

MORPHOLOGY AND TIME EVOLUTION OF THERMAL JETS
ASSOCIATED WITH LOW-MASS YOUNG STARS

RACHAEL EVELYN AINSWORTH

B. S., University of Tennessee, 2010

A dissertation submitted to the University of Dublin
for the degree of
DOCTOR OF PHILOSOPHY



School of Physics
Trinity College
University of Dublin

SUPERVISED BY:

Prof. Tom Ray, *Dublin Institute for Advanced Studies, Dublin, Ireland*

Dr. Anna Scaife, *University of Manchester, Manchester, UK*

2016

(Submitted in original form August 2014)

Rachael Ainsworth: *Morphology and Time Evolution of Thermal Jets Associated with Low-mass
Young Stars,*

© 2016

DECLARATION

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

I agree to deposit this thesis in the University's open access institutional repository or allow the Library to do so on my behalf, subject to Irish Copyright Legislation and Trinity College Library conditions of use and acknowledgement.

Rachael Ainsworth
Dublin, Ireland
2016

SUMMARY

Jets are one of the most ubiquitous processes in the Universe, observed from astrophysical objects spanning an extreme range of masses. Despite the difference in scale, the similar morphologies and other characteristics between astrophysical jets suggest that the launching mechanism may be universal, although this suggestion is still controversial. It is widely accepted that many astrophysical jets, including those from young stars, are driven by accretion and launched through magnetohydrodynamic (MHD) processes, in particular, the centrifugal acceleration of material along magnetic field lines anchored to a rotating disk. However, many open questions remain: Where is the precise origin of jet launch? What is the role of the magnetic field? How does the jet evolve with time? These questions are best answered within the domain of low-mass star formation, as the large numbers of (relatively) nearby young stellar objects (YSOs) uniquely allows the region of jet launch to be studied. The latest generation of radio interferometers are the prime instruments to examine this region as they possess high angular resolution, improved sensitivity and can penetrate the encompassing circumstellar material.

The aim of this thesis is to investigate the jets driven by young stars over a wide range of radio frequencies and angular resolutions to study the role of their outflows on all scales and how they evolve with time. Data at well-sampled frequencies are crucial to precisely model and differentiate between competing emission mechanisms. Firstly, I investigate a sample of Class 0-I YSOs at 16 GHz with low spatial resolution with the Arcminute Microkelvin Imager (AMI) to explore these protostellar systems on large scales where the outflow has interacted with the surrounding envelope and/or molecular cloud. I subtract the contribution of the circumstellar material from the radio luminosity through modelling of the spectral energy distributions and show that free-free emission produced by the jet is the dominant mechanism responsible for the radio emission in this sample. I next extend this investigation to sub-arcsecond scales at 5 GHz with the highest angular resolution observations to date of the Class II YSO, DG Tau, taken with the expanded Multi-Element Radio Linked Interferometer Network (e-MERLIN). With these data I measure the initial opening angle of the DG Tau jet, a vital constraint for the origin of MHD jet launch, and demonstrate that the jet is initially generated as a poorly collimated wind which then becomes collimated on scales of 50 au. I calculate the mass-loss rate in the ionised component of the DG Tau jet and find it compatible with MHD disk-wind theory. Finally, I explore a spatial scale intermediate to AMI and e-MERLIN with observations of Class I-II YSOs taken with the Giant Metrewave Radio Telescope (GMRT) at 325 and 610 MHz, which are

the first investigations of young, low-mass stars at such low frequencies. The most significant result from this investigation is the detection of a prominent bow shock associated with the DG Tau outflow which exhibits a synchrotron spectrum. This result provides tentative evidence for the acceleration of particles to relativistic energies due to the shock impact of this otherwise very low-power jet against the ambient medium which suggests the possibility of low energy cosmic rays being generated by young Sun-like stars.

For my family.

Do I dare
Disturb the universe?

— T. S. Eliot —

ACKNOWLEDGEMENTS

First and foremost I would like to thank my supervisor, Tom Ray, for providing the opportunity for me to move to Ireland and study such an interesting topic. I appreciate all of the guidance, support and for being able to knock on your door whenever I had questions. I would like to acknowledge my other supervisor, Anna Scaife, who has been a constant source of inspiration and motivation. Thank you for all of the encouragement and for continuing to mentor me beyond your time at DIAS.

A special thanks to Dave Green for flying all the way to India with me, for teaching me all things GMRT, for being so accessible and for proof reading the thesis. Thanks to Rob Beswick for assistance with the e-MERLIN data reduction and to the rest of my collaborators, Andrew Taylor, Jane Buckle, Jane Greaves and the AMI Consortium, for all your contributions to this work. Thank you to Luke Drury, Antonella Natta, Malcolm Walmsley, Turlough Downes and Rene Breton for thorough discussions related to this thesis. I am also indebted to Donna Rodgers-Lee, Paul Dawson, Colm Coughlan, John Kenny, Lucy Rowell and Peter Clare for their constant supply of support during the past two years.

Thank you to my DIAS family, for making these years in Dublin so special. I am especially grateful for Gráinne, my partner in crime who has always been there, and Lisa for all the late nights and long chats. Thank you to Eileen for all the advice, Philippe for keeping AIPS running, and everyone in 31 Fitzwilliam for making it such an amazing place to work. Thanks to the lads for all the craic, especially Olaf, Andrew, Thomas, Martin, Carlo, Rob, Andrea, Florian, Joan and the rest of the Geos and Theos we've picked up along the way. Go raibh míle maith agaibh.

Most importantly, I would not be where I am today without the unconditional love and support from my family. To my parents, your enthusiasm and encouragement is appreciated more than you will ever know. To my siblings, it has been difficult to watch your achievements from afar, I am so proud of you all. To Grandma Ruth, thanks for hanging on. Finally, thank you to Daniel, my MVP, for your limitless patience and love.

I acknowledge support from Science Foundation Ireland under grant 11/RFP/AST3331 and the School of Physics, Trinity College Dublin.

PUBLICATIONS

1. **Ainsworth, R. E.**, Scaife, A. M. M., Ray, T. P., Taylor, A. M. Green, D. A., and Buckle, J. V., 2014, Tentative Evidence for Relativistic Electrons Generated by the Jet of the Young Sun-like Star DG Tau, *Astrophysical Journal Letters*, **792**, L18–L22.
doi:10.1088/2041 – 8205/792/1/L18
2. **Ainsworth, R. E.**, Ray, T. P., Scaife, A. M. M., Greaves, J. S., and Beswick, R. J., 2013, Subarcsecond high-sensitivity measurements of the DG Tau jet with e–MERLIN, *Monthly Notices of the Royal Astronomical Society Letters*, **436**, L64–L68.
doi:10.1093/mnrasl/slt114
3. **Ainsworth, R. E.**, Scaife, A. M. M., Ray, T. P., and AMI Consortium, 2012, AMI radio continuum observations of young stellar objects with known outflows, *Monthly Notices of the Royal Astronomical Society*, **423**, 1089 – 1108.
doi:10.1111/j.1365 – 2966.2012.20935.x
4. Scaife, A. M. M., Buckle, J. V., **Ainsworth, R. E.**, and AMI Consortium, 2012, Radio continuum observations of Class I protostellar discs in Taurus: constraining the grey-body tail at centimetre wavelengths, *Monthly Notices of the Royal Astronomical Society*, **420**, 3334 – 3343.
doi:10.1111/j.1365 – 2966.2011.20254.x
5. Scaife, A. M. M., Hatchell, J., **Ainsworth, R. E.**, and AMI Consortium, 2012, AMI-LA radio continuum observations of Spitzer c2d small clouds and cores: Serpens region, *Monthly Notices of the Royal Astronomical Society*, **420**, 1019 – 1033.
doi:10.1111/j.1365 – 2966.2011.19957.x

