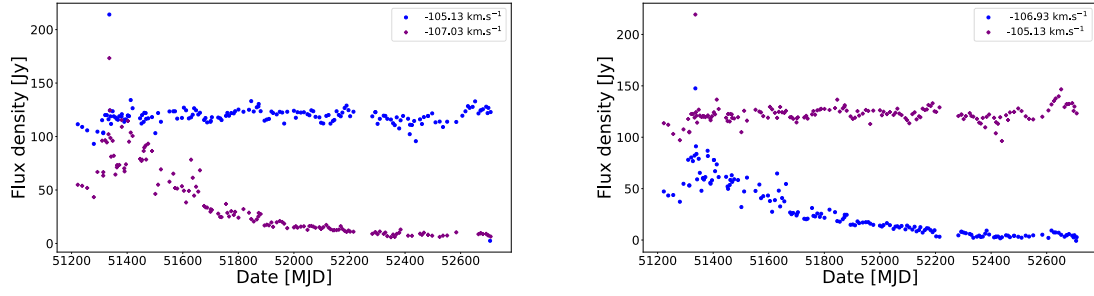


G340.79 - 0.10 averaged spectrum with upper and lower envelope.



G340.79 - 0.10 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

As can be seen from the dynamic spectra of G340.79 - 0.10, the Gaussian fit to the second feature located around $\sim -107 \text{ km s}^{-1}$ does not appear to fit the data well despite a high R^2 value; this is a result of the complex spectrum and heavy overlap of features. The velocity drift detected in the bright feature at $\sim -105 \text{ km s}^{-1}$ does appear to be a good fit, both visually and statistically with a high R^2 value.



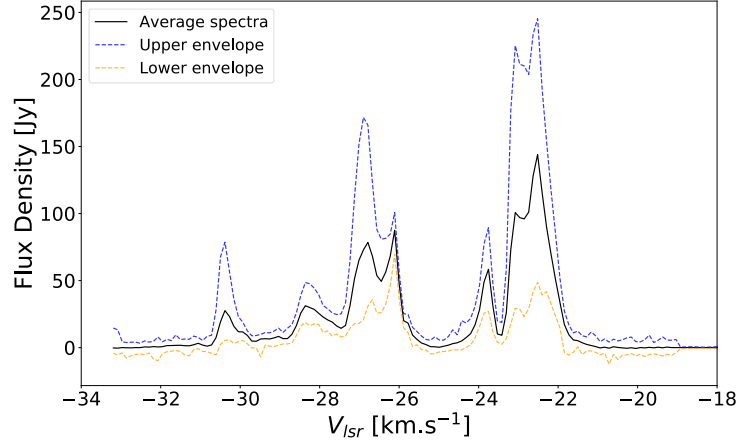
G340.79 - 0.10 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)	
G340.79	-105.13	0.99	0	0.45	3.18	79	
- 0.10	-106.93	-4.14	1	0.39	23.9	80	

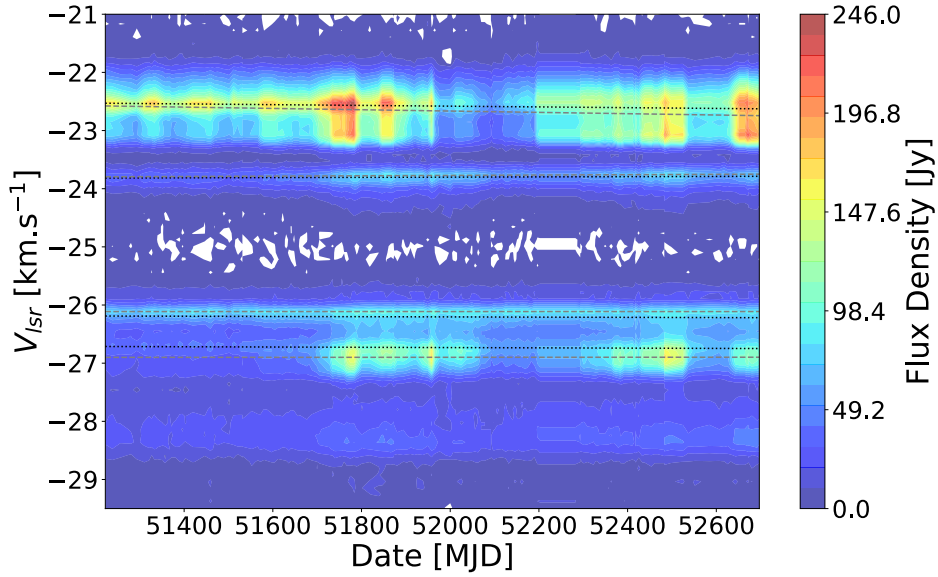
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.20 G345.00 - 0.22

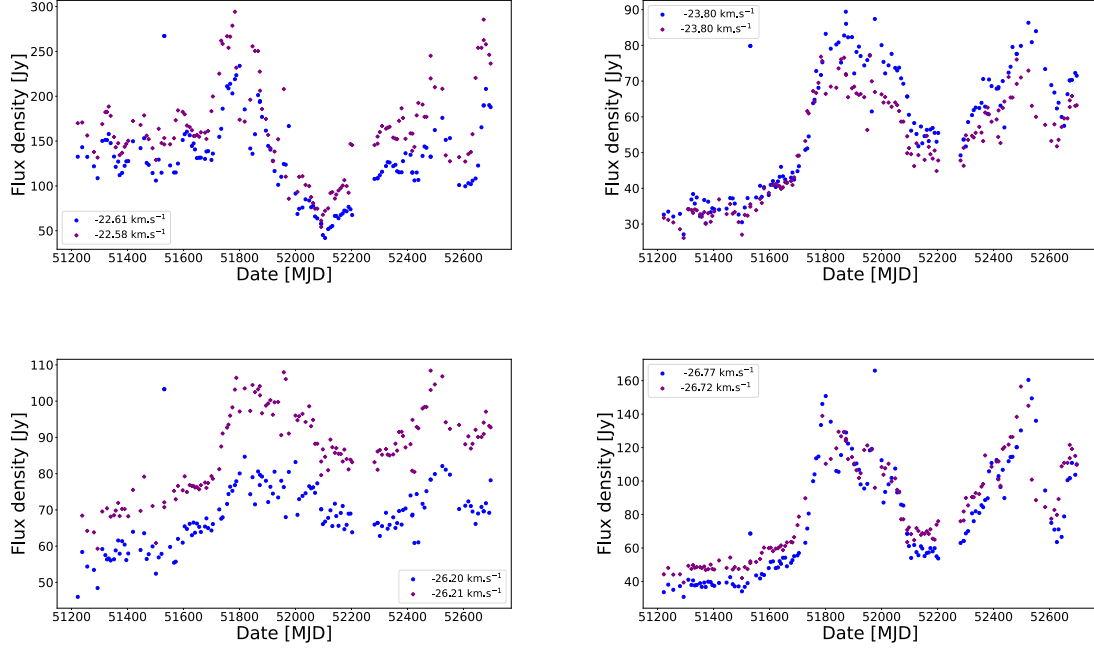


G345.00 - 0.22 averaged spectrum with upper and lower envelope.



G345.00 - 0.22 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G345.00 - 0.22 displays a high degree of variability as can be seen in both the dynamic spectra and the light curves. There appears to be some time delay between the flaring behaviour of different maser features which may represent the physical separation between maser spot and the corresponding time stimulating photons take to travel the distance. While velocity drifts seem promising in this source, longer observations are needed as the archival data only include 149 observations; higher cadence or longer term observations would be helpful in accurately characterising the behaviour of the source.



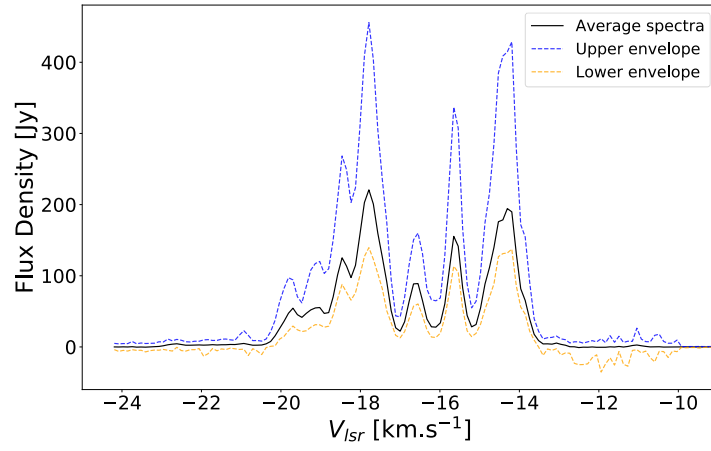
G345.00 - 0.22 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G354.61	-22.58	-11.3	4	0.47	-6.48	19
+ 0.47	-23.80	3.05	6	0.41	1.99	34
	-26.20	0	98	0.45	-1.90	50
	-26.73	-0.19	0	0.71	-2.37	25

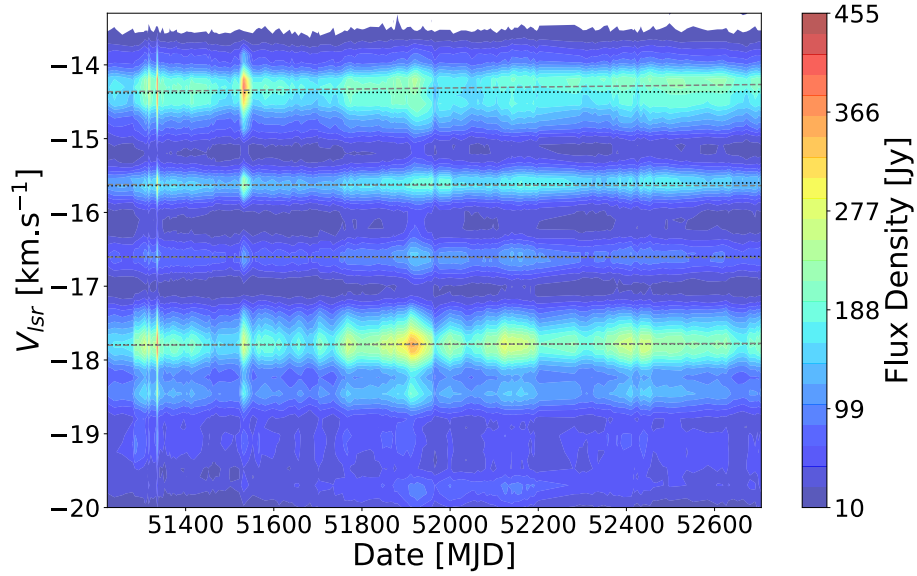
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.21 G345.50 + 0.35

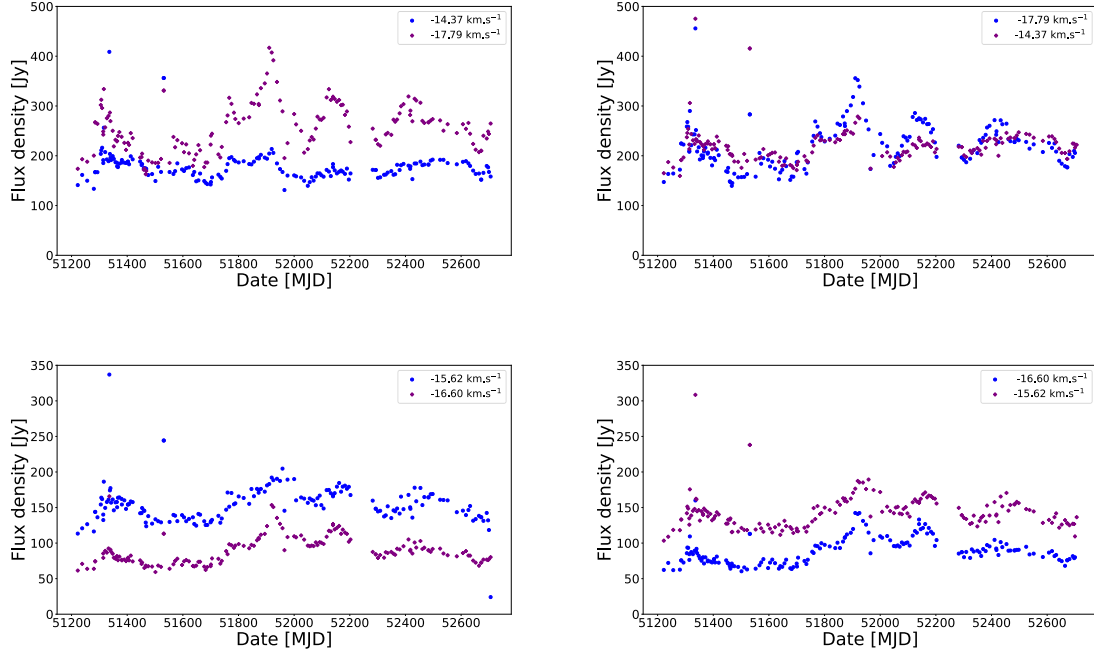


G345.50 + 0.35 averaged spectrum with upper and lower envelope.

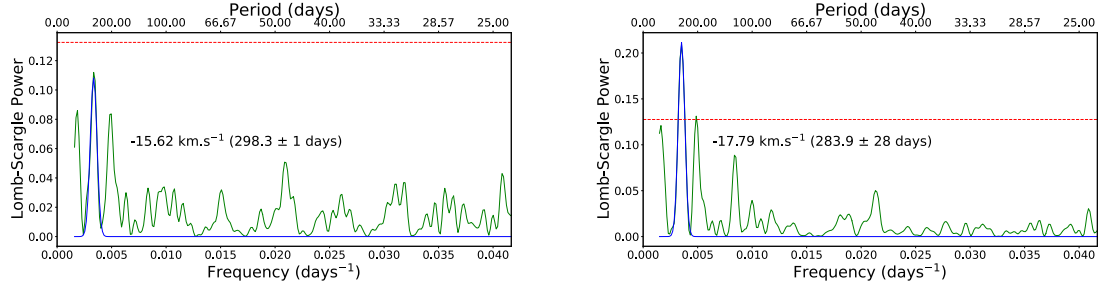


G345.50 + 0.35 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

None of the velocity drifts cross out of a single velocity channel. Only the light curve associated with -17.79 km.s^{-1} displayed periodicity which was larger than the Lomb-Scargle false detection peak.



G345.50 + 0.35 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



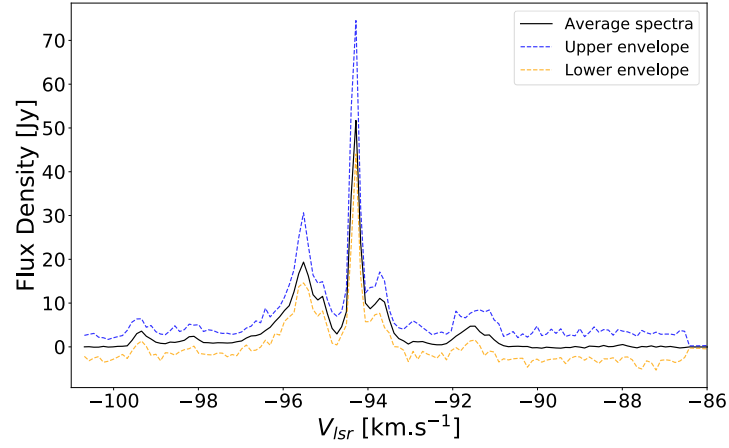
G345.50 + 0.35 Lomb-Scargle of light curves determined from Gaussian fitting

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G345.50	-14.37	6.61	6	0.58	1.05	11
+ 0.35	-15.62	-0.94	0	0.51	2.56	73
	-16.60	-0.37	0	0.52	0.31	2
	-17.79	1.63	0	0.47	1.05	15

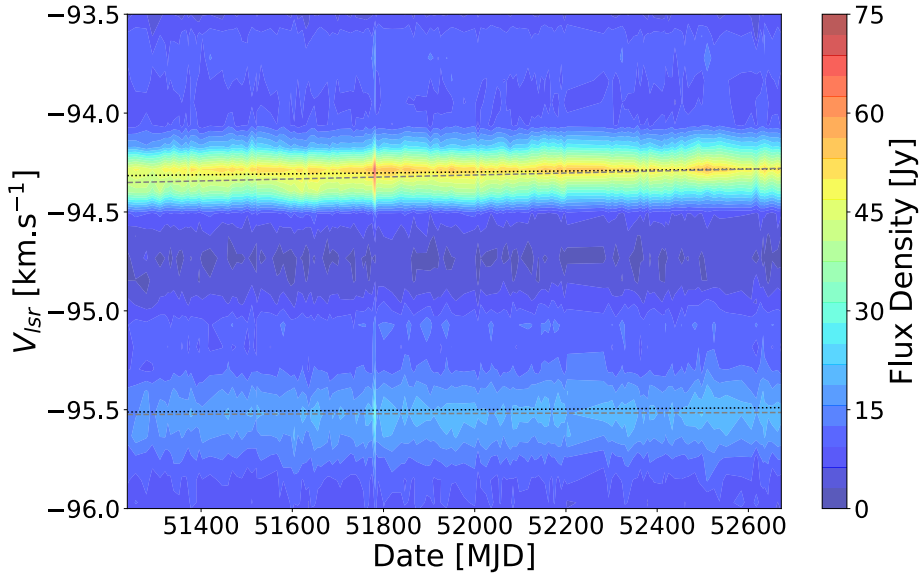
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.22 G351.58 - 0.35



G351.58 - 0.35 averaged spectrum with upper and lower envelope.