CONTENTS

Declaration.....	iii
Summary.....	v
Dedication.....	vii
Acknowledgements	xi
Publications	xiii
Table of Contents	xvii
List of Figures.....	xx
List of Tables.....	xxi
i INTRODUCTION	1
1 MOTIVATION AND THESIS OUTLINE	3
1.1 Motivation	3
1.2 Thesis Outline	4
2 THEORY: LOW-MASS STAR FORMATION	5
2.1 Protostellar Evolution: From Cloud to Sun-like Star	5
2.1.1 Class 0	7
2.1.2 Class I	8
2.1.3 Class II	9
2.1.4 Class III	9
2.1.5 ZAMS.....	10
2.2 Protostellar Jets and Outflows	10
2.2.1 Morphology	11
2.2.2 Jet Physics	11
2.2.3 Molecular Outflows	14
2.2.4 The Jet–Disk (Ejection–Accretion) Connection	15
2.3 Current Jet-launching Theory	16
2.3.1 D-winds vs X-winds	18
2.3.2 Stellar Winds	19
2.4 Radio Emission from Protostellar Systems	19
2.4.1 Thermal Bremsstrahlung	19
2.4.2 Thermal Dust Emission	20
2.4.3 Non-thermal Emission	21
2.4.4 The Need for Multi-scale, Multi-frequency Observations	22

3	INSTRUMENTATION: PRINCIPLES OF RADIO ASTRONOMY	23
3.1	Some Basic Definitions	24
3.2	Radiative Transfer	25
3.2.1	Thermal Bremsstrahlung	27
3.3	Aperture Synthesis	30
3.3.1	The Two-Element Interferometer	30
3.3.2	The u, v -plane	33
3.3.3	Sensitivity	35
3.4	Specific Telescopes	35
3.4.1	AMI	35
3.4.2	e-MERLIN	36
3.4.3	GMRT	37
ii	MULTI-FREQUENCY, MULTI-SCALE INVESTIGATIONS OF LOW-MASS PROTOSTEL- LAR SYSTEMS	39
4	LARGE-SCALE STUDIES OF YSOS AT 16 GHz WITH AMI.....	41
4.1	The Sample	42
4.2	Observations and Data Reduction.....	46
4.3	Results.....	47
4.4	Notes on Individual Fields	49
4.5	Discussion.....	56
4.5.1	Detections and Non-detections.....	56
4.5.2	Expected Contamination by Extragalactic Radio Sources	57
4.5.3	Spectral Energy Distributions.....	58
4.5.4	Dust Temperatures	63
4.5.5	Radio Spectral Indices.....	65
4.5.6	Correlations.....	67
4.5.7	Variability	74
4.6	Summary	75
5	SUB-ARCSECOND STUDIES OF YSOS AT 5 GHz WITH E-MERLIN.....	77
5.1	Observations and Data Reduction.....	78
5.2	Results.....	79
5.3	Discussion.....	79
5.3.1	DG Tau	79
5.3.2	DG Tau B	83
5.3.3	Jet Opening Angle.....	83
5.3.4	Mass-loss Rates	85
5.4	Summary	87

6	INTERMEDIATE-SCALE STUDIES OF YSOS AT 325 AND 610 MHz WITH THE GMRT	89
6.1	Observations and Data Reduction.....	90
6.2	Results.....	92
6.3	Discussion.....	97
6.3.1	L1551.....	97
6.3.2	T Tau.....	98
6.3.3	DG Tau.....	99
6.3.4	Spectral Energy Distributions.....	100
6.3.5	The DG Tau Bow Shock.....	102
6.4	Summary	109
7	CONCLUSIONS AND FUTURE PROSPECTS	111
7.1	Conclusions.....	111
7.2	Future Prospects	115
iii	APPENDICES	117
A	AMI COMBINED CHANNEL MAPS.....	119
B	AMI SAMPLE SPECTRAL ENERGY DISTRIBUTIONS.....	125
C	AMI SAMPLE SPECTRAL ENERGY DISTRIBUTION REFERENCE TABLE	133
D	GMRT DATA REDUCTION PIPELINE.....	147
E	GMRT FIELD MAPS.....	153
F	GMRT SAMPLE SPECTRAL ENERGY DISTRIBUTION REFERENCE TABLE.....	161
iv	REFERENCES	167
	References.....	169

LIST OF FIGURES

Figure 2.1	Stages of low-mass star formation	6
Figure 2.2	SEDs of Class 0–III YSOs	7
Figure 2.3	Pillar and jets HH 901/902 in the Carina Nebula	12
Figure 2.4	Astrophysical jets	13
Figure 2.5	Jet collimation	17
Figure 2.6	MHD jet-launching models	18
Figure 2.7	Radio jet	20
Figure 3.1	The radio window	24
Figure 3.2	The definition of flux density	25
Figure 3.3	Radiative transfer	26
Figure 3.4	Free–free spectrum	29
Figure 3.5	The two-element interferometer	31
Figure 3.6	Radio coordinate system	34
Figure 3.7	AMI	36
Figure 3.8	e–MERLIN	37
Figure 3.9	GMRT	38
Figure 4.1	AMI: L1448 at 16 GHz	50
Figure 4.2	AMI: L1448 IRS 3 SED	51
Figure 4.3	AMI: L1551 NE SED comparison	64
Figure 4.4	AMI: correlation of radio luminosity with bolometric luminosity	69
Figure 4.5	AMI: correlation of radio luminosity with envelope mass	71
Figure 4.6	AMI: correlation of radio luminosity with outflow force	73
Figure 5.1	e–MERLIN: DG Tau at 5 GHz	80
Figure 5.2	e–MERLIN: DG Tau B at 5 GHz	81
Figure 5.3	e–MERLIN: DG Tau jet opening angle	84
Figure 6.1	GMRT: central facet of the L1551 field at 610 MHz	93
Figure 6.2	GMRT: L1551 IRS 5 at 325 and 610 MHz	94
Figure 6.3	GMRT: T Tau at 325 and 610 MHz	95
Figure 6.4	GMRT: DG Tau at 325 and 610 MHz	96
Figure 6.5	GMRT: SEDs for L1551 IRS 5 and T Tau	101

Figure 6.6	GMRT: SED for DG Tau	102
Figure 6.7	GMRT: DG Tau bow shock	103
Figure 6.8	GMRT: Spectrum for DG Tau bow shock	106
Figure A.1	AMI: HH 7 – 11 and L1551 IRS 5 at 16 GHz	120
Figure A.2	AMI: L1527 and HH 1 – 2 at 16 GHz	121
Figure A.3	AMI: HH 26 IR and HH 111 at 16 GHz	122
Figure A.4	AMI: NGC 2264 G and Serpens SMM 1 at 16 GHz	123
Figure A.5	AMI: L723 and L1251 A at 16 GHz	124
Figure B.1	AMI: SEDs for HH 7 – 11 and L1551 IRS 5	126
Figure B.2	AMI: SEDs for L1527 and HH 1 – 2	127
Figure B.3	AMI: SEDs for HH 26 IR and HH 111	128
Figure B.4	AMI: SEDs for NGC 2264 G and Serpens SMM 1	129
Figure B.5	AMI: SEDs for L723 and L1251 A	130
Figure B.6	AMI: SEDs for L1448 C and NGC 1333 <i>IRAS</i> 2A	131
Figure B.7	AMI: SEDs for NGC 1333 <i>IRAS</i> 2B and HH 25 MMS	132
Figure E.1	GMRT: L1551 IRS 5 <i>FLATN</i> field at 325 MHz	154
Figure E.2	GMRT: L1551 IRS 5 <i>FLATN</i> field at 610 MHz	155
Figure E.3	GMRT: T Tau <i>FLATN</i> field at 325 MHz	156
Figure E.4	GMRT: T Tau <i>FLATN</i> field at 610 MHz	157
Figure E.5	GMRT: DG Tau <i>FLATN</i> field at 325 MHz	158
Figure E.6	GMRT: DG Tau <i>FLATN</i> field at 610 MHz	159

LIST OF TABLES

Table 4.1	AMI: observational details	43
Table 4.2	AMI: additional detected sources	44
Table 4.3	AMI: source information	45
Table 4.4	AMI: flux calibrators	46
Table 4.5	AMI: integrated flux densities	48
Table 4.6	AMI: summary of detection statistics	57
Table 4.7	AMI: model results for fixed T_d	60
Table 4.8	AMI: model results for variable T_d	61
Table 5.1	e-MERLIN: flux calibrators	78
Table 6.1	GMRT: observational details	91
Table 6.2	GMRT: SED results	100
Table 6.3	GMRT: DG Tau bow shock results	107
Table C.1	AMI: SED references	133
Table D.1	GMRT: data reduction pipeline	147
Table F.1	GMRT: SED references	161

Part I

INTRODUCTION

MOTIVATION AND THESIS OUTLINE

1.1 MOTIVATION

Astrophysical jets are powered by objects spanning an extreme range of masses, from young brown dwarfs ($< 0.08 M_{\odot}$) and protostars ($\sim 1 M_{\odot}$) to Galactic microquasars and active galactic nuclei (AGN, $\sim 10^8 M_{\odot}$). In spite of the enormous differences in scale, their similar morphologies and other characteristics suggest that the launching mechanism may be universal (e.g. [Livio, 2011](#)), although this suggestion is still controversial. It is widely accepted that many astrophysical jets, including those from young stellar objects (YSOs), are driven by accretion and launched through magnetohydrodynamic (MHD) processes, in particular, the centrifugal acceleration of material along magnetic field lines anchored to a rotating disk (e.g. [Blandford & Payne, 1982](#); [Pudritz & Norman, 1983](#)). In the case of YSOs, the rotation of a circumstellar disk, and therefore of the magnetic field lines, creates a helical configuration that is believed to collimate the jet via “hoop stresses” occurring tens of au from the protostar. The role of the magnetic field on larger scales, however, is not well understood ([Ray, 2009](#)) and direct observational support for its existence is still lacking. In addition, open questions regarding the precise origin of jet launch and how the jet evolves with time remain.

Jets from AGN have been mapped extensively in the radio. The intensity of their emitted synchrotron radiation can be used to estimate the strength of the magnetic field whilst the polarisation can be used to measure the direction of the magnetic field once the degree of Faraday rotation is known. However, relatively little is known about the other basic physical characteristics of AGN jets. In contrast, the fundamental parameters such as density, temperature, velocity, mass-loss rate and ionisation fraction are known for jets from YSOs; the only element missing to obtain a complete physical demography of low-mass YSO jets is the strength of their magnetic fields ([Ray, 2010](#)).

Synchrotron radiation has been detected in the jet of a massive YSO using linear polarisation measurements at radio wavelengths, allowing for the direct measurement of the strength and direction of the magnetic fields within the young system (HH 80 – 81,

Carrasco-González et al., 2010a). This is a remarkable result as the presence of relativistic particles was previously thought to be unlikely in jets from young stars where the velocities are only of the order of hundreds of kilometres per second, in comparison with jets from AGN where the jet velocities are close to the speed of light. Many features of the observed polarisation in HH 80 – 81 are similar to those seen in more highly energetic AGN jets, strengthening the argument that certain jet formation characteristics span huge mass and energy scales.

Due to their proximity (140 pc to the nearest star-forming regions), numbers (hundreds), and diversity of available tracers, jets from low-mass young stars make ideal laboratories for investigations of the physics, chemistry, acceleration, collimation, propagation and region of jet launch in these systems (e.g. Bally et al., 2007). The latest generation of radio interferometers are the prime instruments to make these investigations as they possess high angular resolution, improved sensitivity and can penetrate the encompassing circumstellar material. The results of these studies can potentially be applied to astrophysical jets on all scales.

1.2 THESIS OUTLINE

The aim of this thesis is to explore young stars over a wide range of radio frequencies and angular resolutions to study the role of their jets on all scales and how they evolve with time. Chapter 2 provides an introduction to the current understanding of how stars like the Sun form, the characteristics and role of the outflow in star formation, current jet-launching theory and the radio emission observed from these young systems. Chapter 3 introduces the principles of radio astronomy with some basic definitions, the modelling of radio emission with radiative transfer, a crash course in aperture synthesis and technical details on the specific instruments used for the work in this thesis. Chapter 4 presents my large-scale investigations of a sample of protostellar jets at 16 GHz using AMI, Chapter 5 extends these investigations to sub-arcsecond scales at 5 GHz with the e-MERLIN and Chapter 6 explores these systems on intermediate-scales in a new, very low frequency regime with the GMRT. In Chapter 7, I summarise the main results of this thesis and make some brief concluding remarks.

THEORY: LOW-MASS STAR FORMATION

Over sixty years ago, George Herbig and Guillermo Haro were believed to have discovered the nebulous cradles within which stars are formed (Herbig, 1950; Haro, 1952). It was not until some time later that these Herbig–Haro (HH) objects were identified as the optical manifestations of highly supersonic protostellar jets. Their spectra were indicative of mostly low-excitation radiative shock waves (e.g. Bally et al., 2007), and the objects powering these highly collimated outflows were sometimes found to be located light-years away from the HH object. Outflows are now known to be a fundamental aspect of star formation.

This chapter introduces the current understanding of low-mass star formation and the important role of the outflow. *Low-mass* refers to stars which will have final main-sequence masses of $0.2 - 2 M_{\odot}$, where $M_{\odot}$ is the mass of the Sun. Stars with masses in the range $2 - 8 M_{\odot}$ are *intermediate-mass* and stars with masses $> 8 M_{\odot}$ are *high-mass*. This chapter additionally presents the characteristics of the radio emission typically associated with these young systems.

2.1 PROTOSTELLAR EVOLUTION: FROM CLOUD TO SUN-LIKE STAR

The stage for star formation is set with the fragmentation of a molecular cloud into a number of gravitationally bound cores (see Figure 2.1). These cores are initially supported against gravity due to a combination of magnetic, thermal and turbulent pressures, but eventually succumb to the Jeans instability (i.e. when the core mass, M_{core} , is greater than the Jeans mass, M_{Jeans} , which scales with the temperature and density as $T^{3/2}\rho^{-1/2}$) and collapse isothermally (see Figure 2.1; e.g. Larson, 1969). The released gravitational energy is radiated away and the collapsing fragment produces a prestellar core, consisting of a strong central concentration of matter with a radial density gradient approaching $\rho \propto r^{-2}$. The prestellar core phase ends with the formation of an opaque, hydrostatic protostellar object and the young system enters the main accretion phase of evolution, building up its mass ($M_{\star}$) from a surrounding infalling envelope (of mass M_{env}) and accretion disk while progressively heating up (see Figure 2.1).