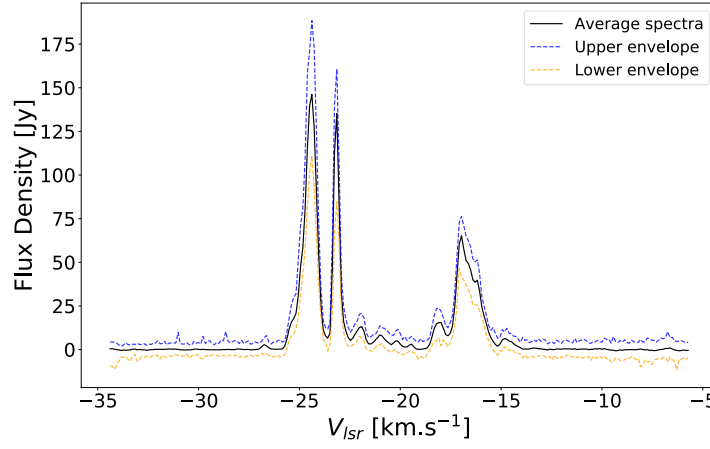
G351.58 - 0.35 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)	
G351.58	-94.30	5.0	14	0.27	2.43	69	
- 0.35	-95.52	0.70	1	0.71	1.54	15	

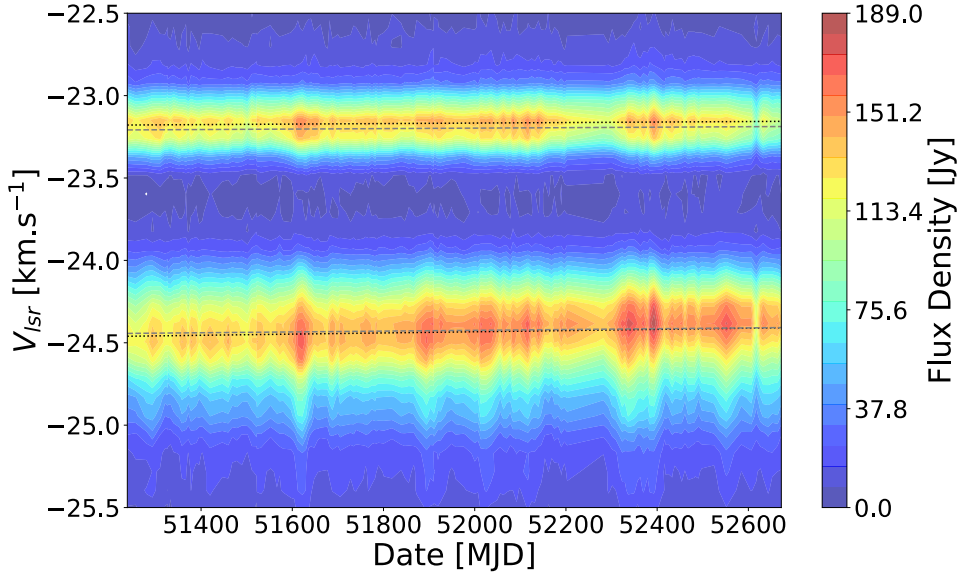
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

6.2.23 G354.61 + 0.47

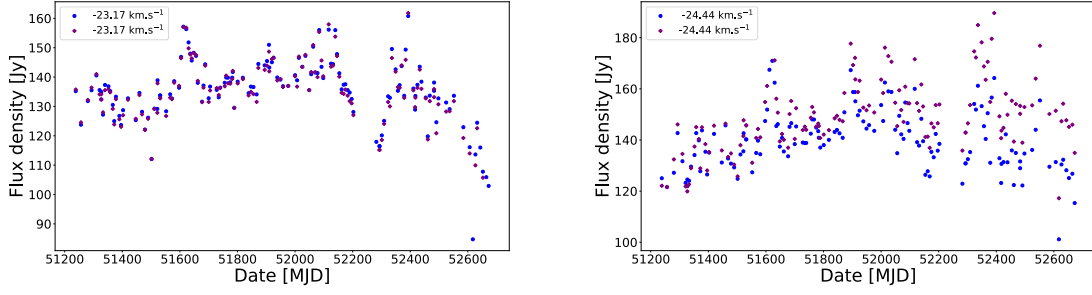


G354.61 + 0.47 averaged spectrum with upper and lower envelope.

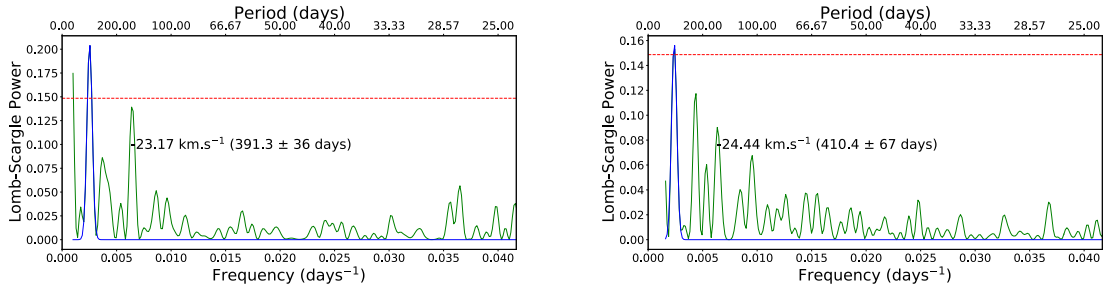


G354.61 + 0.47 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

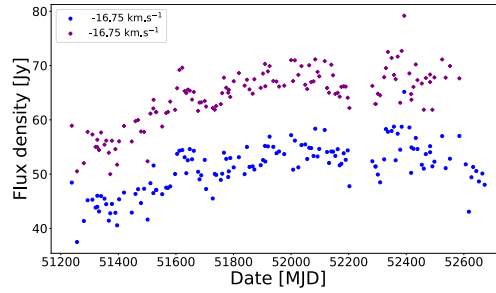
The likelihood of a velocity drift being present in G354.61 + 0.47 seems promising. The features investigated are bright and distinct, as can be seen on the average spectra and the dynamic spectra. While the drift value does not exceed the width of a single velocity channel, high goodness of fit and visual inspection of the fit leads me to believe that higher resolution observations over longer time periods will reveal velocity drifts within the source.



G354.61 + 0.47 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



G354.61 + 0.47 Lomb-Scargle periodograms determined from Gaussian fitting



G354.61 + 0.47 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G354.61	-23.17	1.43	1	0.61	1.56	50
+ 0.47	-24.44	2.47	1	0.34	3.45	74
	-16.74	1.31	1	0.94	8.84	66

^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

Chapter 7

Discussion

7.1 Maser source G358.460 - 0.391

G358.460 - 0.391 is a known source of maser emission; [Chen et al. \(2013\)](#) found that the source is likely a HMYSO in its earliest evolutionary stage undergoing rapid accretion and possesses molecular outflows. [Chen et al. \(2013\)](#) also stated that there is evidence of bipolar outflows and this was confirmed by [Ugwu et al. \(2023\)](#). From dust continuum emission observations, [Csengeri et al. \(2017\)](#) found that G358.46 - 0.39 is associated with two emission cores, G358.46-0.39-MM1 and G358.46-0.39-MM2, both of which are associated with 6.7 GHz class II methanol maser emission ([Chibueze et al., 2017](#)) but only G358.46-0.39-MM1¹ is associated with periodic variability ([Maswanganye et al., 2015](#); [Ugwu et al., 2023](#)). Strong evidence also suggests that G358.46-0.39-MM1 hosts a rotating structure; C¹⁷O emission appears to trace a slowly rotating envelope largely dominated by blueshifted emission and the methanol emission appears to trace a disc ([Ugwu et al., 2023](#)). A highly collimated bipolar outflow observed towards the maser region of G358.46-0.39-MM1 has a knotted appearance along the outflow lobes, this appearance may be indicative of episodic ejection from the stellar environment ([Ugwu et al., 2023](#)).

The maser spectrum of source G358.460 - 0.391 comprises a strong primary feature and a weaker secondary feature which overlap one another slightly. This slight overlap, or blending, can be seen in both the maser spectrum and the dynamic spectrum, presented in figures [5.1](#) and [7.1](#) respectively. Based on an argument made by [Morgan et al. \(2021\)](#), when a disc system is viewed face-on, the maser spectrum may only reveal a singular peak. In the case of G358.460 - 0.391, where there is a main feature and a small blended feature on the shoulder, the spectrum may result from an imperfect face-on disc view. There may also be more than one maser feature within the main feature which cannot be separated due to relative velocity values and blending.

¹G358.46-0.39-MM1 is the source of interest in this research. Please note that all references to G358.460 - 0.391 are referring to G358.46-0.39-MM1 or more specifically G358.46-0.39-MM1a unless otherwise stated.

7.1.1 Periodicity and light curve behaviour of G358.460 - 0.391

Maser source G358.460 - 0.391 long-term behaviour appears to have a distinct bunny hop shape as seen in the light curves and the Kernel-density estimation of the light curve behaviour. Another distinct feature which can be noted from the light curves is that the baseline of the light curves are not horizontal, this behaviour can be seen very distinctly in figures 5.2 to 5.7. In the velocity channel 1.70 km.s^{-1} , the light curve baseline can be described as approximating a linear increase, while in the other evaluated channels, the baseline can only be described by means of a polynomial. The light curve associated with the minor feature, $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$, shows very little change in the baseline, only a very slight increase over time. The underlying cause of the different baseline behaviours may be due to blending of the maser features or some intrinsic behaviour at the maser source or within the star forming environment.

The primary feature of maser source G358.460 - 0.391, $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$, is initially very strongly blended with weaker feature $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$, refer to figure 7.1. Over time, the features become more separated and distinguishable from one another, the weaker feature, $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$, becomes brighter while the main feature, $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$, appears to become less bright over time. The flux density changes of the features can be seen in their respective light curves and on the dynamic spectra. Now an important distinction should be made when a feature is described as increasing or decreasing in flux density, this description refers only to behaviour observed in the light curves and not necessarily behaviour which is present at or intrinsic to the source. As these features were initially very blended, the weaker feature may have resulted in the main feature initially appearing brighter than it actually was and as the weak feature drifted away, it contributed less to the main feature resulting in an appearance of dimming. However, if this were strictly the case, then it would be expected that the light curves corresponding to the main feature would display a linear decrease in baseline flux as the weak feature displays a linear increase in flux; however, this is not what was observed, as the weak feature separates from the main feature there is an initial decay in baseline flux, followed by a brightening of the main feature which lasts around 1200 days before weakening again. From this, one can assume that the brightening of the main feature between 57000 MJD to 58200 MJD is intrinsic to the main maser feature. Furthermore, it is important to note that the blending of maser features may not be responsible for changes in baseline flux of the maser features, this is a hypothesis we have forward which may explain the observed behaviour of the source.

Periodicity determined from the light curves using the Lomb-Scargle periodogram yielded periodicities of ~ 222 days which is consistent with previous observations and literature, see table 5.2. The light curves were folded and appear to display a distinct bunny-hop shape with a short amount of time spent at the minima. Periodic cycles of G358.460 - 0.391 repeat very well, therefore, any deviation from this periodicity would most likely be due to stochastic changes in the natal environment. Furthermore, since the cycles repeat so well, the periodicity cannot be due to destructive events such as shocks passing through the masing region. It is also interesting to note from the shape of the light curves and the behaviour around the minima that G358.460 - 0.391 spends more time at its peak compared to the minima, this

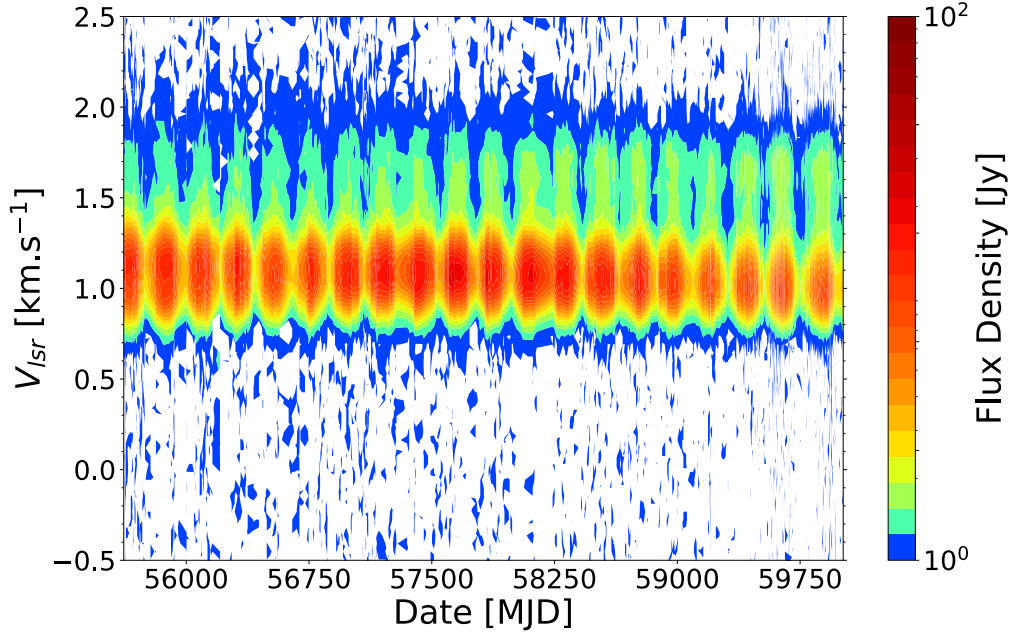


Figure 7.1: Dynamic Spectra of maser source G358.460 - 0.391.

differs in comparison to maser sources with flare profiles, such as G9.62 + 0.2, which spend more time at quiescence and short periods at their peaks. This difference in light curve shape may be due to different mechanisms underlying the periodic behaviour or the different light curve shapes may be a consequence of source is orientation.

The behaviour of the light curve on increasing and decreasing sides of the minimum appears to be very close to symmetric; this symmetric profile is similar to those observed in eclipsing binary sources. In the eclipsing binary scenario, a secondary star may be eclipsing the primary high-mass star, thereby blocking out ionising radiation which propagates in the direction of the HII region where the maser sources are projected; there would be a reduction of seed photons and therefore a reduction in maser intensity. Young high-mass stars are very often observed with companion stars, so the likelihood of a binary system is relatively high. However, the eclipsing binary scenario is not the cause of periodicity in G358.460 - 0.391 based on the current theoretical understanding. In proceeding sections it is discussed that G358.460 - 0.391 is likely an outflow system with a face on view, which is inconsistent with the binary system model. The binary system hypothesis requires the masers to be projected onto the HII region which is not the case in a face on orientation. The symmetric shape of the light curve does not confirm that the origin of periodicity in G358.460 - 0.391 is an eclipsing binary system; however, it does imply that the origin of the periodicity has a symmetric nature.

7.1.2 Separation of maser spots

When studying masers and maser environments, an integral part of understanding their behaviour is understanding the natal environment of these sources and their distribution

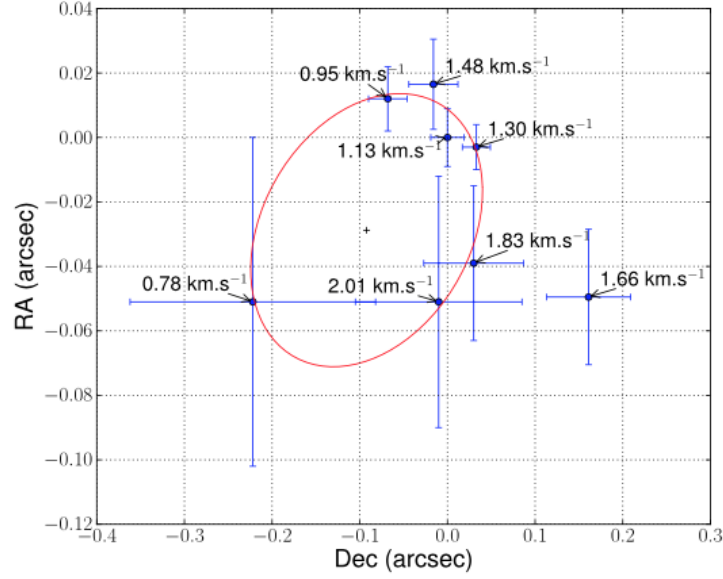


Figure 7.2: The 6.7 GHz methanol maser spot map for G358.460-0.391 fitted by an elliptical function. The distribution of maser spots is centred on the 1.13 km.s^{-1} maser feature. Figure taken from [Maswanganye et al. \(2015\)](#)

within their environment. In the single dish observations, the maser features are differentiated by means of their velocity, however maser spots which are close in velocity are not necessarily close in physical distance. [Chen et al. \(2013\)](#) estimated the kinematic distance to G358.460 - 0.391 as ~ 2.9 kpc and [Ugwu et al. \(2023\)](#) estimated a kinematic distance of ~ 3.9 kpc. Coordinates of masers were not provided by [Maswanganye et al. \(2015\)](#), but using the spot map, the distance between the maser spots corresponding to the 1.13 km.s^{-1} and 1.66 km.s^{-1} features was estimated as ~ 0.168 arcseconds, see figure 7.2. For a source distance of ~ 2.9 kpc, the separation of the maser spots was calculated as ~ 485.9 AU, and for a source distance of ~ 3.9 kpc the separation was calculated as ~ 653.5 AU; therefore the separation between maser spots corresponding to 1.13 km.s^{-1} and 1.66 km.s^{-1} is between ~ 486 AU and ~ 654 AU. This separation means that the maser spots are in the same star-forming region, but, they are not co-spatial despite their relative velocity values. If the system is face-on, maser velocities are close together, therefore there may be multiple maser features which comprise the singular main feature. Furthermore, since the maser spots are in the same environment it is likely that they have the same underlying cause of periodicity.

7.1.3 Bipolar outflows

The systemic velocity of G358.460 - 0.391 is estimated as $\sim -3.36 \pm 0.01 \text{ km.s}^{-1}$ ([Chen et al., 2013](#)) which is slightly offset from the observed maser velocities. The shape of the C^{17}O ($J = 3 - 2$) line, presented by [Ugwu et al. \(2023\)](#), shows that the line is broadened in comparison to the Gaussian fit; this winged appearance is typically an indicator of an outflow viewed face on, i.e., in a disc outflow scenario in which the disc is viewed face-on and the outflow axis is orientated along the line of sight. The velocity field map of the C^{17}O ($J = 3 - 2$) emission, presented by [Ugwu et al. \(2023\)](#), shows the 6.7 GHz methanol masers

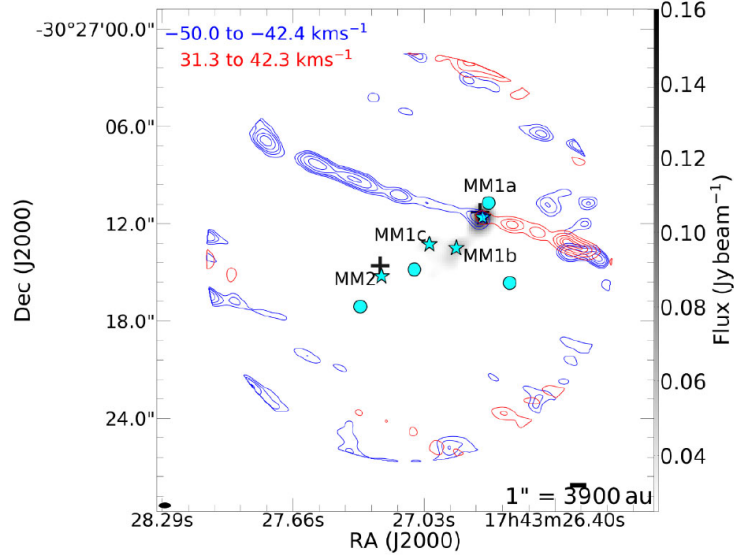


Figure 7.3: Collimated bipolar outflow of G358.460 - 0.391 MM1a traced by ^{12}CO emission as presented by Ugwu et al. (2023).

to be overlapped with blue-shifted emission, however, the maser velocities are redshifted with respect to the systemic velocity of the source and the observer, based on the single-dish observations and data analysis conducted in this research. The C^{17}O emission and the maser gas are not necessarily kinematically related, this overlap may be a result of source orientation. When observing sources in astronomy, the sky is viewed as a two-dimensional projection, and observations are not always straightforward to interpret. In the case where an outflow direction is along the line of sight, the redshifted and blueshifted outflow components may be spatially coincident.

Ugwu et al. (2023) utilised observations of the ^{12}CO emission to map the collimated bipolar outflows associated with G358.460 - 0.391-MM1a, see figure 7.3. The outflow lobes have a knotted distribution which may be indicative of episodic ejections (Ugwu et al., 2023; Burns et al., 2016; Reipurth, 1989). While episodic accretion is impractical to observe it can be inferred from evidence of episodic ejection (Burns et al., 2016). Episodic accretion can also be inferred from maser behaviour as masers are very sensitive to changes in the physical conditions of their natal clouds. An accretion burst will result in an increase of the local radiation field, i.e., increasing incident photons, and therefore, increasing maser emission in the case of radiatively pumped masers such as methanol masers (Miao et al., 2022). It is unclear as to whether or not episodic accretion can result in a light curve profile with a bunny hop shape. The current hypothesis is that episodic accretion will result in flare profiles, with rapid rise and slow decay of flux density, in the light curve similar to that observed in G9.62 + 0.20 and G351.42 + 0.64 (Parfenov and Sobolev, 2014). However, the potential influence of the orientation of the maser region has not yet been constrained.

7.1.4 Orientation of maser region

As previously discussed, from the winged appearance of the C^{17}O spectrum it is likely that G358.460 - 0.391 has a face-on orientation with the outflow axis along the line of sight. Other

bunny-hop maser sources, such as G25.411 + 0.105, have been associated with a similar face on orientation. Maswanganye et al. (2015) fitted an ellipse to the maser spots as can be seen in figure 7.2, in the case of a face-on view of the disc, the elliptical fit implies a slight inclination angle relative to the line of sight. In the argument presented by Morgan et al. (2021) the authors stated that a consequence of their scenario, in which the orientation of the maser source impacts the shape of the light curve, would be that the maser velocities must be close to the systemic velocity of the source and/or have a small velocity range. In observations of G358.460 - 0.391 the conditions seem to hold, the velocity of the maser features differ by less than 1 km.s^{-1} , and while there is a difference between the systemic velocity and the maser velocity this could be a result of the slight inclination angle of the maser region, Morgan et al. (2021) considered a perfectly face on orientation. A perfectly face on orientation is an idealised scenario, in practice most environments will have a slight angle which offsets the environment, as seen in the maser spot diagram of G358.460 - 0.391. Assuming a disk outflow system where the disc is viewed face-on, different to a source such as G9.62 + 0.19E which has perpendicular outflow orientation and an edge-on view of the disc (Morgan et al., 2021). It is possible that the asymmetric periodic profiles such as those observed in G9.62 + 0.19E and the symmetric periodic profiles such as the bunny-hop profile have similar underlying causes but when observed have different profile as a result of the orientation of the disc outflow system.

7.1.5 Episodic accretion

Protostars can experience accretion bursts where there is a sudden and intense increase in the accretion rate onto a protostar (Durjasz et al., 2021). Accretion bursts can be due to instabilities in the protostellar disk or interactions with surrounding material. Massive protostars can display episodic outbursts which which can drastically change maser flux density (Szymczak et al., 2018a). When a massive protostar rapidly accretes material there will be a sudden increase in ionising radiation from the protostar as well as an increase in the outflows from the stellar object (Stahler and Palla, 2008). The increase in ionising radiation from the stellar object will increase the dust temperature and therefore the pumping of maser molecules will increase (Gray, 2012). Burns et al. (2023) found that there is strong evidence linking disc accretion and spiral arm instability to episodic accretion in high mass star formation. As already stated, the outflow lobes of G358.460 - 0.391 have a knotted structure which may be indicative of episodic accretion events (Ugwu et al., 2023; Burns et al., 2016; Reipurth, 1989).

7.1.6 Stellar Pulsation and Periodic variability

Inayoshi et al. (2013) propose that periodicity in 6.7 GHz methanol masers could be a result of stellar pulsation of stars residing in the instability strip which are actively undergoing accretion. A massive protostar will become pulsationally unstable when it is bloated and has not yet evolved to a main sequence star. Pulsation periods of these protostars are estimated as ranging between ~ 10 to 100 days, which explains the observed periodicity in many observed maser sources, as well as why masers which are periodic on very short timescales have not yet

been observed (Inayoshi et al., 2013). As the central protostar pulsates on some timescale, the dust in the maser environment heats up increasing maser flux and the maser will appear to be periodic on a similar timescale as the protostar.

7.1.7 Velocity drift of G358.460 - 0.391

The Gaussian evaluation of the velocity drift yields a very high goodness of fit R^2 value of $\sim 88\%$ for the linear fit and $\sim 95\%$ for the second-order polynomial fit, the fits to the Gaussian evaluated data points is clearly shown in figure 5.28. The linear fit is represented by the equation $y = (-1.93 \pm 0.12 \times 10^{-5})x + 2.19$ where y is the local standard of rest velocity, v_{lsr} , and x is the modified Julian date; the second-order polynomial fit is given by the equation $y = (-5.18 \times 10^{-9})x^2 + (5.82 \times 10^{-4})x - 15.23$. The high R^2 values, along with the drift passing over multiple velocity channels, gives a high level of confidence that the velocity drift is real. It is interesting to note that the secondary feature of G358.460 - 0.391, which on the dynamic spectra extends from approximately 1.5 km.s^{-1} to 1.8 km.s^{-1} appears to be very stable on the 1.8 km.s^{-1} line, as can be seen in figure 5.24. The secondary feature is not drifting at the same rate as the primary feature, and in fact, by looking at the dynamic spectra it appears that the feature becomes more separated from the main feature as the main feature appears to drift away from the weaker feature. This is very interesting to note, as determined from the maser spot map, these two features are not cospatial, therefore environmental conditions causing velocity drifting are not present throughout the environment.

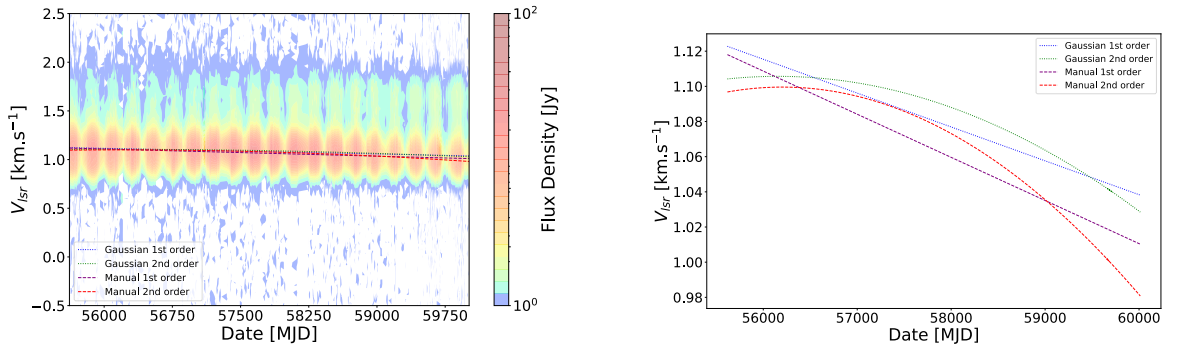


Figure 7.4: The above two figures demonstrate the different methods used when fitting the velocity drift to G358.460 - 0.391. On the right figure, four plots can be seen, these plots include: a first and second order fit to the Gaussian determined data points; the figure also includes first and second order fit to the manually selected velocity range which included the main feature. On the left figure the same four fits are plotted on the dynamic spectra.

Methanol maser source G338.93 - 0.06 is very similar to maser source G358.460 - 0.391 in terms of behaviour and drift, as presented in chapter 6; G338.93 - 0.06 is a periodic bunny-hop source with a velocity drift in the main feature. It is unclear if the velocity drift observed in G358.460 - 0.391 is a result of spectrally blended features (Szymczak et al., 2014) or motion of the gas (Goddi et al., 2011). MacLeod et al. (2021) state that the velocity drift observed in G9.62 + 0.20E was potentially due to disc precession or infall motions from the disc, G9.62 + 0.20E is an edge-on orientation but disc precession and infall motions can be present regardless of the orientation. However it is important that velocity drifts have been observed

in both disc orientations. Multi-epoch interferometric observations and continuous single-dish monitoring will be essential in explaining the cause of velocity drifts in both edge-on and face-on orientations.

7.1.8 In summary

G358.460 - 0.391 is a source of maser emission. The primary source is a HMYSO whose behaviour is consistent with a source undergoing episodic accretion. The HMYSO has bipolar outflows, a circumstellar disc, and a slowly rotating envelope associated with it. There is strong evidence supporting the system being viewed in an almost face-on orientation, i.e., where the circumstellar disc is viewed face-on and the outflow axis is orientated along the line of sight. In an approximately face-on orientation, maser features will have a small velocity range, as can be seen in the spectrum and dynamic spectrum of G358.460 - 0.391. The maser features associated with G358.460 - 0.391 fall within a velocity range of approximately 1.5 km.s^{-1} . This small velocity range results in blending and overlapping of maser features in the dynamic spectrum despite these features being spatially separated. Several investigated features and velocity channels display periodic variability which appears to be well modeled by an absolute cosine function, which is the distinct ‘bunny-hop’ shape. Periodicity in all investigated channels and features was approximately 220 days. It is interesting to note that the baselines of the light curves are not horizontal but are better described by means of a polynomial, this may point to an environmental condition which alters maser pumping in addition to the mechanism responsible for the periodicity. When investigating the behaviour of the maser features around the minima, it is clear that the time spent in the minima is very short in comparison to the time spent at the peak and there does not appear to be any notable period of quiescence. In most cases the maser spend only around two weeks in minima versus approximately 50 days in maxima; it was difficult to constrain exact times in minima and maxima, the presented values are only estimates. This behaviour is very different in comparison to maser sources such as G9.62 + 0.2, which have flare profiles and spend more time at their minima. It is not yet clear what is the underlying cause of the maser periodicity in G358.460 - 0.391; the underlying cause of periodicity is likely symmetric in nature and not due to destructive events, such as shocks, in the star-forming environment. It is also unclear as of yet, if the distinct bunny-hop shape is potentially due to the orientation of the star forming environment. Finally, a notable velocity drift was observed in the primary feature of G358.460 - 0.391 while the secondary feature appeared to be relatively stable. Therefore, if the velocity drift is due to environmental conditions at the source, these conditions are not present throughout the star forming environment.

7.2 Discussion of archival data results

Table 7.1: Summary of investigated maser sources displaying velocity drifts; only sources displaying goodness of fit values above 50% in the Gaussian evaluation were included in this table. All source information summarised in this table was derived from the archival data.

	Linear regression fit	Gaussian-fitted velocity
Source		

	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G9.62 +	1.24	2.52	2	0.312	2.05	79
0.2	-0.12	-0.41	1	0.273	-0.50	23
G10.33 -	10.01	3.14	3	0.55	4.25	75
0.17	11.54	-2.90	1	0.70	0.38	1
G12.68 -	57.54	-6.88	13	0.57	-7.51	93
0.18	52.09	6.32	2	1.05	7.41	90
	58.32	5.59	4	0.38	5.85	69
	59.81	1.98	2	0.28	0.43	2
G12.91 -	39.36	2.05	1	0.31	0.13	12
0.26	39.81	-0.26	0	0.57	-2.77	74
G35.20 -	42.37	0.65	0	0.28	0.95	25
1.74	44.65	3.63	7	0.47	2.74	57
G174.20	1.57	-8.46	7	0.52	-10.05	69
- 0.08	3.98	-8.80	1	0.93	-2.40	3
G196.45	15.22	-5.99	6	0.47	-4.04	79
- 1.68	15.80	-2.96	7	0.20	0.70	0
G308.92	-54.79	0.32	0	0.24	0.80	26
+ 0.12	-54.39	3.98	4	0.47	0	0
	-55.39	-4.48	0	0.24	0.04	0
	-52.79	-4.65	10	0.40	-4.43	61
G318.95	-34.71	0.88	0	0.58	0.90	57
- 0.2	-36.83	6.77	11	0.52	5.72	74
G328.24	-44.76	3.51	4	0.48	2.25	72
- 0.55	-43.25	0.04	0	0.53	0.09	0
	-37.44	0.17	0	0.58	0.77	14
G328.81	-43.88	2.15	1	0.47	1.40	71
+ 0.63	-44.48	2.61	4	0.26	1.21	70
	-46.35	0.76	0	0.47	1.29	63
	-45.26	1.97	1	0.47	1.69	52
G337.92	-37.93	1.80	0	43	-2.38	50
- 0.46	-38.74	4.65	4	44	11.8	88
G338.93	-42.04	3.16	2	0.49	3.05	61
- 0.06	-41.36	0	0	0.28	1.15	8
G339.62	-32.84	0.48	1	0.47	-0.91	11
- 0.12	-35.83	8.50	2	0.65	11.3	59
G339.88	-38.77	3.14	3	0.35	1.80	66
- 1.26	-35.19	-2.86	2	0.99	1.91	24
	-37.47	0.02	0	0.54	1.09	26
	-36.67	-0.62	2	0.54	1.85	56
G340.79	-105.13	0.99	0	0.45	3.18	79
- 0.10	-106.93	-4.14	1	0.39	23.9	80
G345.50	-14.37	6.61	6	0.58	1.05	11
+ 0.35						

	-15.62	-0.94	0	0.51	2.56	73
	-16.60	-0.37	0	0.52	0.31	2
	-17.79	1.63	0	0.47	1.05	15
G351.58	-94.30	5.0	14	0.27	2.43	69
- 0.35	-95.52	0.70	1	0.71	1.54	15
G354.61	-23.17	1.43	1	0.61	1.56	50
+ 0.47	-24.44	2.47	1	0.34	3.45	74
	-16.74	1.31	1	0.94	8.84	66

7.2.1 Variability in maser sources

A number of the archival maser sources display some degree of variability or periodicity; this was covered in earlier work done by [Goedhart et al. \(2003\)](#), [Goedhart \(2004\)](#), and [Goedhart et al. \(2004\)](#). Correlated maser variations are expected if the variations have a common origin. Phase lags represent velocity of the masing region or distance between maser spots or masing cloudlets. [van der Walt \(2011\)](#) suggest that periodicity in sources G9.62 + 0.2 and G188.95 + 0.89 are caused by periodic wind interactions in a binary system, i.e., the colliding wind binary (CWB) model. This model considers a periodic wind interaction in a binary system, the wind interaction produces ionising waves which periodically change the seed photon flux and consequently the observed brightness of 6.7 GHz methanol masers present in the system. The CWB model produces light curves with asymmetric flare profiles where there is a more rapid increase in maser intensity followed by a slower decay period.

7.2.2 Maser velocity drifts

Velocity drifts have been observed in the methanol maser sources presented in table 7.1. The jury is still out on what is causing these observed drifts; they may be the result of heavily line-blended maser features, a precessing accretion disc, or alternatively they may indicate some gas motion or infalling gas onto a HMYSO ([MacLeod et al., 2021](#)). Sources which did not yield any significant findings can be found in Appendix A; these sources yielded R^2 values less than 50%.

A few sources displayed velocity drifts with high confidence levels. In this research we are choosing to define a high confidence as an R^2 value above 70%. These sources include G9.62 + 0.2, G10.33 - 0.17, G12.68 - 0.18, G12.91 - 0.26, G196.45 - 1.68, G318.95 - 0.2, G328.24 - 0.55, G328.81 + 0.63, G337.92 - 0.46, G340.79 - 0.10, G345.50 + 0.35, and G354.61 + 0.47 as can be seen in table 7.1.

Many investigated sources contained only one feature whose velocity drift was evaluated having an R^2 value above 50%; a few sources had a number of features supporting the presence of velocity drifts. Sources with multiple features displaying velocity drifts which yield goodness of fit values greater than 50% include G12.68 - 0.18, G318.95 - 0.2, G328.81 + 0.63, G337.92 - 0.46, G339.88 - 1.26, G340.79 - 0.10, and G354.61 + 0.47.

Sources which display both periodic behaviour and velocity drifts with goodness of fit values greater than 50% are G9.62 + 0.2, G12.68 - 0.18, G196.45 - 1.68, G328.24 - 0.55, G338.93 - 0.06, and G339.62 - 0.12. The light curves of these periodic maser sources are significantly different from one another suggesting that the underlying mechanism behind the periodicity is likely different.

All the maser sources presented in table 7.1 are promising candidates of velocity drifting. However, since these sources were all observed with relatively low cadence and limited correlator resolution it is recommended that longer term observations with improved resolution are considered prior to making any definitive statements on the presence or degree of velocity drifting.

7.2.3 Line blending in maser features

A number of maser sources evaluated displayed line blending to some degree. Line blending in maser sources can occur for a multitude of reasons: broadening of spectral lines may cause overlap and blending; multiple maser sources or cloudlets within the same line of sight can overlap and blend together leading to complicated spectral features; observational limitations can also lead to line blending as a result of limited spectral resolution or sensitivity. Sources where line blending hindered the search for velocity drifts include G12.68 - 0.18 (W33B), G12.91 - 0.26 (W33A), G188.95 + 0.89, G196.45 - 1.68, G308.92 + 0.12, G340.79 - 0.10, and G345.00 - 0.22. In these mentioned maser sources, velocity drifting was difficult to observe in some or all features. It would be beneficial to consider longer-term observations with an improved spectral resolution. Interferometric observations would also be beneficial in resolving the different velocity components from one another.