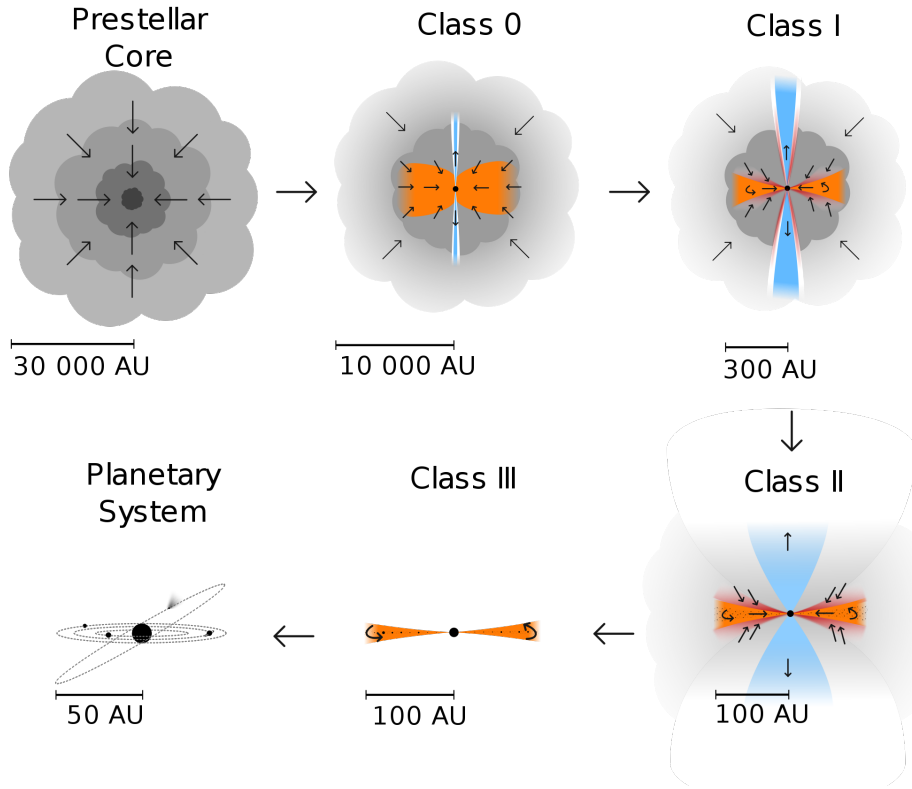


Figure 2.1.: Current view of protostellar evolution. Image credit: [Persson \(2014a\)](#).

The youngest protostars have $M_{\text{env}} \gg M_{\star}$ and the only source of energy in these systems is their accretion luminosity:

$$L_{\text{acc}} \approx \frac{GM_{\star}\dot{M}_{\text{acc}}}{R_{\star}}, \quad (2.1)$$

where G is the gravitational constant, $R_{\star}$ is the protostellar radius, and $\dot{M}_{\text{acc}}$ is the mass accretion rate. The protostar becomes a pre-Main Sequence (PMS) star once it has accumulated most ($\gtrsim 90\%$) of its final main-sequence mass, and continues to evolve approximately at fixed mass on the Kelvin–Helmholtz contraction timescale (see [Figure 2.1](#)). When most of the PMS star’s energy output is derived from hydrogen fusion, it evolves to a zero-age Main Sequence (ZAMS) star (see [Figure 2.1](#)). The internal pressure then exactly balances gravity, and the star begins a long-lived phase of overall equilibrium on the Main Sequence.

Historically, the classes of evolutionary sequence were designated by the slope of their spectral energy distributions (SEDs) at infrared (IR) wavelengths between $\lambda \sim 2.2 - 25 \mu\text{m}$. This slope is also referred to as the spectral index (α_{IR}) and is defined as

$$\alpha_{\text{IR}} = \frac{d \log(\lambda F_{\lambda})}{d \log \lambda}, \quad (2.2)$$

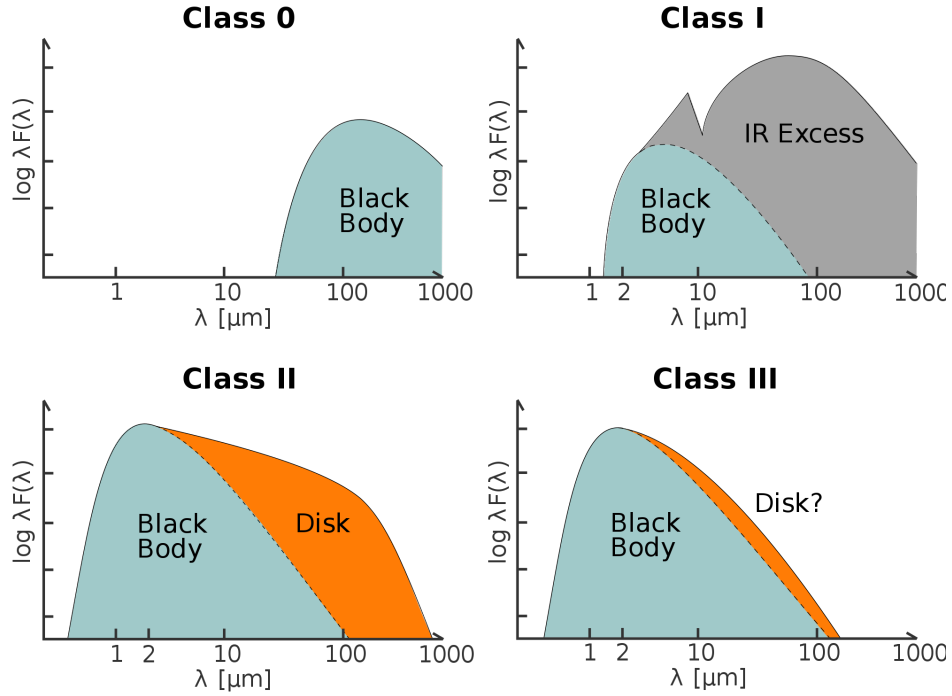


Figure 2.2.: The proposed classification scheme for protostellar evolutionary Classes 0–III is based on the slope of the spectral energy distribution (Equation 2.2) between $\sim 1 - 100 \mu\text{m}$. Image credit: Persson (2014b).

where F_λ is the flux at wavelength λ . Originally, three distinct classes were identified (Class I, II and III, Lada, 1987) according to their infrared excess with respect to stellar blackbodies as measured by α_{IR} . This classification scheme was revised (Greene et al., 1994) to include an additional “flat spectrum” class, where the evolutionary status is uncertain. Finally, observations of molecular clouds in the sub-millimetre led to the discovery and designation of the youngest class (Class 0, André et al., 1993). What follows are the observational properties associated with each protostellar evolutionary class, however the observational divides are not clear-cut as these processes are gradual and can suffer from observational limitations.

2.1.1 Class 0

Class 0 protostars (André et al., 1993) represent the youngest stage of low-mass star formation and are still deeply embedded in their natal circumstellar envelopes. As they have not yet accumulated most of their mass, $M_{\text{env}} \gtrsim M_\star$ (where $M_{\text{env}} \sim 0.5 M_\odot$ or more). Powerful, highly collimated (jet-like) outflows are generated as a result of active accretion from the infalling envelope, with mass-loss rates of $\dot{M}_{\text{jet}} \sim 10^{-6} M_\odot \text{ yr}^{-1}$ (e.g. Bachiller, 1996). The

morphology and dynamical timescales of these outflows indicate lifetimes in this phase of $\sim (1 - 3) \times 10^4$ yr.

Due to their deficit of emission shortward of $\sim 10 \mu\text{m}$ (see [Figure 2.2](#)), Class 0 sources are often identified indirectly such as through the detection of a compact centimetre radio continuum source, a collimated molecular outflow or an internal heating source, which are all evidence for a central YSO. These properties distinguish them from prestellar (starless) cores. The Class 0 SED is dominated by centrally peaked but extended sub-millimetre continuum emission tracing the dense and dusty envelope and is typically well characterised by a single-temperature blackbody with $15 \lesssim T_d \lesssim 30$ K ([André et al., 1993](#)), where T_d is the dust temperature. As the envelope mass exceeds the mass of the central star, Class 0 YSOs have a high ratio of sub-millimetre to bolometric luminosity ($L_{\text{smm}}/L_{\text{bol}}$) at wavelengths longer than $350 \mu\text{m}$, distinguishing them from the more evolved Class I–II systems. For further distinction, bolometric temperature (T_{bol} , the effective temperature of a blackbody with the same flux-weighted mean frequency as the observed SED) is also used to differentiate between evolutionary classes ([Myers & Ladd, 1993](#)), where $T_{\text{bol}} < 70$ K for Class 0 YSOs ([Chen et al., 1995](#)).