Chapter 8

Summary and Conclusion

8.1 Maser source G358.460 - 0.391

Source of maser emission G358.460 - 0.391 comprises of a primary HMYSO possibly undergoing episodic accretion. The HMYSO has bipolar outflows, a circumstellar disc, and a slowly rotating envelope associated with it. Strong evidence supports the hypothesis that the system being viewed at an almost face-on orientation. In an approximately face-on orientation, maser features will have a small velocity range, as can be seen in the spectrum and dynamic spectrum of G358.460 - 0.391. The maser features associated with G358.460 - 0.391 fall within a velocity range of approximately 1.5 km.s^{-1} . This small velocity range results in blending and overlapping of maser features in the dynamic spectrum despite these features being spatially separated.

Several investigated features and velocity channels display periodic variability which appears to be well modeled by an absolute cosine function, which is the distinct ‘bunny-hop’ shape. Periodicity in all investigated channels and features was approximately 220 days, as determined by the Lomb-Scargle periodogram. It is interesting to note that the baselines of the light curves are not horizontal but are better described by means of a polynomial, this may point to an environmental condition which influences maser pumping in addition to the mechanism responsible for the periodicity. When investigating the behaviour of the maser features around the minima, it is clear that the time spent in the minima is very short in comparison to the time spent at the peak and there does not appear to be any notable period of quiescence. In most cases the maser spend only around two weeks in minima versus approximately 50 days in maxima; it was difficult to constrain exact times in minima and maxima, the presented values are only estimates. This behaviour is very different in comparison to maser sources such as G9.62 + 0.2, which have flare profiles and spend more time at their minima. It is not yet clear what is the underlying cause of the maser periodicity in G358.460 - 0.391; the underlying cause of periodicity is likely symmetric in nature and not due to destructive events, such as shocks, in the star-forming environment. It is also unclear as of yet, if the distinct bunny-hop shape is potentially due to the orientation of the star forming environment.

Finally, a notable velocity drift was observed in the primary feature of G358.460 - 0.391, $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$, while the secondary feature, $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$, appeared to be relatively stable. These two features are spatially removed from one another but are very close in velocity. When looking at the average spectra and the dynamic spectra the two features appear blended, particularly in the earlier observations. As the observations progress the features corresponding to $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ and $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$ appear to separate and become less blended as $v_{\text{cen}} \sim 1.07 \text{ km.s}^{-1}$ experiences a velocity drift whilst $v_{\text{cen}} \sim 1.65 \text{ km.s}^{-1}$ remains relatively stable. Since a velocity drift is not present in both features it is likely not due to instrumental or observational error. Furthermore, if the velocity drift is due to environmental conditions at the source, these conditions are not present throughout the star forming environment.

8.2 Archival data

Evidence of velocity drifts was found in nineteen of the investigated maser sources. Twelve of the nineteen maser sources displayed very high goodness of fit for the Gaussian evaluation of velocity drifts; a high goodness of fit was defined as an R -squared value greater than 0.7 or 70%. Six archival sources displayed evidence supporting both periodic variability as well as velocity drifts. Considering that a significant number of the archival sources displayed velocity drifting behaviour it is possible that velocity drifts are a more common, maybe even ubiquitous, phenomenon associated with methanol masers. Whilst these findings are very promising, due to the limited velocity resolution of the archival data used, more observational data with improved resolution will be necessary in confirming and constraining these findings. However, this research has provided a good reference point for searching for more sources which are velocity drifting.

8.3 Recommendations for Future Work

- Maser sources should be continuously monitored, particularly those with noteworthy features such as significant variability, periodicity, and velocity drifts. Longer time series and higher cadence observations allow researchers to confirm behaviour and observe long-term trends in the behaviour of masers.
- Observing multiple transitions of methanol maser sources, such as the 6.7 GHz and 12.2 GHz transitions, which will allow for comprehensive study and cross validation of findings.
- Long-term, high cadence observations of methanol maser sources which displayed a high likelihood of velocity drifting. Many of the archival sources evaluated in this research are good candidates for velocity drifting, however, due to limited velocity resolution it was difficult to make concrete conclusions.
- More thorough statistical methods should be employed in future research. While the goodness of fit R^2 test used in this research can be useful it can give misleadingly low

confidence levels for sources with larger, blended, or Zeeman splitted features. Goodness of fit appears to be more suited for sources with bright or distinct features.

- High-resolution mapping in cases where the maser structure or the environmental structure is complex would be beneficial for further study of maser variability.
- Mid-infrared imaging can map stars and compact cores in regions where maser emission has been detected. Concurrently monitoring mid-infrared and maser emissions may help solidify links between accretion, pumping, and observed flaring behaviour of the maser sources.
- Mapping the structure of the molecular core can provide evidence for structures which are present but small angular sizes make them difficult or impossible to observe.

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Appendix A

Survey of Methanol Maser Sources

The following appendix presents the archival maser sources which did not yield substantially significant findings. These sources have been included for future reference and for the sake of completeness.

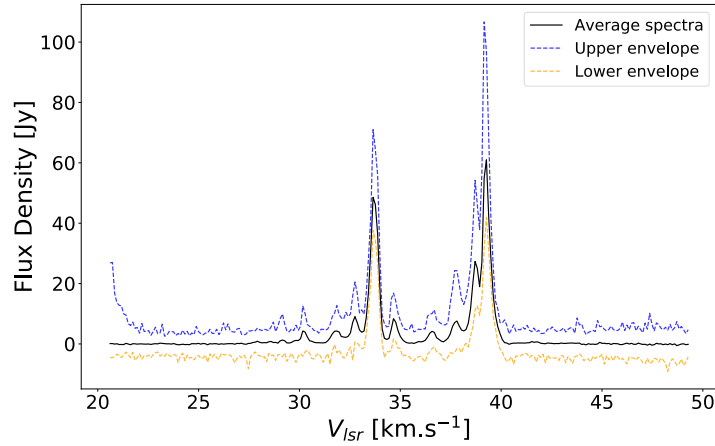
Table A.1: Summary of investigated maser sources which did not yield convincing results when investigated for velocity drifts. All source information summarised in this table was derived from the archival data.

Source	v_{cen} (km s ⁻¹)	Linear regression fit			Gaussian-fitted velocity	
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G12.89	39.25	1.57	1	0.47	0.25	0
+ 0.49	33.71	1.78	1	0.47	1.73	42
G23.44 -	103.3	1.33	0	0.49	0.07	0
0.18	96.61	-1.71	2	0.43	0.75	6
G52.668	64.64	9.25	22	0.48	-9.72	39
- 1.09	65.75	1.57	0	0.43	1.61	1
G189.03	8.86	-0.91	0	0.30	-2.47	12
+ 0.79	9.65	-1.19	0	0.31	0.52	1
G192.60	4.63	-2.52	4	0.47	-2.06	33
- 0.05	5.36	-1.50	1	0.38	-1.08	30
G291.27	-29.71	-2.66	1	0.67	-1.12	14
- 0.71	-30.45	-3.70	3	0.35	-2.73	23
G309.92	-59.76	0.46	0	0.47	0.56	16
+ 0.48	-58.60	1.19	1	0.28	0.75	25
G312.11	-49.96	1.23	1	0.47	1.24	18
+ 0.26	-50.94	1.51	0	0.31	1.05	3
G322.16	-63.17	21.7	1	0.35	11.3	31
+ 0.64	-56.38	-1.37	0	0.52	2.34	33
G331.13	-84.34	0.59	0	0.50	-0.66	2
- 0.24	-85.58	5.16	5	0.49	-5.08	2
	-90.84	4.61	2	0.49	3.48	1

G331.278	-78.12	2.27	2	0.55	0.89	26
- 0.188	-81.56	-1.44	0	0.94	-1.54	8
	-85.14	-2.08	2	0.38	-3.90	46
	-83.30	-0.36	0	0.35	1.45	27
G335.55	116.48	2.68	1	0.66	0.75	5
- 0.31	113.10	3.13	2	0.47	2.64	9
G336.99	125.84	2.75	1	0.38	1.69	31
- 0.03	120.60	-1.37	0	0.38	2.73	9
G344.23	-19.73	-1.34	1	0.46	-0.57	8
- 0.57	-26.34	1.26	0	0.47	0.83	10

A.1 Notes on individual sources

A.1.1 G12.89 + 0.49



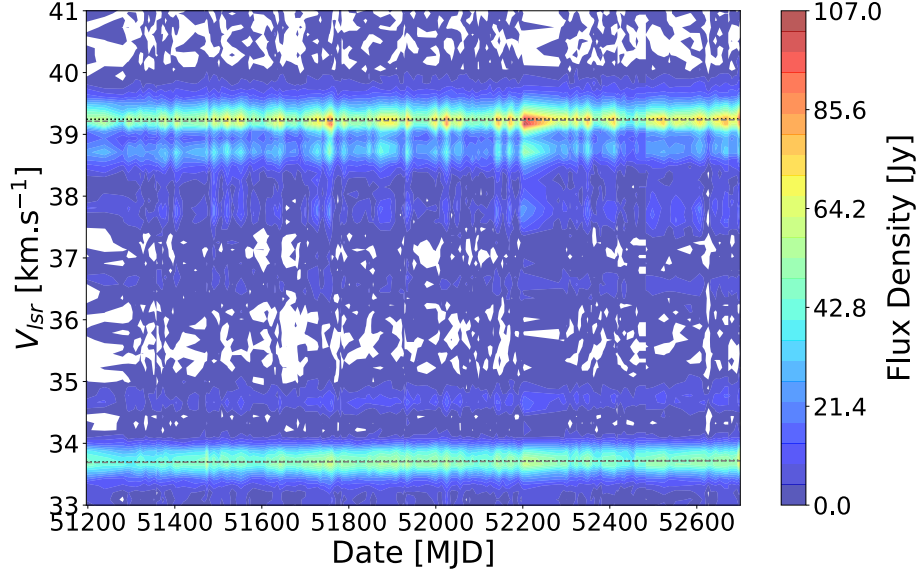
G12.89 + 0.49 averaged spectrum with upper and lower envelope

The periodicity determined is consistent with the findings of [Goedhart et al. \(2009\)](#).

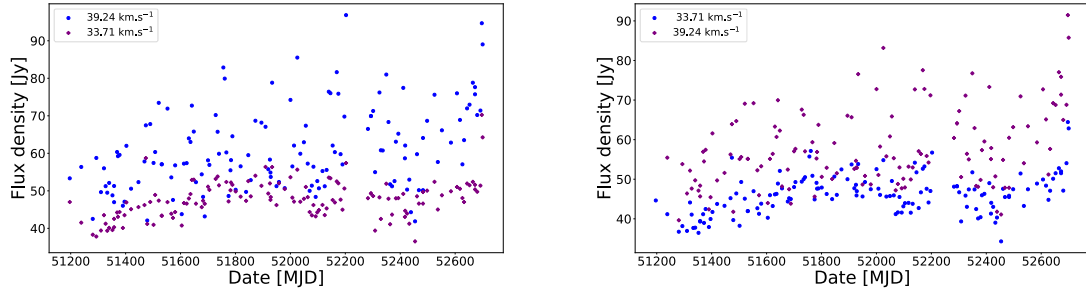
Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a			Gaussian-fitted velocity ^b	
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G12.89	39.25	1.57	1	0.47	0.25	0
+ 0.49	33.71	1.78	1	0.47	1.73	42

^a Linear regression fitting to associated velocities of determined flux densities.

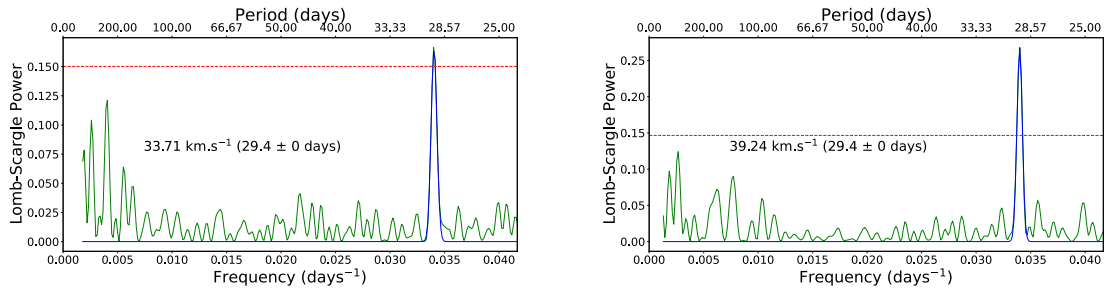
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.



G12.89 + 0.49 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

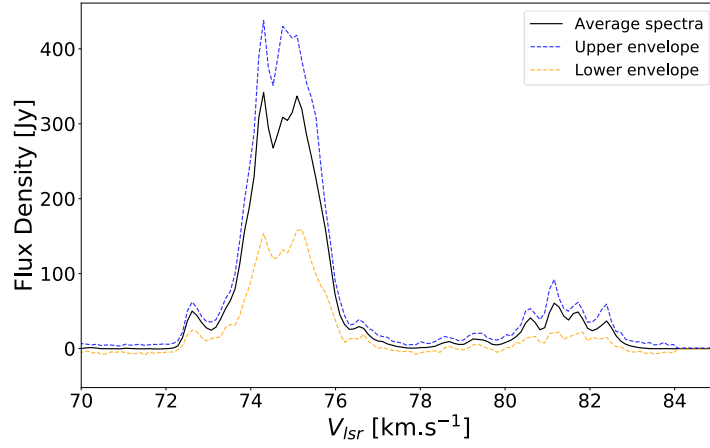


G12.89 + 0.49 light curves determined from Gaussian fitting

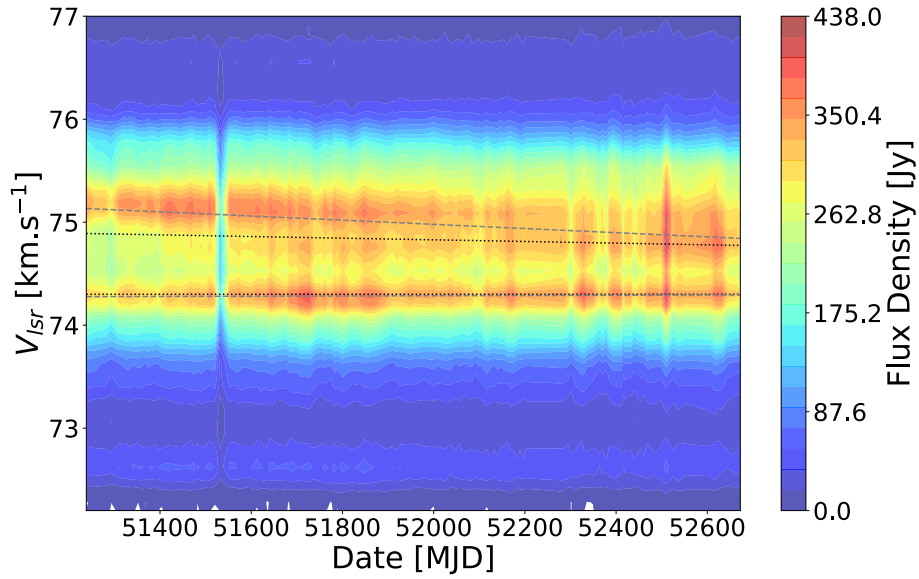


G12.89 + 0.49 Lomb-Scargle maser features associated with velocity channels 33.71 km.s⁻¹ and 39.24 km.s⁻¹ respectively.

A.1.2 G23.01 - 0.41



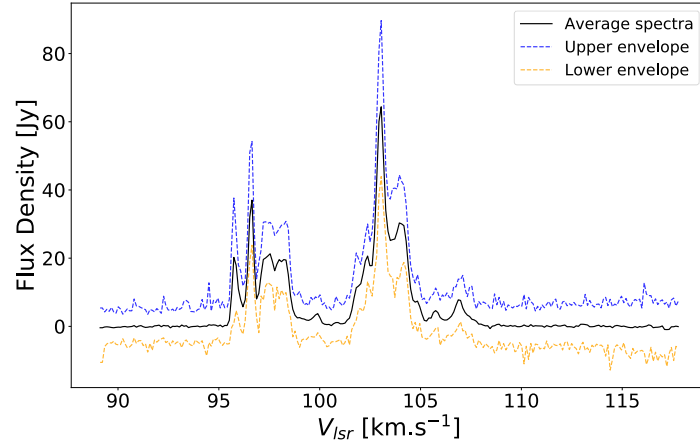
G23.01 - 0.41 averaged spectrum with upper and lower envelope



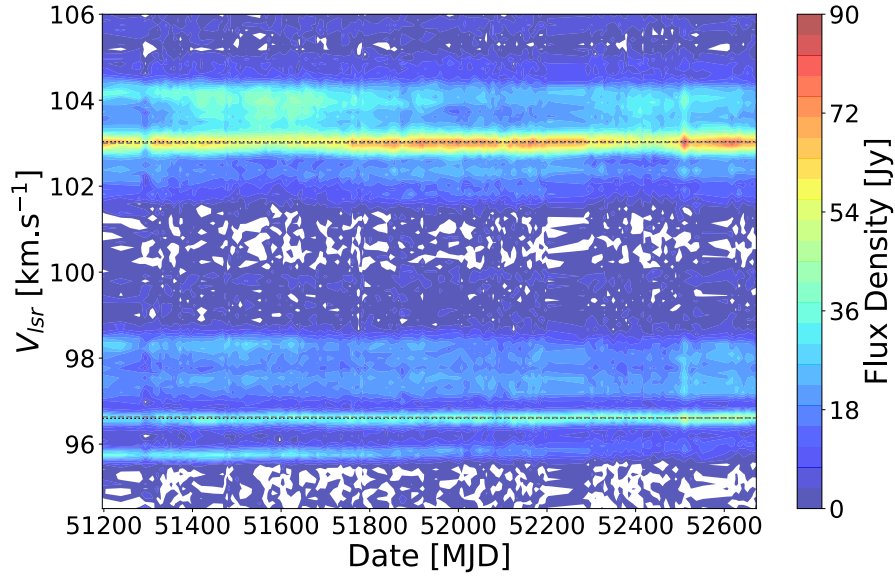
G23.01 - 0.41 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

No periodicity or velocity drifts were determined from the archival data. The spectrum is complicated and the velocity resolution of the maser source observation is insufficient. Higher resolution observations would have to be performed on such a source in order to determine with any level of confidence the presence of a velocity drift. From visual inspection it can be noted that the feature around 75 km.s^{-1} appears to have a velocity drift while the feature around 74.2 km.s^{-1} appears to be relatively stable. Due to heavy blending it was difficult to accurately determine velocity drifts in the feature around 75 km.s^{-1} .

A.1.3 G23.44 - 0.18



G23.44 - 0.18 Average spectra with upper and lower envelope



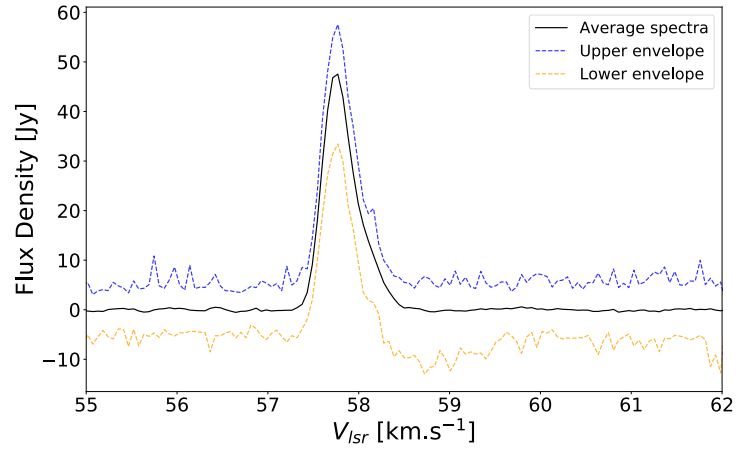
G23.44 - 0.18 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a			Gaussian-fitted velocity ^b	
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)
G23.44 -	103.3	1.33	0	0.49	0.07	0
0.18	96.61	-1.71	2	0.43	0.75	6

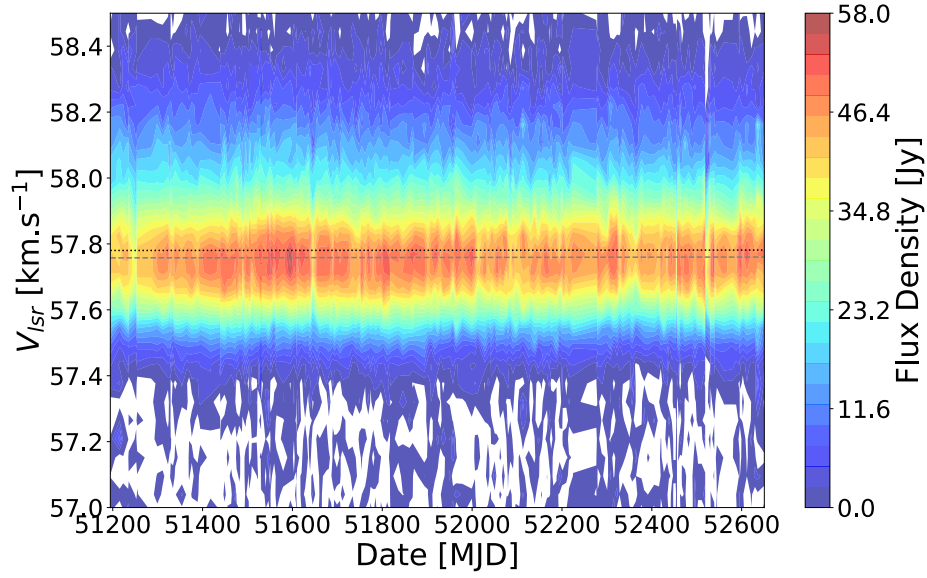
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.4 G45.07 + 0.13



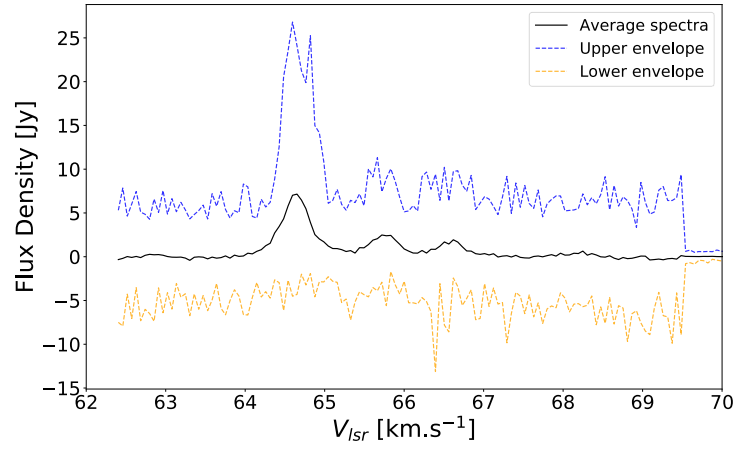
G45.07 + 0.13 averaged spectrum with upper and lower envelope



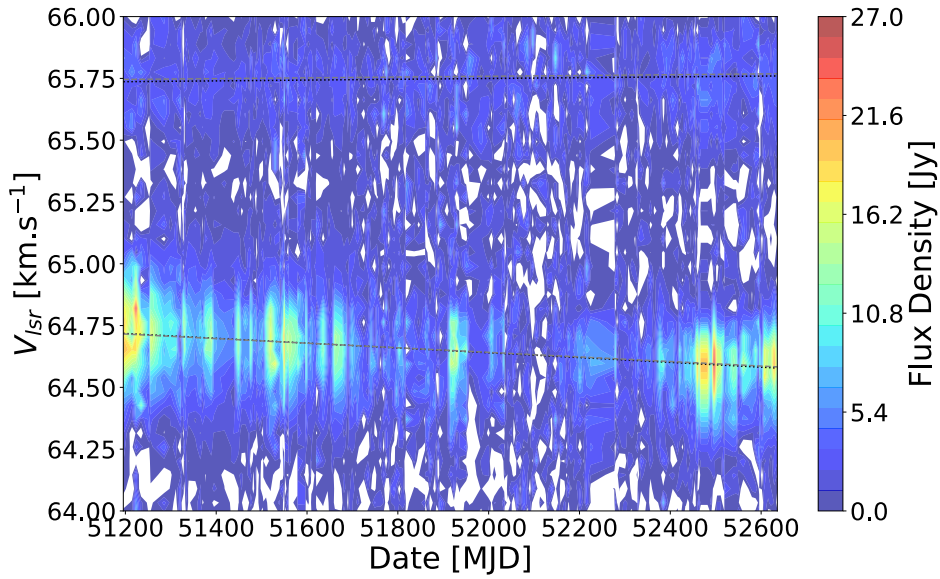
G45.07 + 0.13 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

No velocity drifts were found.

A.1.5 G52.668 - 1.09



G52.668 - 1.09 averaged spectrum with upper and lower envelope



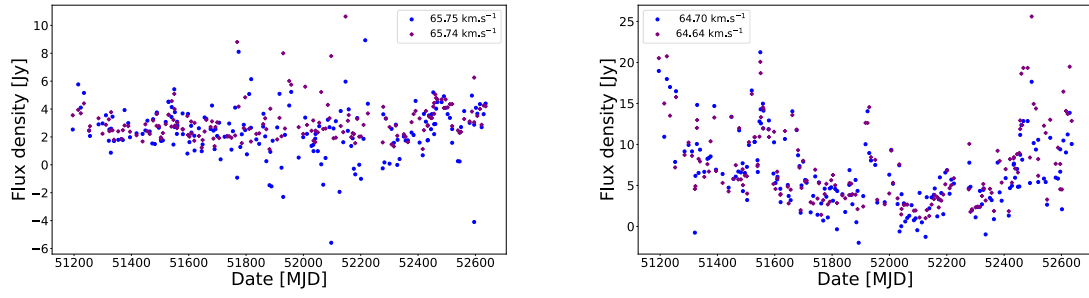
G52.668 - 1.09 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a			Gaussian-fitted velocity ^b	
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)
G52.668	64.64	9.25	22	0.48	-9.72	39
- 1.09	65.75	1.57	0	0.43	1.61	1

^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

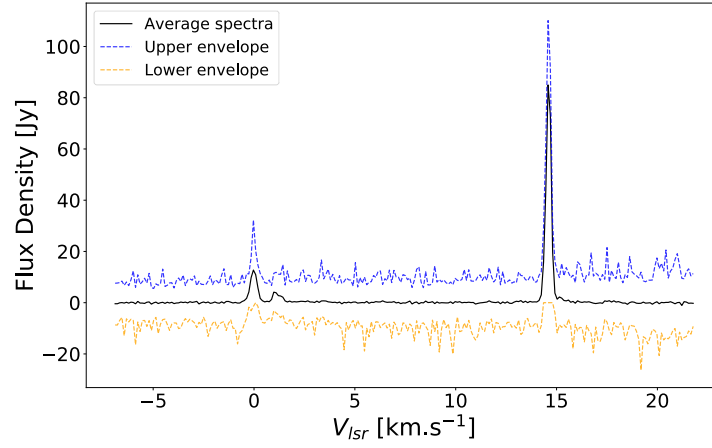
Two velocity drifts were detected in this source. However, since this source is largely dominated by noise, higher quality observations will be necessary to verify observations made in



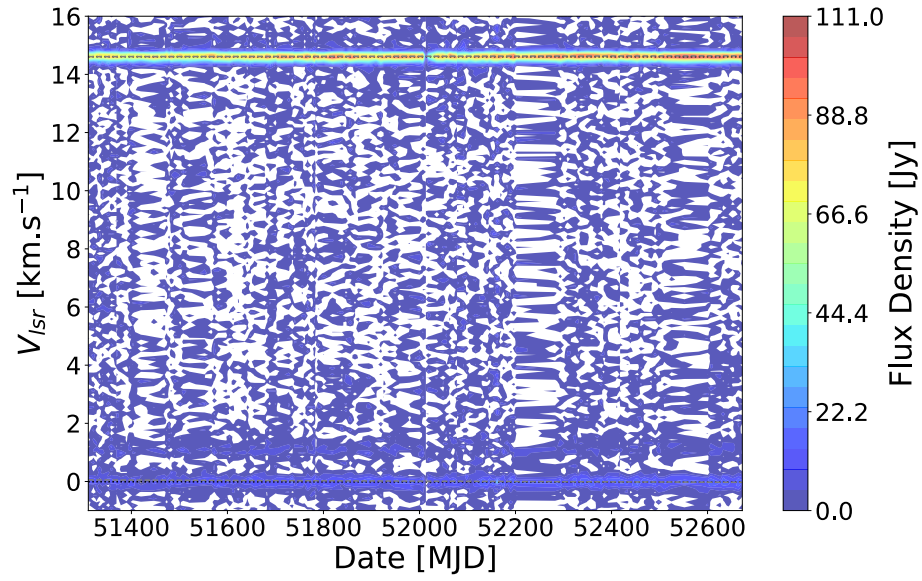
G52.668 - 1.09 light curves determined from Gaussian fitting and channel specific evaluation. The blue dots represent the manually, channel specific, determined light curve. The purple markers represent the Gaussian fit determined light curves.

the archival data. The light curves do not have any noteworthy features such as periodicity present.

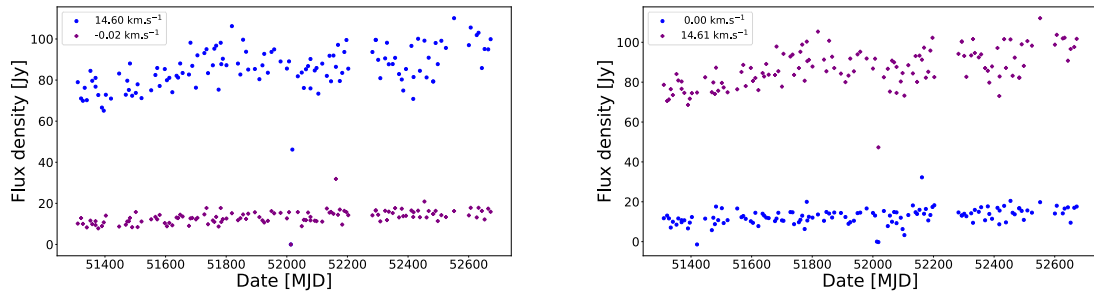
A.1.6 G69.54 - 0.98



G69.54 - 0.98 averaged spectrum with upper and lower envelope

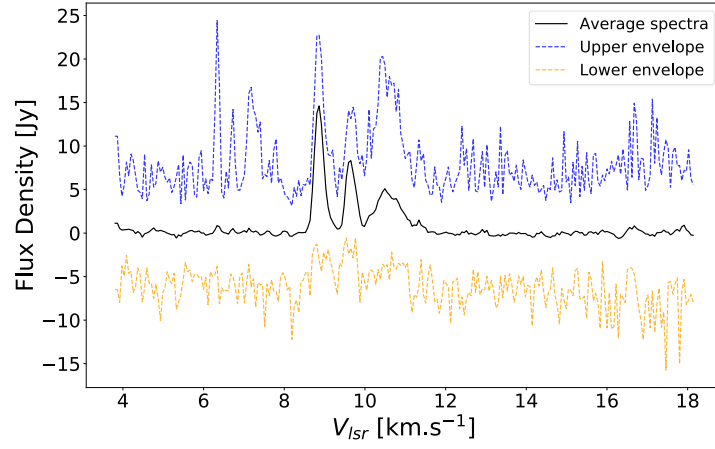


G69.54 - 0.98 Dynamic spectra. No significant velocity drifts were derived from the data; both maser features appear relatively stable.

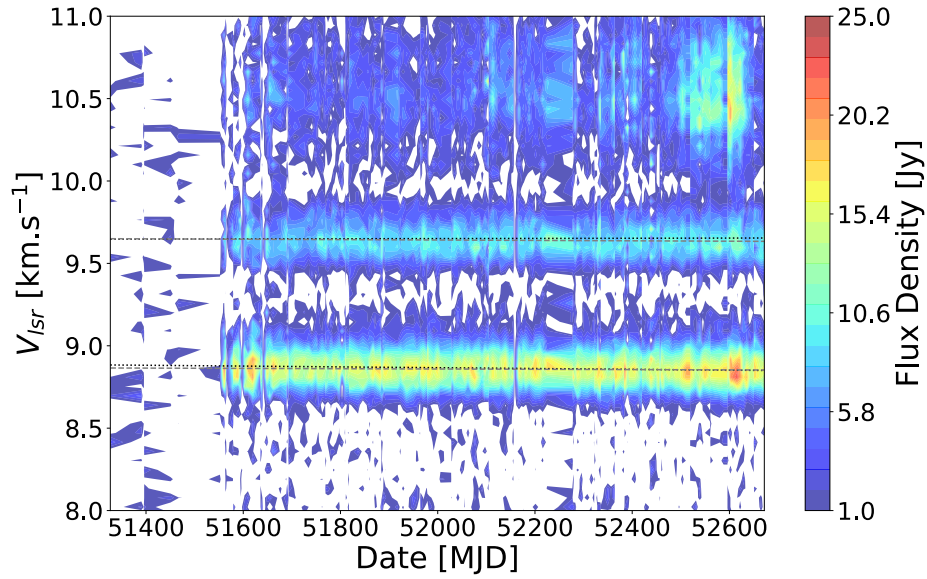


G69.54 - 0.98 light curves determined from Gaussian fitting and channel specific evaluation. The blue dots represent the manually, channel specific, determined light curve. The purple markers represent the Gaussian fit determined light curves.

A.1.7 G189.03 + 0.79



G189.03 + 0.79 averaged Spectra with upper and lower envelope



G189.03 + 0.79 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser feature associated with G189.03 + 0.79 is very weak with flux densities only reaching maximums of ~ 25 Jy in the strongest feature. The changes in the time series are dominated by noise. Despite the high noise present in this observation a search for velocity drifts was still conducted.

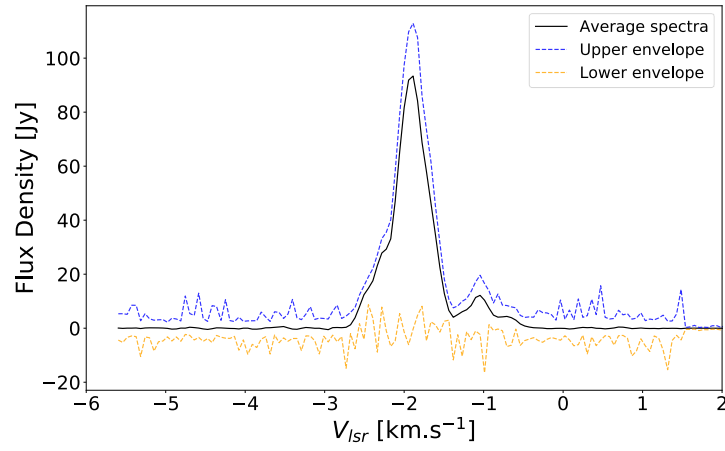
A.1.8 G287.36 + 0.64

No significant velocity drift detected in maser source G287.36 + 0.64.

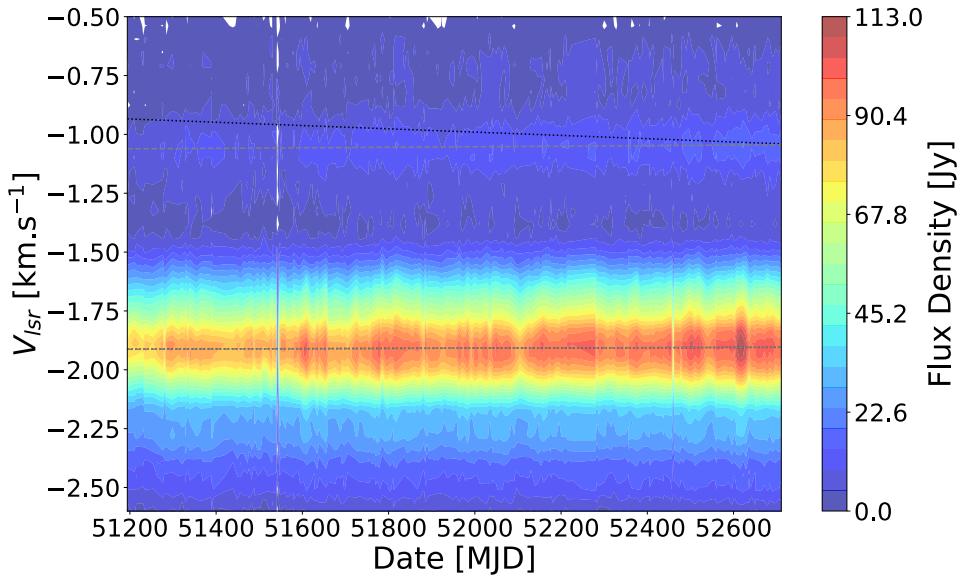
Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b	
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)
G189.03	8.86	-0.91	0	0.30	-2.47	12
+ 0.79	9.65	-1.19	0	0.31	0.52	1

^a Linear regression fitting to associated velocities of determined flux densities.