2.1.2 Class I

The protostar enters the subsequent Class I phase ([Lada, 1987](#)) when a majority of the envelope has accreted onto the protostar or circumstellar disk and $M_{\text{env}} < M_*$. These YSOs are relatively evolved with typical ages $\sim (1 - 2) \times 10^5$ yr (e.g. [Kenyon & Hartmann, 1995](#)). The outflows from Class I sources are typically much less powerful and less collimated than those from Class 0 objects due to a decline in the accretion rate, with $\dot{M}_{\text{jet}} \sim 10^{-8} M_{\odot} \text{yr}^{-1}$ ([Bontemps et al., 1996](#)). Although the accretion rate declines, the stellar mass increases and the luminosity is dominated by the accretion luminosity, L_{acc} ([Equation 2.1](#); [Greene & Lada, 1996](#)). For accretion rates of the order $\dot{M}_{\text{acc}} \sim 10^{-6} - 10^{-7} M_{\odot} \text{yr}^{-1}$, the luminosity should be of order $L_{\text{acc}} \sim 10 - 50 L_{\odot}$, however observed luminosities are more than an order of magnitude lower than predicted at $\sim 1 L_{\odot}$ ([Kenyon & Hartmann, 1995](#)). Episodic accretion could explain this discrepancy, where most of the matter accretes in eruptive bursts followed by long periods of quiescence such as that observed in FU Orionis stars ([Hartmann & Kenyon, 1996](#)).

Observational diagnostics for Class I protostars include $\alpha_{\text{IR}} \gtrsim 0.3$ (see [Figure 2.2](#); [Greene et al., 1994](#)) and $70 \text{ K} < T_{\text{bol}} < 650 \text{ K}$ ([Chen et al., 1995](#)) although misclassifications can be made due to inclination effects, aspherical geometry and extinction. In particular, a Class I object may resemble a Class 0 system when observed at high inclination angles to the line of sight ([Yorke et al., 1995](#)). However, the fact that Class 0 outflows are typically an order

of magnitude more powerful than outflows from Class I protostars (Bontemps et al., 1996) provides a qualitative difference between the two classes.

2.1.3 Class II

The protostar enters the Class II phase (Lada, 1987) when the envelope has dissipated and the star has accumulated most ($\gtrsim 90\%$) of its final main-sequence mass. Class II objects are optically visible due to the dissipation of the envelope and were therefore the first young low-mass stars to be detected (Joy, 1945) through strong hydrogen Balmer ($H\alpha$) line emission. The physical characteristics of these objects were observed to be similar to those of the star T Tau in the Taurus Molecular Cloud, and thus were dubbed T Tauri stars. The young variable stars observed by Joy (1945) exhibited irregular light-variations, spectral types F5–G5 with emission lines resembling the solar chromosphere, low luminosity and association with dark or bright nebulosity. They served as prototypes for Class II objects, or “classical” T Tauri stars (CTTS).

The further depletion of the envelope exposes the central object, base of the outflows and surrounding optically thick protoplanetary disk (of size ~ 100 au, from which the young star still accretes) and the system can now be observed at all wavelengths. Accretion lessens to $\dot{M}_{\text{acc}} \sim 10^{-7} - 10^{-9} M_{\odot} \text{ yr}^{-1}$ (Gullbring et al., 1998) and the outflows become weaker still at around 10% of the accretion rate (e.g. Cabrit, 2007). In the IR classification scheme, the SEDs of Class II YSOs peak between $1 - 10 \mu\text{m}$ with moderate IR excesses reaching beyond $100 \mu\text{m}$ and $-1.6 \lesssim \alpha_{\text{IR}} < -0.3$ (see Figure 2.2; Greene et al., 1994). Their bolometric temperatures are found to range between $670 \text{ K} < T_{\text{bol}} < 2800 \text{ K}$ (Chen et al., 1995).

2.1.4 Class III

The star enters the Class III phase (Lada, 1987) when accretion and ejection abates and the disk becomes optically thin. These objects are also referred to as “weak-lined” T Tauri stars (WTTS) as they do not show strong $H\alpha$ emission like CTTS. They also no longer show IR excesses and have $\alpha_{\text{IR}} < -1.6$ (see Figure 2.2; Greene et al., 1994) with bolometric temperatures $T_{\text{bol}} > 2800 \text{ K}$ (Chen et al., 1995). Most of the emission from WTTS comes from the stellar surface and coronal activity and non-thermal processes begin to dominate (White et al., 1992).

2.1.5 ZAMS

The *zero-age main sequence* is the endpoint of PMS evolution, defined by the the onset of sustained fusion. This is the first time when energy generation by nuclear reactions in the stellar core fully compensates the energy losses due to radiation from the stellar photosphere. The interior of the star is hot enough ($> 1.5 \times 10^7$ K) to ignite hydrogen burning and establish a dominant CNO cycle (Schulz, 2005). It takes stars of $\sim 1 M_{\odot}$ about 1.6×10^7 years to reach this state.

2.2 PROTOSTELLAR JETS AND OUTFLOWS

As mentioned at the beginning of this chapter, outflows from young stars were inadvertently and independently discovered by Herbig and Haro, but it was decades later before the origin of the HH objects was realised. The original HH objects were located in a dark cloud region in the vicinity of Orion population stars which associated them with processes of star formation and the exciting sources were initially suggested to be either sub-luminous hot stars or late K or M dwarfs (Herbig, 1951). Herbig suggested that the infall of material onto a protostar could produce enough energy to excite the nebula, although this was refuted by Böhm (1956). However, the lack of visually detectable stars at the HH sites raised more questions than answers regarding the energy source for these emission nebulae. Throughout the first two decades of research, no evidence was presented to confirm the presence of protostars within the HH objects (Schwartz, 1983).

In the 1970s, studies in the infrared revealed optically obscured IR sources spatially displaced from the sites of the HH objects, although close enough (within $5'' - 1'$) to suggest association. They exhibited energy distributions similar to T Tau (Strom et al., 1974a,b) and were proposed to be direct predecessors of T Tauri stars. Although the nearby HH objects were believed to be associated with the IR sources, it was becoming apparent that the HH objects themselves were not newly forming stars. Schwartz (1975) noticed the similarity between the spectra of HH objects to that of quasi-stationary knots in supernova remnants and suggested that HH objects were shock waves produced by supersonic winds from young stars, interacting with the ambient medium. It was not until the advent of the CCD camera that the protostellar jet origin of HH objects was fully realised (e.g. Mundt & Fried, 1983). It is now well established that HH objects are shocks in bipolar outflows from newborn stars, but the range of environments, varying evolutionary stages and the chaotic nature of shocks all contribute to a rich morphological menagerie (Reipurth & Bally, 2001).

Although jets were not initially predicted by star formation theory, it is now clear that outflows play an important role in forming stars. Jets are believed to remove angular momentum from the circumstellar disk therefore allowing accretion to proceed, dictate the

final stellar mass, and inject feedback into the parent molecular cloud preventing it from collapsing under the force of gravity.

2.2.1 Morphology

The classical picture of a protostellar jet involves two tightly collimated, oppositely directed (bipolar) outflow lobes exhibiting several shocks and knots along their lengths and terminating in a bright, symmetric bow shock (see [Figure 2.3](#)). Such fine morphologies are, however, rare. HH objects come in many irregular shapes and sizes (from ~ 1 to several arcseconds), and appear as linear or gently wiggling chains of compact knots with length-to-width ratios of 10 : 1 or more ([Reipurth & Bally, 2001](#)). The central surface of a bow shock is normal to the axis of the outflow direction, but becomes increasingly oblique away from the axis with swept-back wings. An inhomogeneous pre-shock medium can produce asymmetries in observed bow shock shapes ([Bally et al., 2007](#)).