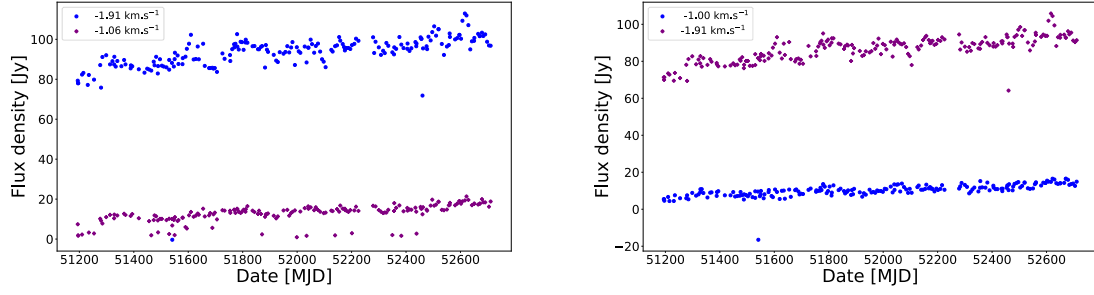
^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.



G287.36 + 0.64 averaged spectrum with upper and lower envelope

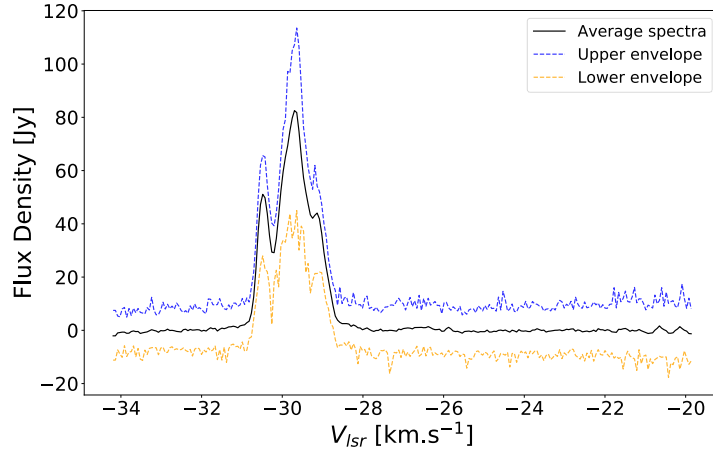


G287.36 + 0.64 Dynamic spectra



G287.36 + 0.64 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

A.1.9 G291.27 - 0.71



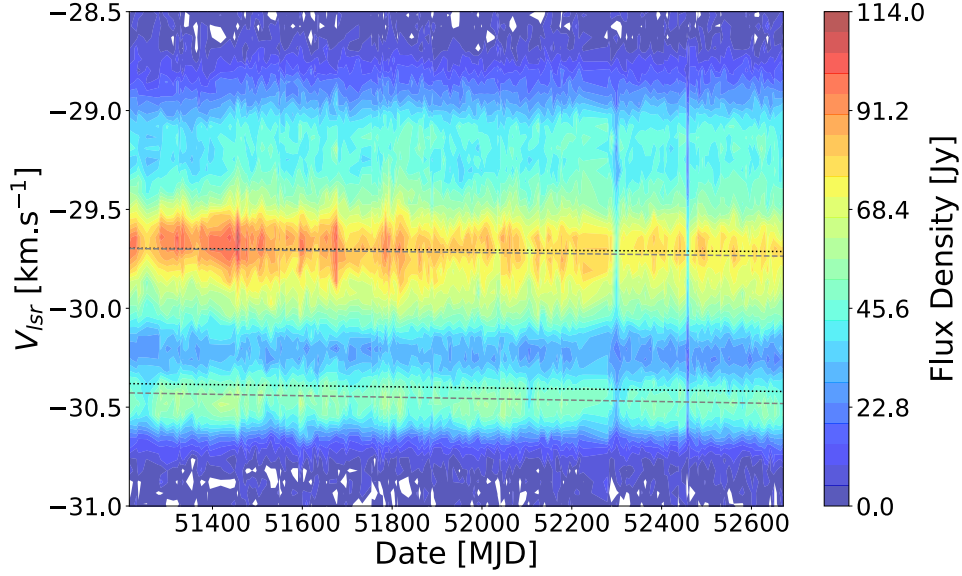
G291.27 - 0.71 averaged spectrum with upper and lower envelope

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G291.27	-29.71	-2.66	1	0.67	-1.12	14
- 0.71	-30.45	-3.70	3	0.35	-2.73	23

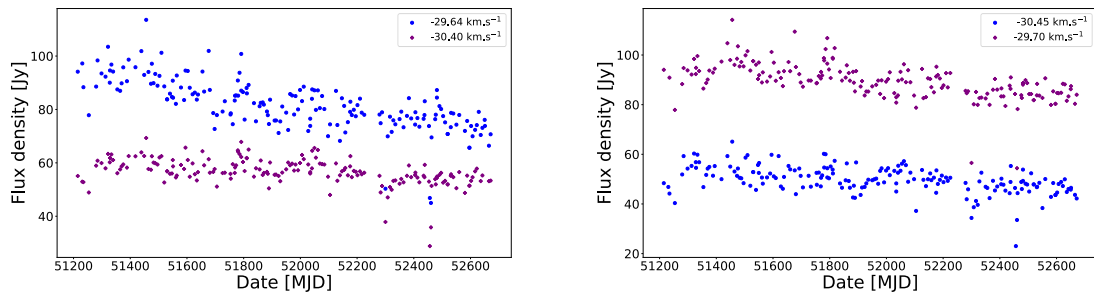
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

The features of maser feature G291.27 - 0.71 are not significantly; the feature at -29.64 km.s⁻¹, -29.68 km.s⁻¹, and the Gaussian fitted flux change centering around -29.70 km.s⁻¹ appear to display a gradual monotonic decrease in flux density. The Gaussian evaluated feature around -29.71 displays a velocity drift while the feature around -30.45 does not display any significant drift when evaluated exclusively with the Gaussian method. The linear regression method successfully determined drifts in both features however as a result of these features being broad and blended it was not possible to determine these values with sufficiently high confidence levels. Higher cadence, longer term observations of this source may yield more conclusive results and velocity drifts.



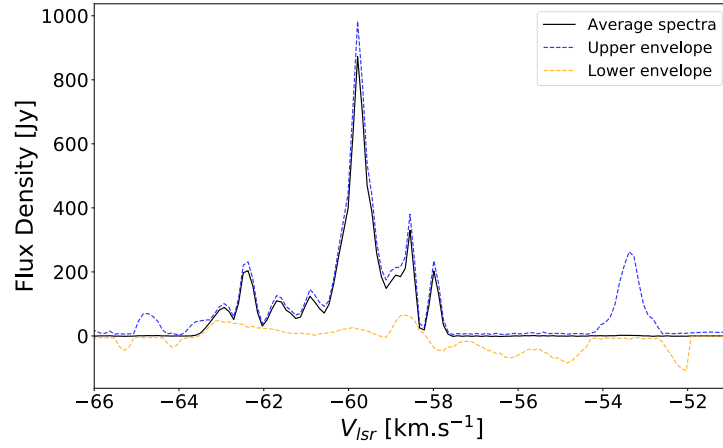
G291.27 - 0.71 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.



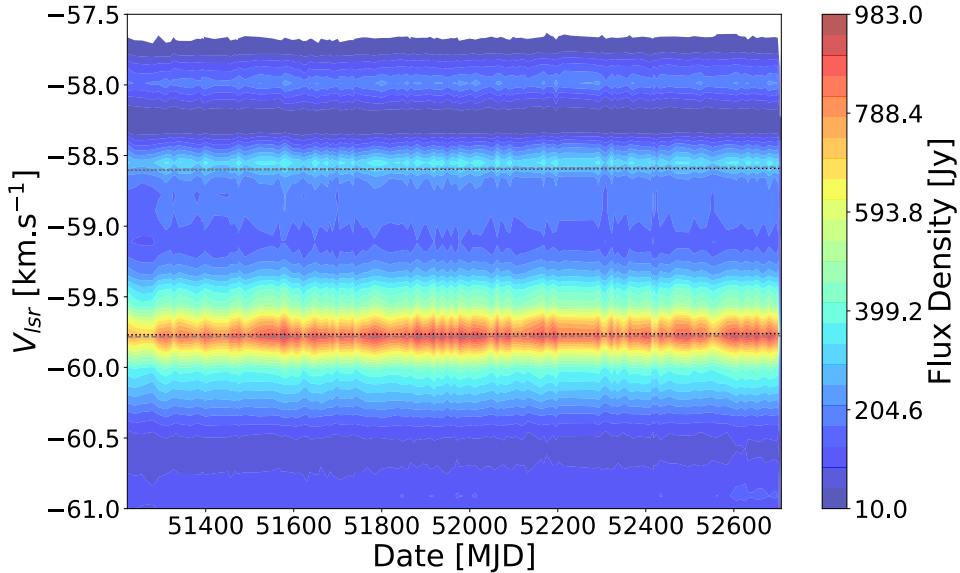
G291.27 - 0.71 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

A.1.10 G309.92 + 0.48

The maser source associated with G309.92 + 0.48 is incident on a luminous UC HII region; the maser components have a arc like structure with a clear velocity graient ([Phillips et al., 1998](#); [Liu et al., 2019](#)). The peak in radio continuum radiation likely traces a highly-embedded protostar ([Liu et al., 2019](#)). [Phillips et al. \(1998\)](#) claimed that the position of the maser components is better explained by a shock front rather than a circumstellar disc however this hypothesis failed to explain the velocity gradient observed.

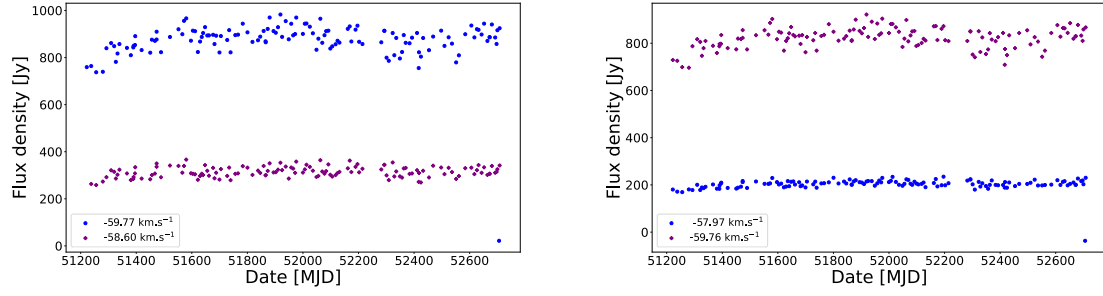


G309.92 + 0.48 averaged spectrum with upper and lower envelope



G309.92 + 0.48 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Sufficient evidence supporting the presence of velocity drifts was not found. Goodness of fit for Gaussian approximation yielded confidence levels of less than 50% and drifts did not cross over multiple velocity channels.



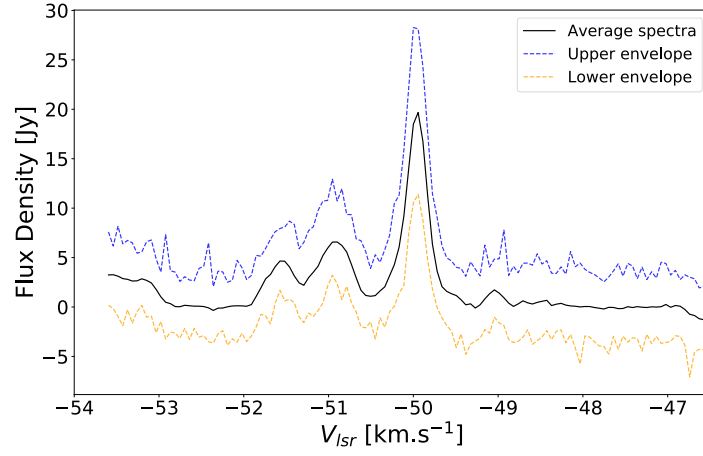
G309.92 + 0.48 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)
G309.92	-59.76	0.46	0	0.47	0.56	16
+ 0.48	-58.60	1.19	1	0.28	0.75	25

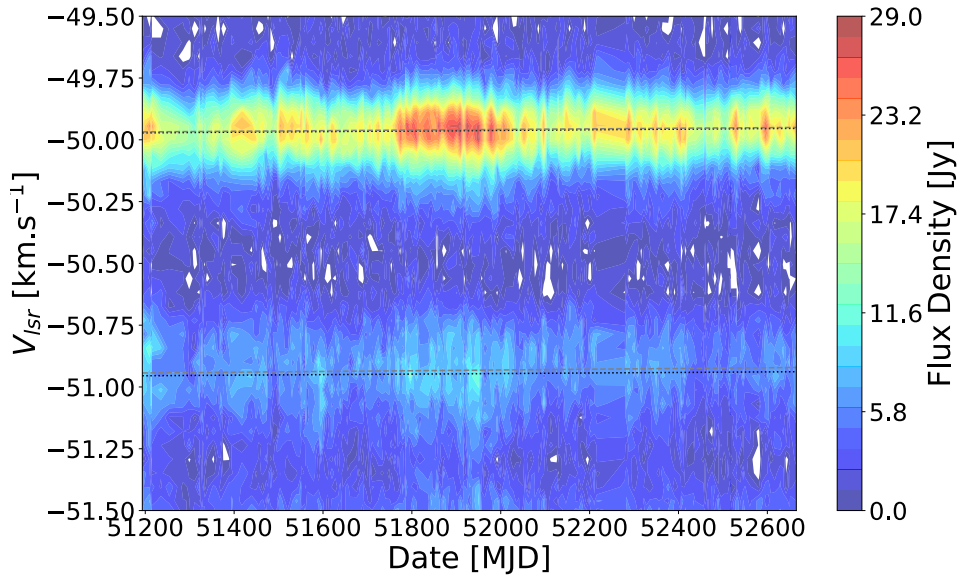
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.11 G312.11 + 0.26

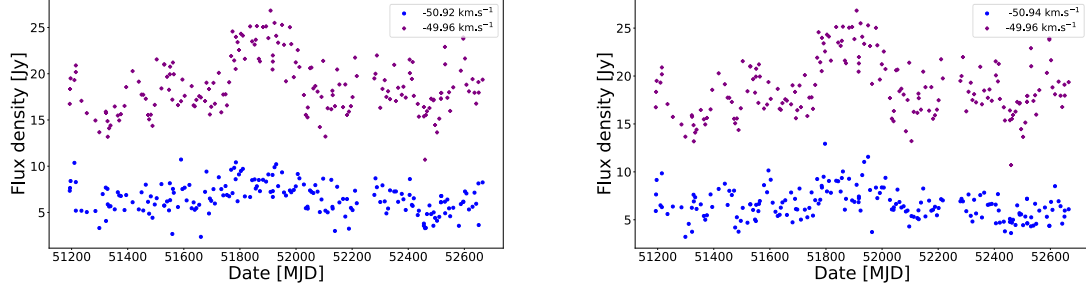


G312.11 + 0.26 averaged spectrum with upper and lower envelope

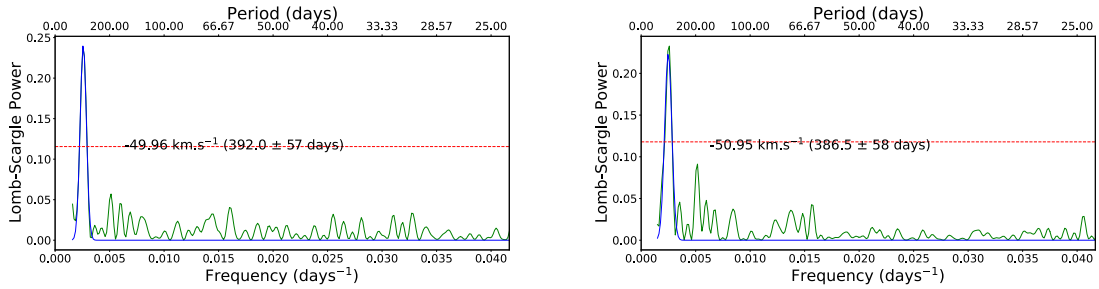


G312.11 + 0.26 Dynamic spectra with determined velocity drifts of two features marked on the figure. The black line in the Gaussian determined drift and the white line is the regression measured drift.

Periodicity has been detected by means of the Lomb-Scargle however since the source spectrum is noisy and the estimated error on the periodicity is reasonably large it is difficult to say with confidence that the observed periodicity is accurate; while observation errors are highly unlikely to result in periodicity longer term observations would be necessary to fully characterise the nature of the source. Long term observations alongside infra-red observations of the surrounding region will aid in characterising the source fully as well as determining the likely cause of observed quasi-periodic behaviour. Furthermore, while the fit of the velocity drift appears to be a good fit on the dynamic spectra, the goodness of fit values for the Gaussian evaluation are too low to confirm the drift with any level of confidence.



G312.11 + 0.26 light curves determined from Gaussian fitting and channel specific evaluation. The blue dots represent the manually, channel specific, determined light curve. The purple markers represent the Gaussian fit determined light curves.



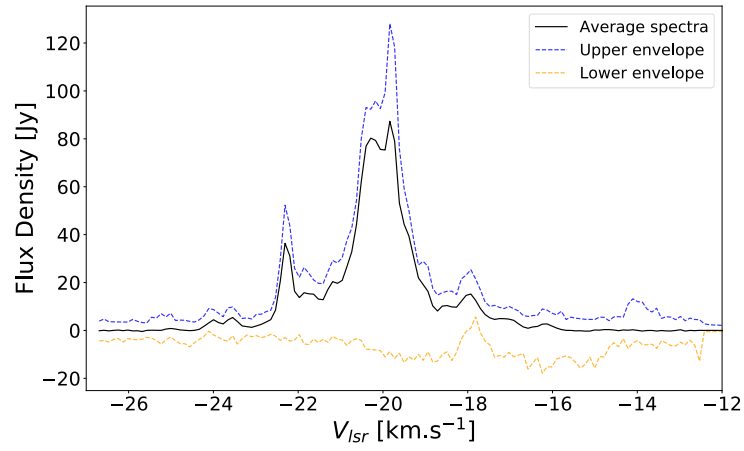
Lomb-Scargle Priodogram for G312.11 + 0.26 maser features coresponding to central velocities -49.96 km.s^{-1} and -50.95 km.s^{-1} .

Source	Linear regression fit ^a			Gaussian-fitted velocity ^b		
	v_{cen} (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_L^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R_G^2 (%)
G312.11	-49.96	1.23	1	0.47	1.24	18
+ 0.26	-50.94	1.51	0	0.31	1.05	3

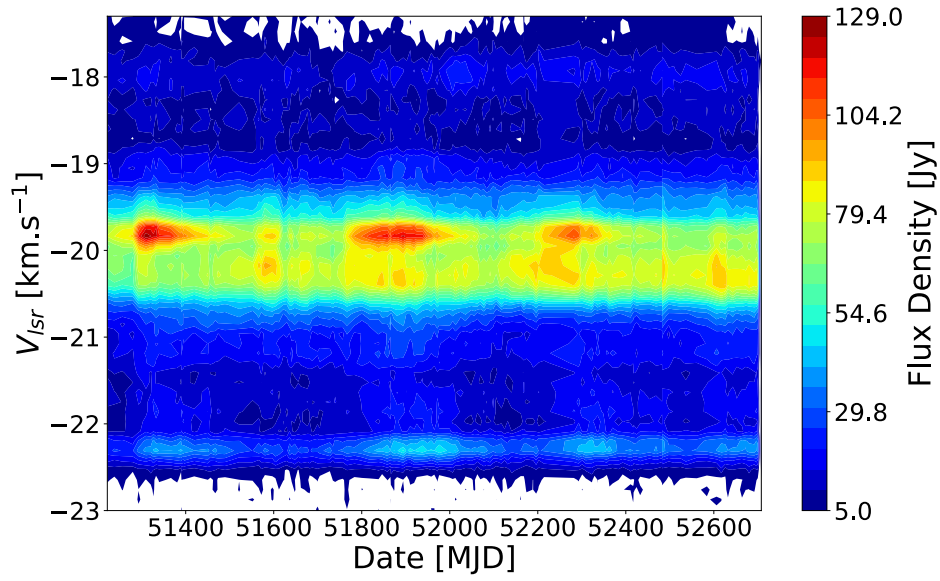
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.12 G316.64 - 0.09



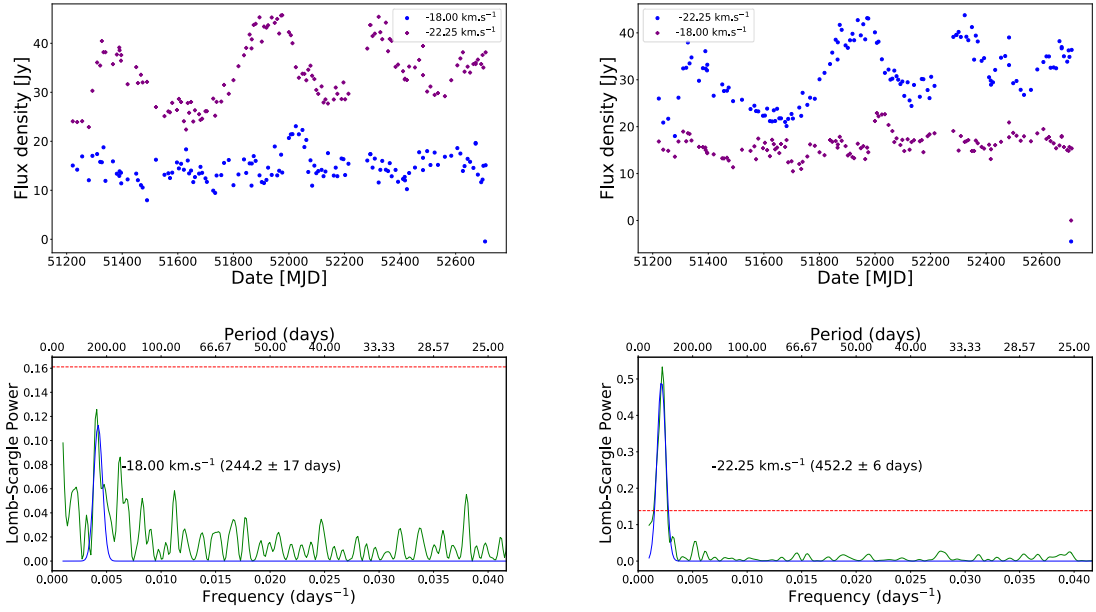
G316.64 - 0.09 averaged spectrum with upper and lower envelope



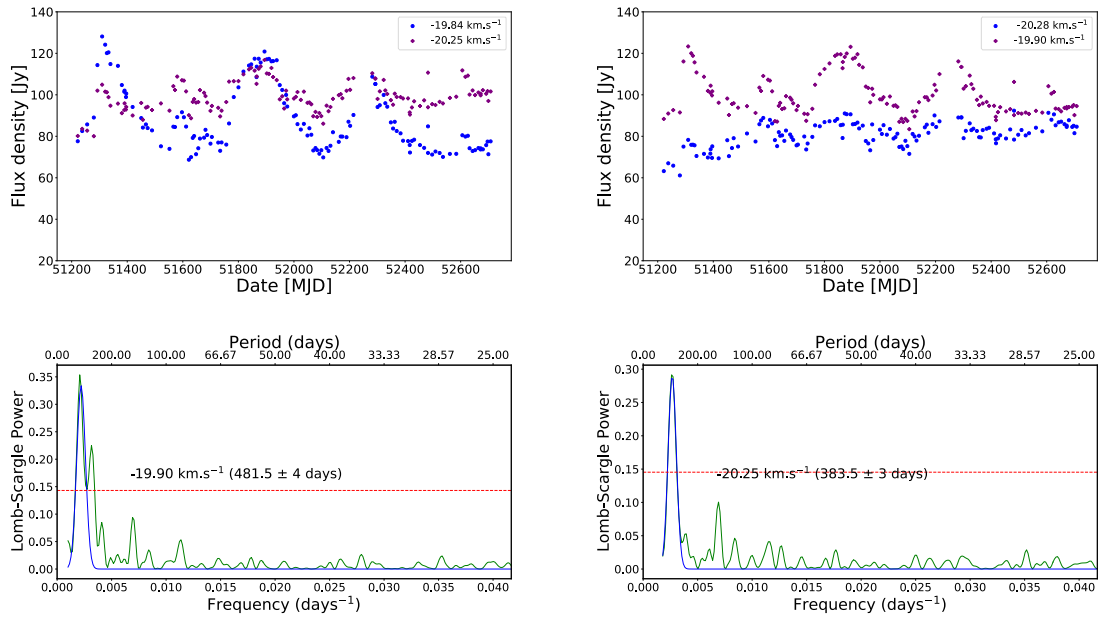
G316.64 - 0.09 Dynamic spectra

Velocity drifts were difficult to accurately determine due to blending of maser features and limited velocity resolution.

Periodicity found, no significant velocity drifts found. Blending made determining velocity drifts difficult to determine. Higher resolution observations needed.

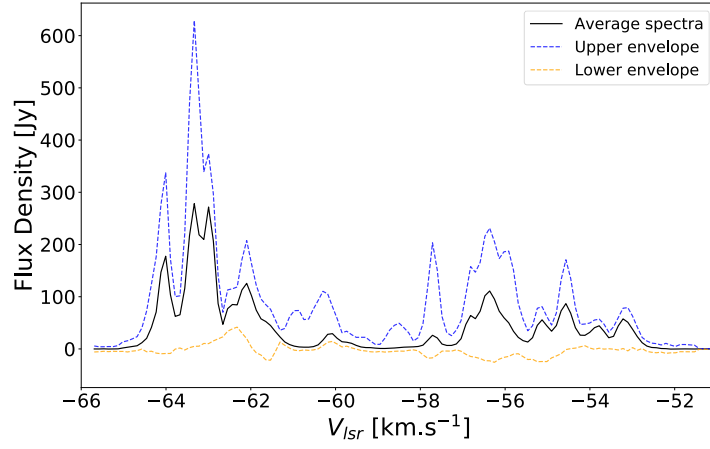


G316.64 - 0.09 light curves determined from Gaussian fitting and associated Lomb-Scargle periodograms

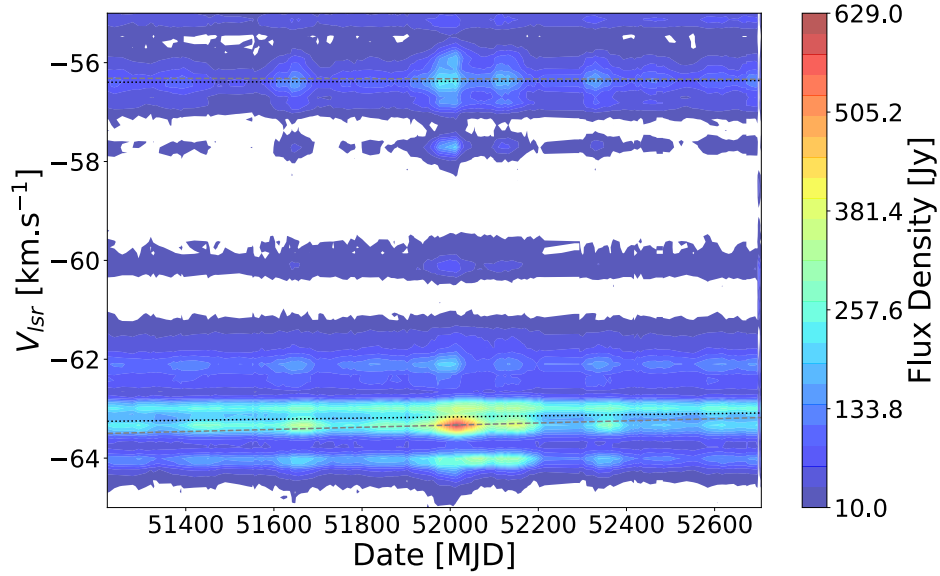


G316.64 - 0.09 light curves determined from Gaussian fitting and associated Lomb-Scargle periodograms

A.1.13 G322.16 + 0.64

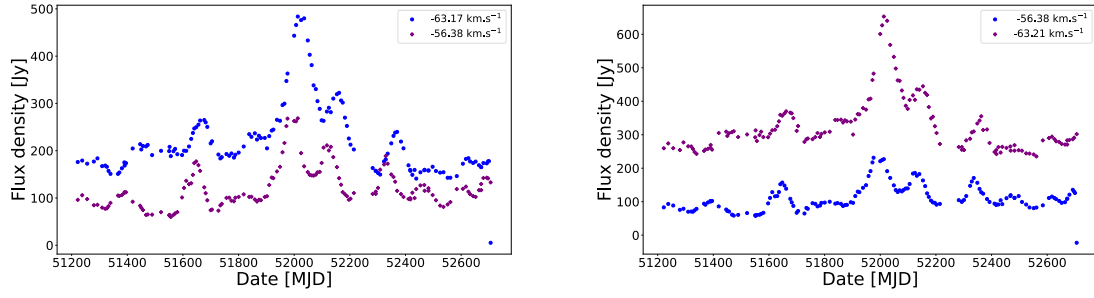


G322.16 + 0.64 averaged spectrum with upper and lower envelope



G322.16 + 0.64 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Maser source G322.16 + 0.64 is highly variable, multiple flares can be observed in the light curves. There does appear to be a small time delay between flaring events of the two investigated features however there is a very strong correlation in the behaviour of the light curves.



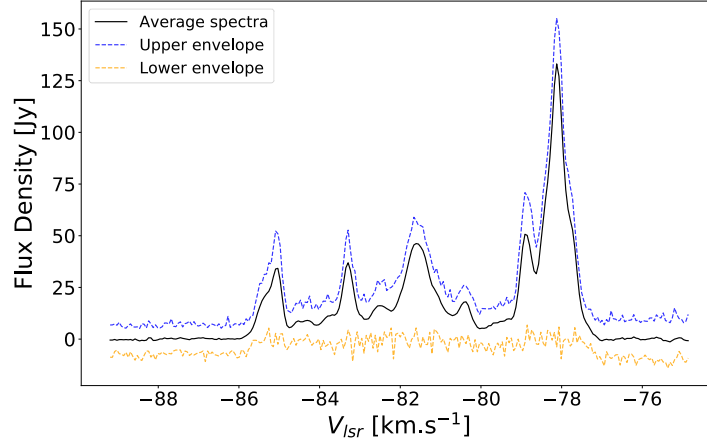
G322.16 + 0.64 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)		FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)
G322.16	-63.17	21.7	1		0.35	11.3	31
+ 0.64	-56.38	-1.37	0		0.52	2.34	33

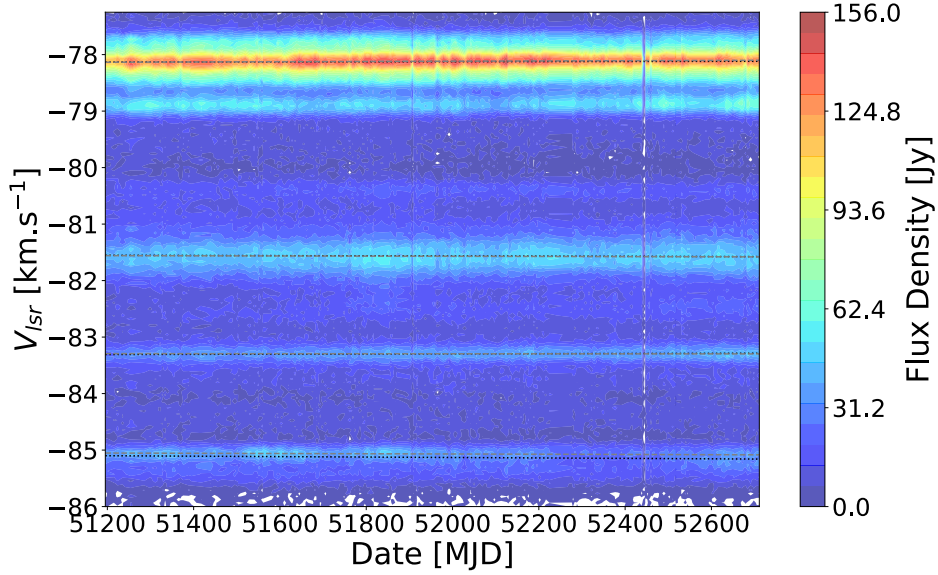
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.14 G331.278 - 0.188

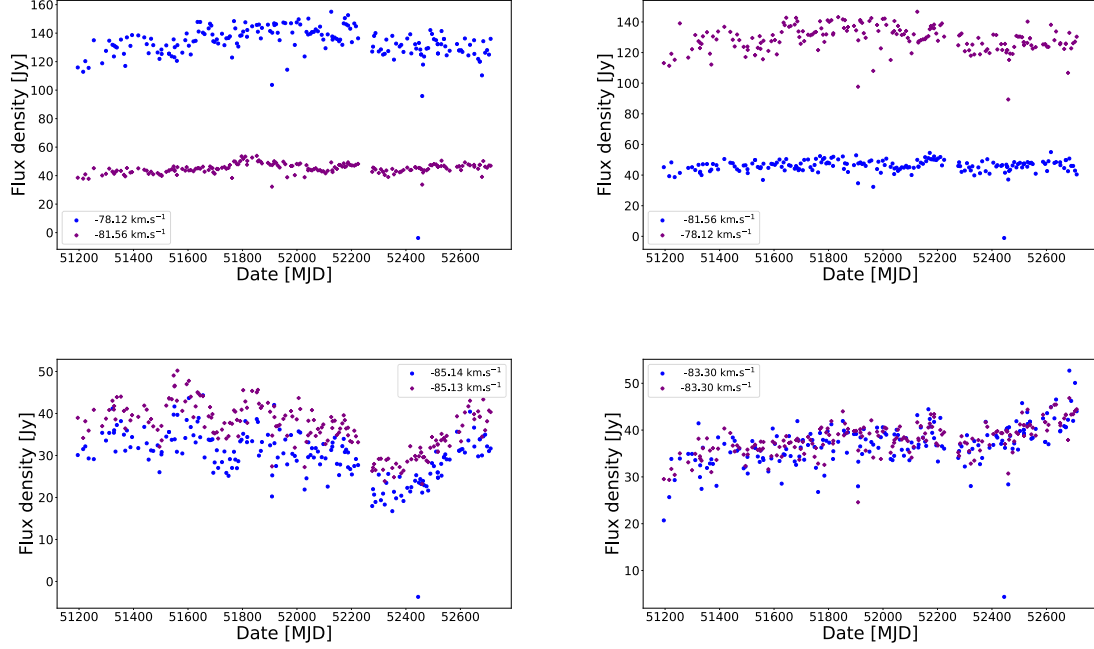


G331.278 - 0.188 averaged spectrum with upper and lower envelope



G331.278 - 0.188 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

None of the maser features display significant variability; Lomb-Scargle evaluation also did not find any periodicity measured above the false detection peak. Velocity drifts were determined however Gaussian evaluation did not find any of the drifts to have R^2 values exceeding 50%, therefore none of the drifts can be thought of as real findings before further monitoring with improved resolution are completed.