Large-format CCDs and the *Hubble Space Telescope* (HST) revealed that protostellar outflows can span parsecs, with some exceeding 10 pc in length and penetrating out of their parent molecular cloud (see e.g. [Figure 2.3](#); [Bally & Devine, 1994](#)). Outflows provide a fossil record of the mass-loss history of forming stars which therefore provides the accretion history due to the intrinsic relationship between accretion and ejection. Additionally, large-scale symmetries in the outflow can provide information on the central jet engine ([Bally et al., 2007](#)). For example, S- and Z-shaped symmetries can infer a change in the outflow axis over time due to precession (induced by a companion or interactions with other stars in a cluster), and C-shaped bends can indicate motion of surrounding gas or motion of the driving source itself.

The highly collimated jets from young stars have similar morphologies to those observed from other astrophysical objects, including pre-planetary nebulae, X-ray binaries and AGN (see [Figure 2.4](#)). It is for this reason, along with their other similar characteristics, that the jet launching mechanism is suspected to be universal (e.g. [Livio, 2011](#), see also [Section 2.3](#)). In particular, collimated outflows occur in most astrophysical systems in which accretion, rotation and magnetic fields interact. Understanding how outflows from young stars are launched and collimated into jets can potentially be applied to all classes of astrophysical jets.

2.2.2 Jet Physics

In order to obtain a complete picture of outflows, observations across the entire electromagnetic spectrum are required to provide information through the diverse range of tracers of physical conditions. The rich optical emission line spectra of protostellar jets can al-



Figure 2.3.: Pillar and jets HH 901/902 in one of the largest known star-forming regions in the galaxy, the Carina Nebula, with the *Hubble Space Telescope* Wide Field Planetary Camera 3. The colours in this composite image correspond to the glow of oxygen (blue), hydrogen and nitrogen (green) and sulfur (red). Image credit: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI).

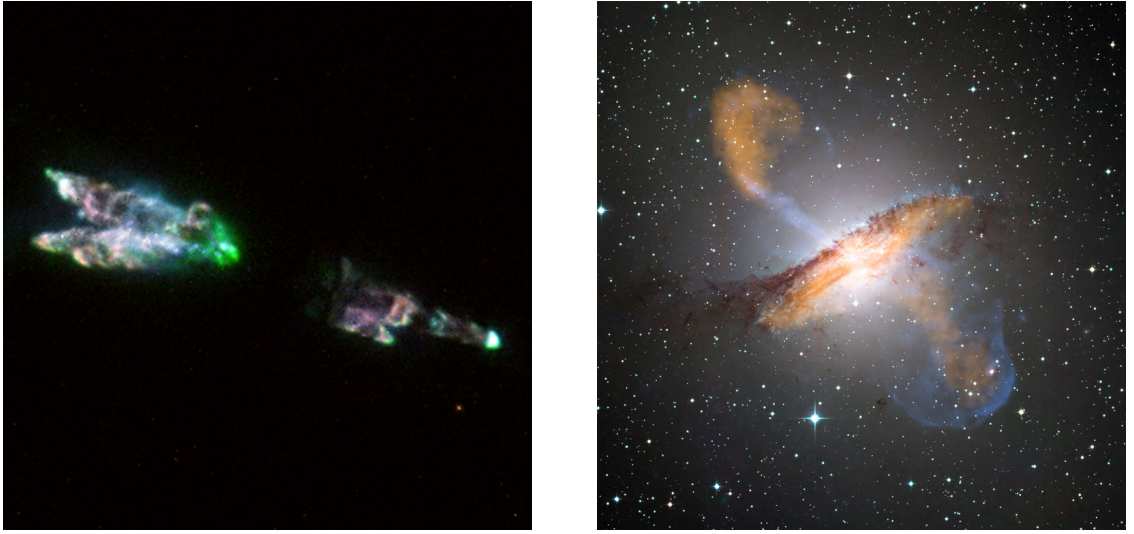


Figure 2.4.: (Left) Jets from the pre-planetary nebula CRL 618. Image credit: ESA & A.G.G.M. Tielens (SRON/Kapteyn Astronomical Institute). (Right) Merging X-ray data (blue) from NASA’s Chandra X-ray Observatory with microwave (orange) and optical images reveals the jets and radio-emitting lobes emanating from Centaurus A’s central black hole. Image credit: ESO/WFI (optical); MPIfR/ESO/APEX/A. Weiss et al. (microwave); NASA/CXC/CfA/R. Kraft et al. (X-ray).

low radial velocities, excitation conditions and electron densities to be determined using long-slit spectroscopy. For example, radial velocities determined from spectroscopy suggest jet velocities of the order of hundreds of kilometres per second, in agreement with tangential velocities determined using images from ground-based instruments over several epochs (e.g. Eislöffel & Mundt, 1998) and close to the gravitational escape velocities expected from young stars. Velocities as fast as 500 km s^{-1} have been measured for the HH 111 jet (Reipurth et al., 1992). Typical temperatures are found to be $\sim 10^4 \text{ K}$ from excitation levels, yielding sound speeds of tens of kilometres per second and therefore the jets are highly supersonic with Mach numbers in the range 10 – 30.

Atomic lines such as $H\alpha$ and forbidden transitions such as [OI], [NI] and [SII] in the optical and near-IR can be used to trace shocks and post-shock cooling layers, analysis of which reveals typical shock velocities of tens of kilometres per second (e.g. Bally et al., 2007). When the supersonic flow slams directly into the undisturbed ambient medium it creates a *terminal working surface*, and milder collisions occur within the outflows due to velocity variations in time. When faster-moving gas over-runs slower-moving material that was ejected earlier, an *internal working surface* can form (Raga et al., 1990). Both cases result in a two-shock structure, consisting of a *reverse shock*, which decelerates the supersonic flow, and a *forward shock*, which accelerates the material with which it collides and typically takes the form of a bow shock (Hartigan, 1989; Reipurth & Bally, 2001). Radiative shocks consist of a thin layer of hot, ionised gas at the shock front followed by an extended *cooling zone*

where most of the radiation from the shock arises (e.g. Bally et al., 2007). The highest velocity shocks can sometimes be detected in X-rays (e.g. Güdel et al., 2008).

If the position of the driving source is known along with its jet inclination angle, the proper motions measured through multi-epoch imaging allow a direct calculation of the dynamical ages of individual HH objects and therefore of ejection timescales from the central star, which suggest an elapsed time between ejections of 1000 – 2000 years (e.g. Reipurth et al., 1992). Episodic accretion (e.g. Kenyon & Hartmann, 1995; Dunham & Vorobyov, 2012), on the scale of FU Orionis outbursts or slightly weaker accretion events, could be responsible for the multiple major jet ejections observed in YSOs. Several trends from proper motion measurements are apparent (Reipurth & Bally, 2001): the jets in these HH complexes often exhibit large flow velocities and small velocity dispersions, and the tangential velocities tend to decline with increasing distance from the outflow axis. The tips of the bow shocks have much faster motion than their wings and in some cases, both upstream- and downstream-facing bow shocks are found (e.g. HH 2, Figure 2.7).

Various line ratios can additionally provide information on the ionisation fraction (x_e) and the electron number (n_e) and total mass (ρ) densities. The measured density can be combined with the jet velocity and radius to derive an estimate of the mass-loss rate using a simple jet density and cross section model: $\dot{M}_j \approx \pi r_j^2 \rho_j v_j$ where r_j is the jet radius, ρ_j is the density and v_j is the velocity. Depending on evolutionary stage, mass-loss rates range from $\dot{M}_j \sim 10^{-9} - 10^{-6} M_\odot \text{ yr}^{-1}$ (see Section 2.1). Accretion rates can be inferred from the accretion luminosity (Equation 2.1) and when compared to the mass-loss rates, imply outflow efficiencies (the ratio of mass ejection rate to mass accretion rate, $\dot{M}_j / \dot{M}_{\text{acc}}$) of 1 – 10% (Cabrit, 2007).

Outflows can appear to have onion-like kinematic structure, with higher velocity and more collimated gas (the so-called *high-velocity component*, HVC) continuously bracketed by wider and slower material (the *low-velocity component*, LVC), and the flow can become gradually denser and of higher excitation close to the central jet axis (e.g. Bacciotti et al., 2000). Evidence for rotation has also been shown in jets from T Tauri stars, which is a fundamental ingredient for the modelling of the acceleration of the outflow and of the interplay between accretion and ejection of matter (e.g. Bacciotti et al., 2002; Coffey et al., 2004).

2.2.3 Molecular Outflows

The molecular emission observed from sub-millimetre to centimetre wavelengths is mostly produced by gas entrained and accelerated by the highly collimated, supersonic jets, which produces the so-called *molecular outflow* (e.g. Arce et al., 2007). These outflows are studied through observations of molecular rotational line transitions, in particular through detec-

tion of their CO emission lines. Molecular outflows are typically much less collimated than the jets. They have typical length-to-width ratios of $\sim 3 - 10$, extend over $0.1 - 1$ pc and the degree of collimation appears to decrease as the driving source evolves (e.g. [Konigl & Pudritz, 2000](#)). The velocities are quite low in comparison to the high speed jets, generally $\leq 25 \text{ km s}^{-1}$, but can exhibit high velocities $> 40 \text{ km s}^{-1}$ near the flow axis from the more highly collimated CO outflows (e.g. [Arce et al., 2007](#)). Momentum rates of $F_{\text{CO}} \sim 10^{-5} \text{ M}_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$ are observed, with mass flux $\dot{M}_{\text{CO}} \sim 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ ([Bontemps et al., 1996](#)).

There are some cases of highly collimated molecular outflows, the so-called “molecular jets”, with high-velocity CO emission tracing jet-like activity from the central (Class 0) protostar, nested within a cavity of lower-velocity gas. HH 211 is a prototypical example of a molecular jet ([Gueth & Guilloteau, 1999](#)), where the high-velocity CO jet terminates at the location of strong H_2 bow shocks, and the low-velocity CO traces a cavity that is located in the wake of the shocks, supporting the theory that the propagation of shocks in a protostellar jet entrain the ambient molecular gas and thus produces the molecular outflow ([Arce et al., 2007](#)). Many of the older outflows (from Class I–II sources) show CO emission dominated by low-velocity cavities with a lack of high-velocity, jet-like features, suggesting that the jet power has decreased over time and that a wide-angle wind is now responsible for driving the outflow ([Richer et al., 2000](#)).

2.2.4 The Jet–Disk (Ejection–Accretion) Connection

Protostellar jets are believed to be powered by the gravitational energy liberated in the accretion process and fed by disk material, which is supported by the strong correlation between the presence of both outflow and accretion signatures (e.g. [Cabrit et al., 1990](#); [Antoniucci et al., 2008](#)). Diagnostics for outflow include P Cygni line profiles, forbidden line emission, thermal radio emission or well developed molecular outflows. Diagnostics for accretion include inverse P Cygni line profiles, ultraviolet, infrared and millimetre excesses ([Konigl & Pudritz, 2000](#)). Additional support is provided by the correlations of evolutionary stage with outflow activity, disk frequency and mass accretion rate ([André et al., 2000](#)). Incidence rates of outflows are almost 100% among Class 0 objects, $\gtrsim 60\%$ among Class I objects, $\sim 10\%$ among Class II objects and 0% among Class III objects ([Gomez et al., 1997](#)). The inference that jets are powered by accretion disks is strengthened by the evidence for disks in the youngest protostars and confirmed by the absence of any detectable jet in stars without accretion disks ([Cabrit et al., 1990](#)).

The ejection-to-accretion correlation in T Tauri stars was quantified by [Hartigan et al. \(1995\)](#), who inferred a mean, one-sided ratio of the mass ejection rate to the mass accretion rate, $\dot{M}_{\text{j}}/\dot{M}_{\text{acc}} \simeq 0.01$ (one-sided due to the fact that the mass loss rate in the jet, $\dot{M}_{\text{j}}$, was

measured from only one side of the bipolar outflow). However, revised accretion rate estimates are an order of magnitude lower on average (Gullbring et al., 1998) and therefore provide a ratio 10 times higher (i.e. $\dot{M}_j/\dot{M}_{\text{acc}} \simeq 0.1$). Multiplying by two to account for the typically occulted (redshifted) counterjets, the two-sided ejection/accretion ratio is of the order $(2\dot{M}_j)/\dot{M}_{\text{acc}} \simeq 0.2$ for Class II objects (Cabrit, 2007), and similar efficiencies have been found for Class I objects (Hartigan et al., 1994). It is therefore clear that the accretion process is essential to the observed jets, however the precise physical connection remains a matter of ongoing debate.

2.3 CURRENT JET-LAUNCHING THEORY

The close association of astrophysical jets and outflows with accretion disks has led to the wide acceptance that jets are driven by accretion and launched through magnetohydrodynamic (MHD) processes. A disk wind was first suggested as the origin of jets from accretion disks around black holes (Blandford & Payne, 1982), where the magnetic field lines are anchored to the rotating disk, and therefore material is accelerated centrifugally like “beads on a wire”. This scenario was soon proposed as the mechanism for protostellar jets (Pudritz & Norman, 1983, 1986). In the case of YSOs, the rotation of the circumstellar disk, and therefore of the magnetic field lines, creates a helical configuration that is believed to collimate the jet via “hoop stresses” occurring tens of au from the protostar. The basic principle of this model is that outflows from magnetised, rotating disks are extremely efficient in extracting angular momentum and rotational energy from the system and therefore allow accretion to proceed and the central protostar to grow (Pudritz & Norman, 1983). In spite of the general consensus that the launching process involves the dynamical interaction of accreted matter with the stellar and/or disk magnetic field, the precise location of jet-launch is still hotly debated.

Launch distances depend on the model: (1) a few stellar radii for stellar winds, (2) around 0.05 au for those launched at the stellar magnetosphere-disk interface or the so-called X-wind and (3) possibly as far as several au for magneto-centrifugal disk winds. However, the projected dimensions on the sky for even the largest launch regions are tens of milliarcseconds, so observing the jet very close to the YSO (ideally within a few stellar radii) is beyond current resolution capabilities, although should be possible in the near future with the next generation of near-IR interferometers. In any case, the region close to the star is often obscured by circumstellar material. The jets often only become optically observable a few arcseconds from the YSO, and are therefore surrounded by what is referred to as a “black box”: an unobservable region with an angular size of up to a few arcseconds (Eisloffel et al., 2000). Luckily, the launch-zone does not have to be spatially resolved to begin to test the different models. The mechanisms on small scales can be inferred from

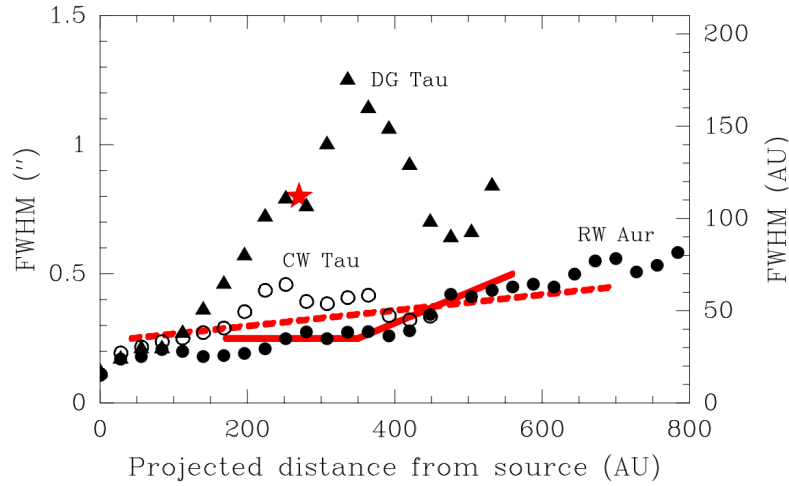


Figure 2.5.: Variation with distance of the measured jet full width at half maximum (FWHM) for a sample of T Tauri stars. Image credit: [Dougados et al. \(2000\)](#).

jet properties measured on larger scales such as the ejection-to-accretion ratio, collimation, angular momentum transport and velocity structure ([Frank et al., 2014](#)).