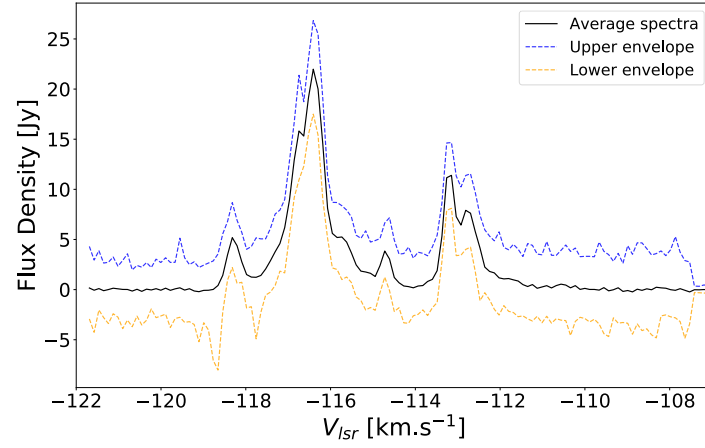
G331.278 - 0.188 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	v_{cen} (km s^{-1})	Linear regression fit ^a		Gaussian-fitted velocity ^b		
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_L^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R_G^2 (%)
G331.278	-78.12	2.27	2	0.55	0.89	26
- 0.188	-81.56	-1.44	0	0.94	-1.54	8
	-85.14	-2.08	2	0.38	-3.90	46
	-83.30	-0.36	0	0.35	1.45	27

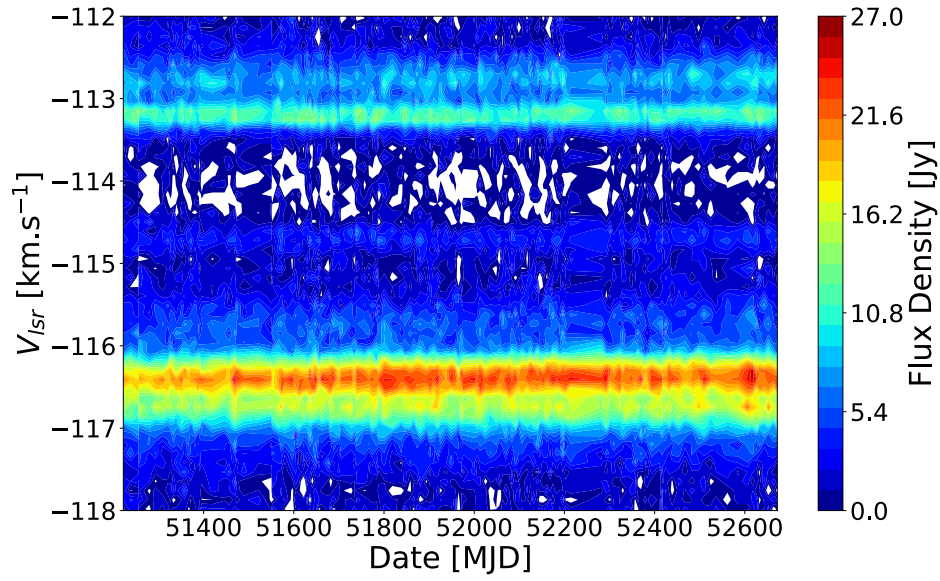
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.15 G335.55 - 0.31



G335.55 - 0.31 Average spectra



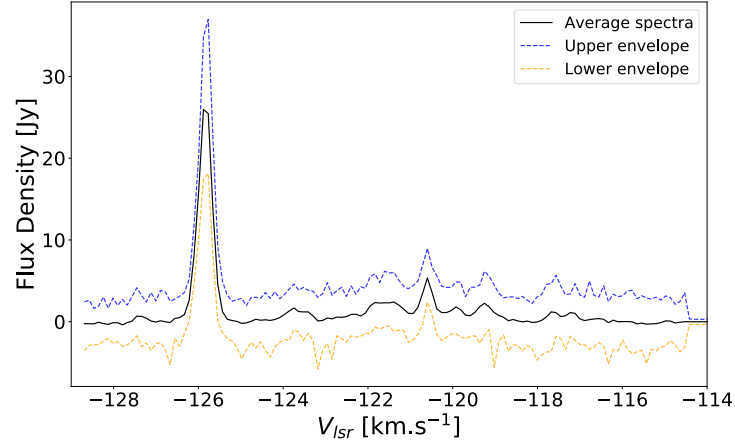
G335.55 - 0.31 Dynamic spectra

Source	v_{cen} (km s^{-1})	Linear regression fit ^a			Gaussian-fitted velocity ^b	
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)
G335.55	116.48	2.68	1	0.66	0.75	5
- 0.31	113.10	3.13	2	0.47	2.64	9

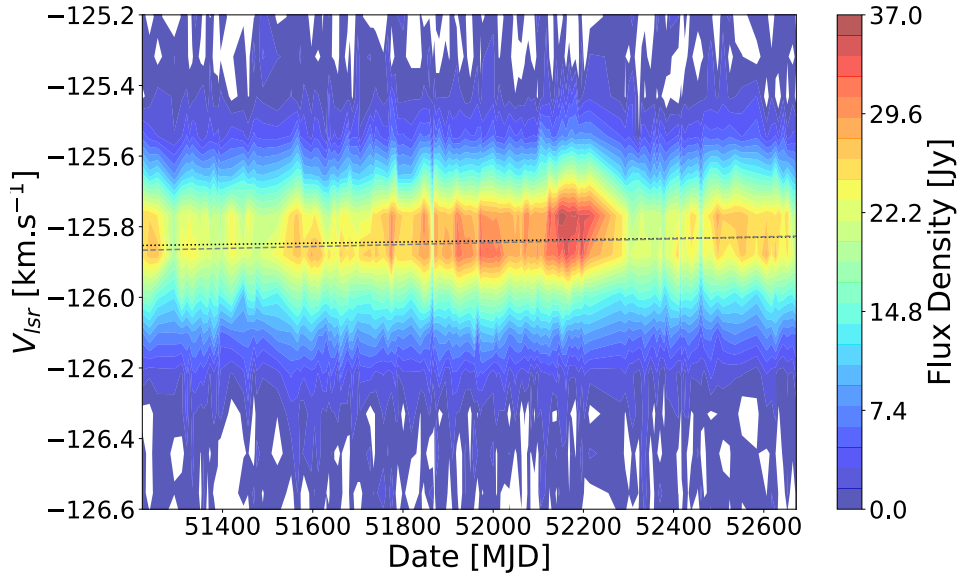
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.16 G336.99 - 0.03



G336.99 - 0.03 Average spectra



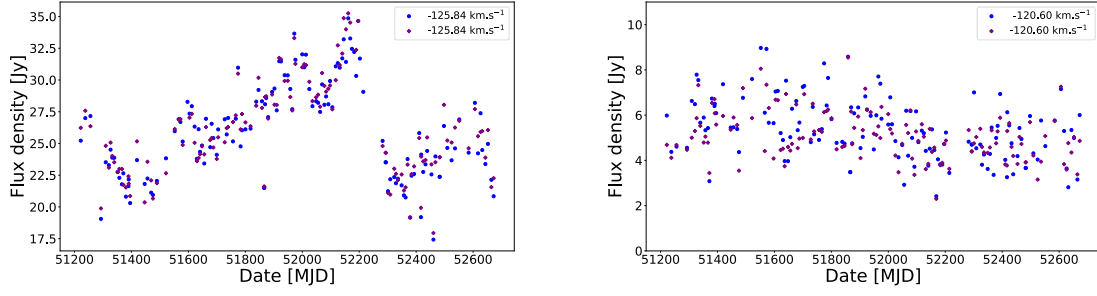
G336.99 - 0.03 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a		Gaussian-fitted velocity ^b		
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)
G336.99	125.84	2.75	1	0.38	1.69	31
- 0.03	120.60	-1.37	0	0.38	2.73	9

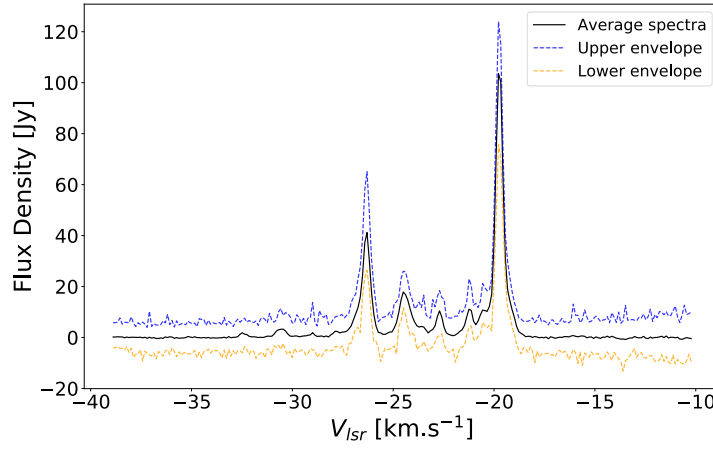
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

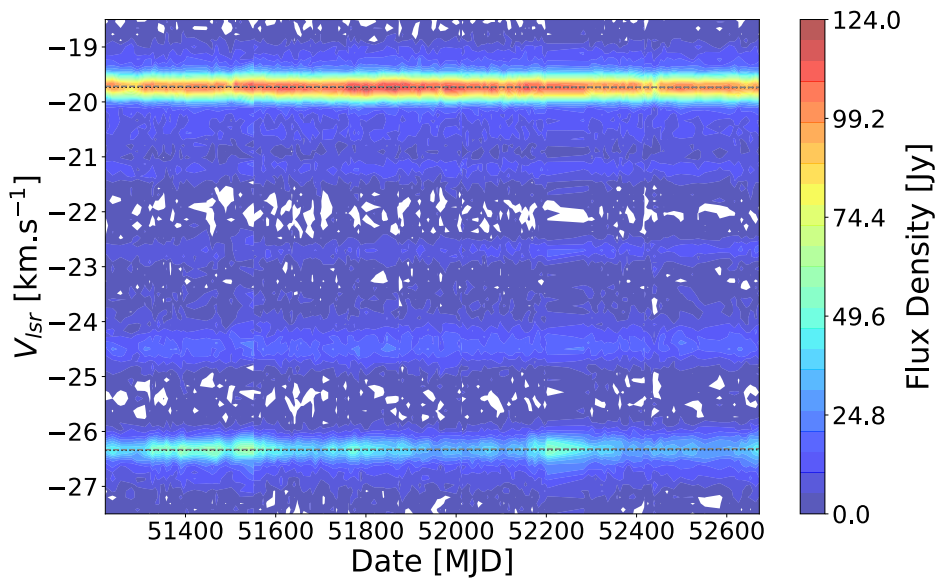
A.1.17 G344.23 - 0.57



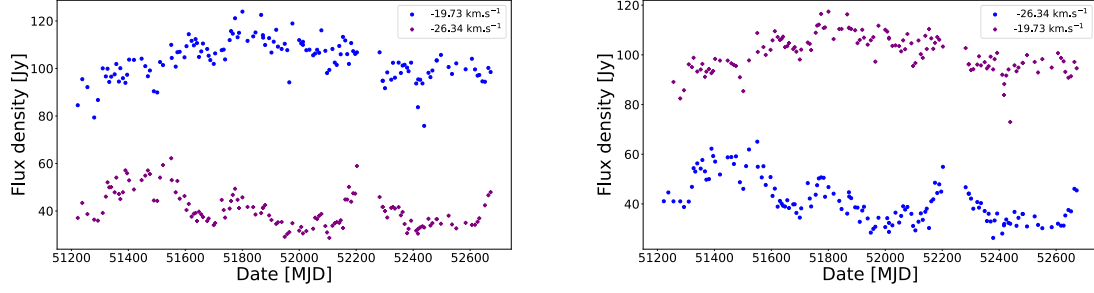
G336.99 - 0.03 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



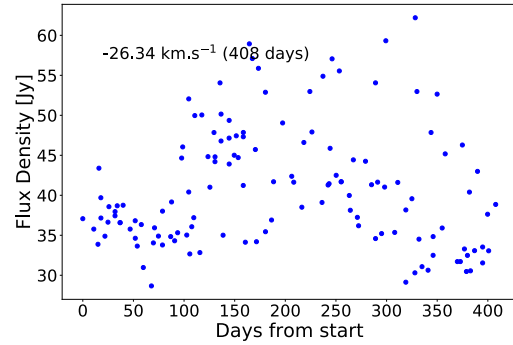
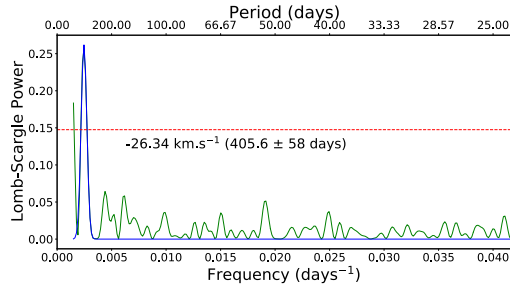
G344.23 - 0.57 averaged spectra with upper and lower envelope



G344.23 - 0.57 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.



G344.23 - 0.57 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.



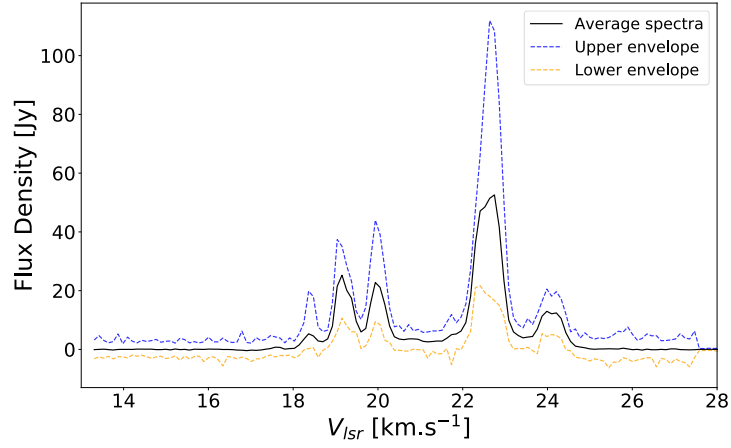
G344.23 - 0.57 Lomb-Scargle and folded light curve corresponding to feature at $v_{\text{cen}} \sim -26.34$ km.s⁻¹.

Source	v_{cen} (km s ⁻¹)	Linear regression fit ^a			Gaussian-fitted velocity ^b		
		Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	FWHM (km s ⁻¹)	Drift (10 ⁻⁵ km s ⁻¹ d ⁻¹)	R^2 (%)	
G344.23	-19.73	-1.34	1	0.46	-0.57	8	
- 0.57	-26.34	1.26	0	0.47	0.83	10	

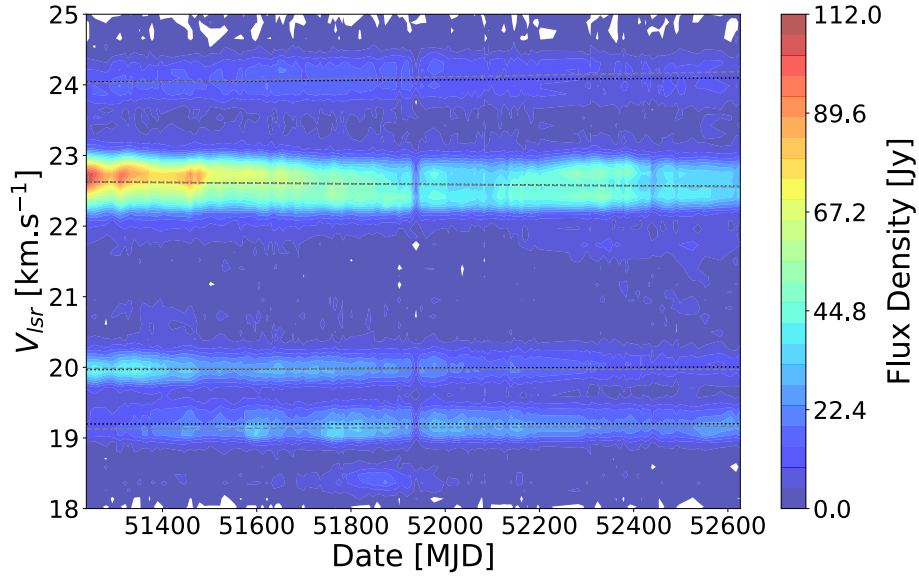
^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.

A.1.18 G359.61 - 0.24

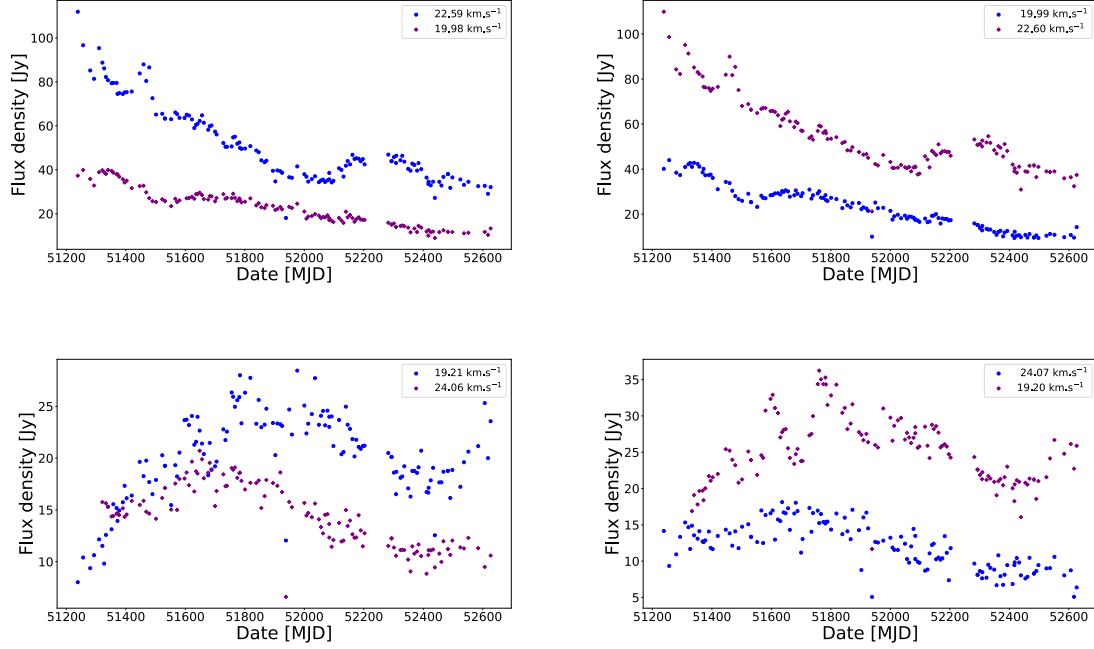


G359.61 - 0.24 averaged spectrum with upper and lower envelope



G359.61 - 0.24 Dynamic spectra with velocity drifts indicated on the figure. The drifts obtained through Gaussian evaluation are indicated with a dotted black line; and, velocity drifts determined through linear regression fits to the data are indicated with grey dashed lines.

This source is highly variable with different behaviour observed in different features. Features associated with central velocities 22.60 km.s^{-1} and 19.98 km.s^{-1} appears to display an almost linear decrease in flux density. Features associated with central velocities 19.21 km.s^{-1} and 24.06 km.s^{-1} appear to display a general trend of a slow increase in flux density and a slow decline in flux density, with some shorter term variability superimposed on the light curve; the feature associated with 19.21 km.s^{-1} displays some sporadic flaring. Search for velocity drifting has not yielded very conclusive results; the strongest maser feature appears to be broadened and goodness-of-fit values for the Gaussian evaluation all yielded less than 50% goodness of fit.



G359.61 - 0.24 light curves determined from Gaussian fitting and by a channelised approach. The blue markers represent the data obtained via the channelised approach; the purple markers represent the flux density measurements obtained from the Gaussian approach.

Source	v_{cen} (km s^{-1})	Linear regression fit ^a		Gaussian-fitted velocity ^b			
		Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)	FWHM (km s^{-1})	Drift ($10^{-5} \text{ km s}^{-1} \text{ d}^{-1}$)	R^2 (%)	
G359.61	22.59	-5.07	1	0.70	-4.58	26	
- 0.24	19.99	-1.10	0	0.47	2.75	41	
	19.21	2.89	1	0.51	0.32	1	
	24.07	11.6	5	0.59	4.11	29	

^a Linear regression fitting to associated velocities of determined flux densities.

^b Linear regression fitting to associated velocities determined by Gaussian-fitting individual spectra.