If the jet is responsible for removing excess angular momentum from the accretion disk, then the angular momentum flux in the jet, $\dot{J}_j \simeq \dot{M}_j \Omega r_A^2$, should equal the amount to be removed from the accreting flow, $\dot{J}_{\text{acc}} \simeq \dot{M}_{\text{acc}} \Omega r_l^2$, where Ω is the angular velocity at the launch radius r_l , and r_A is the Alfvén radius (e.g. [Frank et al., 2014](#)). It follows then that the magnetic field configuration is related to the ejection-to-accretion ratio $\dot{M}_j / \dot{M}_{\text{acc}} \simeq (r_l / r_A)^2 = 1 / \lambda$, with λ defined as the magnetic lever arm parameter braking the rotating star or disk (e.g. [Ferreira et al., 2006](#)). Thus for CTTS, a value of $\lambda \simeq 10$ is expected from the observed ejection-to-accretion efficiencies of 10%, irrespective of the location of jet-launch.

It is well-established that jets become collimated on scales less than 100 au. An important constraint on jet collimation is set by measuring the width of a jet as a function of distance from its source to determine the jet opening angle. There are two opening angles to describe the collimation properties of the jets: an initial jet opening angle θ_0 which is the average opening angle of the jet within the “black box” and an average opening angle θ_a outside the “black box.” To determine θ_0 , a jet width measurement just outside the unobservable region is needed, and zero width at the source must be assumed ([Eisloffel et al., 2000](#)). It has been shown that for most cases, $\theta_0 \gg \theta_a$, implying that the jet must be poorly collimated close to the source ($\theta_0 \sim 20 - 30^\circ$), behaving more like a wide-angle wind that then undergoes collimation further along the flow ([Mundt et al., 1991](#)). Narrow opening angles of $\theta_a \sim 0 - 3^\circ$ are often observed beyond $\simeq 50$ au of the source (e.g. [Ray et al., 1996](#); [Dougados et al., 2000](#), see [Figure 2.5](#)) and since T Tauri stars do not possess dense envelopes that could confine the flow, it is clear that the jets must be intrinsically collimated.

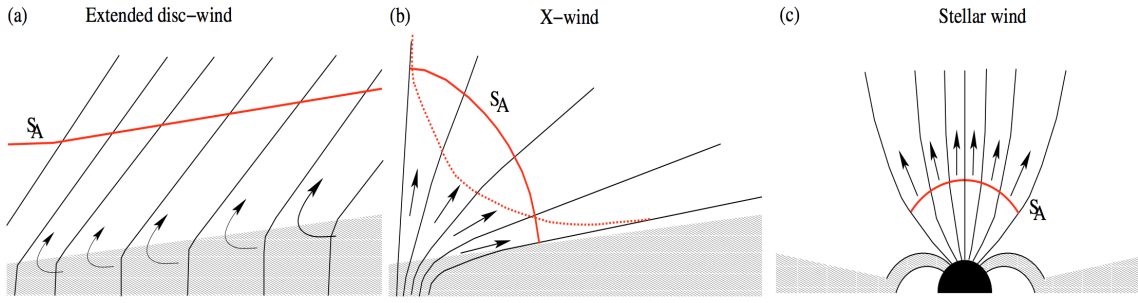


Figure 2.6.: MHD jet-launching models for the (a) D-wind, (b) X-wind and (c) stellar wind scenarios. Image credit: Ferreira et al. (2006).

2.3.1 *D-winds vs X-winds*

The two main competing theories for a MHD jet-launching mechanism are the *X-wind* and *disk wind* (also known as the *D-wind* or *extended disk wind*) models. In both models, the jets are driven magneto-centrifugally from open field lines anchored to the rotating disk; the distinction lies in where precisely in the disk the magnetic field lines are anchored (see Figure 2.6). In the X-wind model, the jet originates from the interface between the star's magnetosphere and disk, at the so-called X-point (for comprehensive reviews, see Shu et al., 2000; Shang et al., 2007, and references therein). In the D-wind model, the foot-points are located in an extended region of the disk, ranging from 0.1 to a few au (for reviews, see Konigl & Pudritz, 2000; Pudritz et al., 2007). Despite this difference in the origin of the magnetic field, the ejection processes are identical: in both models, jets carry away the amount of angular momentum required to allow accretion to proceed. However, since the range in launching radii and the shape of the Alfvén surface are different, predicted terminal velocities and angular momentum fluxes are also different and can be tested against observations (Ferreira et al., 2006).

Signatures of jet rotation infer launching radii of $0.2 - 3$ au (e.g. Bacciotti et al., 2002) suggesting that at least the outer portions of jets from CTTS originate from an extended disk wind. X-winds and stellar winds predict $10 - 100$ times less angular momentum removal than indicated by the rotation signatures observed. The moderate magnetic lever arm parameters $\lambda \simeq 10$ derived from ejection-to-accretion ratios, onion-like kinematic structure and collimation of protostellar jets also favour an extended disk wind origin (Ferreira et al., 2006). Although current observational results cannot be readily explained by the X-wind theory, the large uncertainties and current resolution restrictions can not yet explicitly rule out this model and direct observational evidence is still required to differentiate between the competing theories.

2.3.2 *Stellar Winds*

Pure stellar winds extract their energy from the protostar itself (e.g. Mestel, 1968; Hartmann & MacGregor, 1982; Sauty et al., 1999), however this model is less favoured because observed jets carry far too much momentum. In order to produce a jet, the protostar would have to be much more luminous or rotating faster than observed (Konigl, 1986). However, a scenario in which an accretion powered stellar wind is produced from open stellar magnetic field lines in addition to a disk wind is more plausible (Matt & Pudritz, 2005). It is likely that several MHD ejection sites coexist in young stars, although the relative contribution from each to the observed jet have yet to be determined (Ferreira et al., 2006).

2.4 RADIO EMISSION FROM PROTOSTELLAR SYSTEMS

Radio emission from young stars has been observed for decades (e.g. Cohen et al., 1982). It is typically observed to be compact and elongated along the outflow axis and arising from thermal radiation, leading to the designation of these sources as “thermal radio jets” (e.g. Rodríguez, 1995). In a few YSO sources, the optical jets trace material on scales of several hundred au and larger, while small-scale radio jets from ionised material are only present very close to the projected bases of the optical jets (see Figure 2.7; e.g. Rodríguez et al., 2003a). The youngest protostars (Class 0–I) are still deeply embedded within their embryonic envelopes and are only able to be studied at longer wavelengths which can penetrate the circumstellar dust. The dynamical timescales of the radio emission are of only a few years, indicating that the observed emission traces newly ejected material (Curiel et al., 1993). Proper motions of radio emission indicate jet velocities of hundreds of kilometres per second, in agreement with optical observations.

2.4.1 *Thermal Bremsstrahlung*

Bremsstrahlung (or *free-free*) radiation is emitted continuously by the acceleration of electrons due to Coulomb interactions with positive ions, and in the radio range is expected to occur from any environment populated by an ionised plasma. It is the basic thermal emission process in HII regions and is commonly the source of centimetre ($\sim 1 - 20$ GHz) radio emission for low-mass young stars. A number of mechanisms have been proposed to produce free-free emission from YSOs: a fully ionised, spherical stellar wind with $n_e \propto r^{-2}$ (Panagia & Felli, 1975; Wright & Barlow, 1975, although this may only apply to more evolved stars than very young YSOs), as could a partially ionised, collimated outflow (Reynolds, 1986). Shock induced ionisation through the impact of a neutral stellar wind

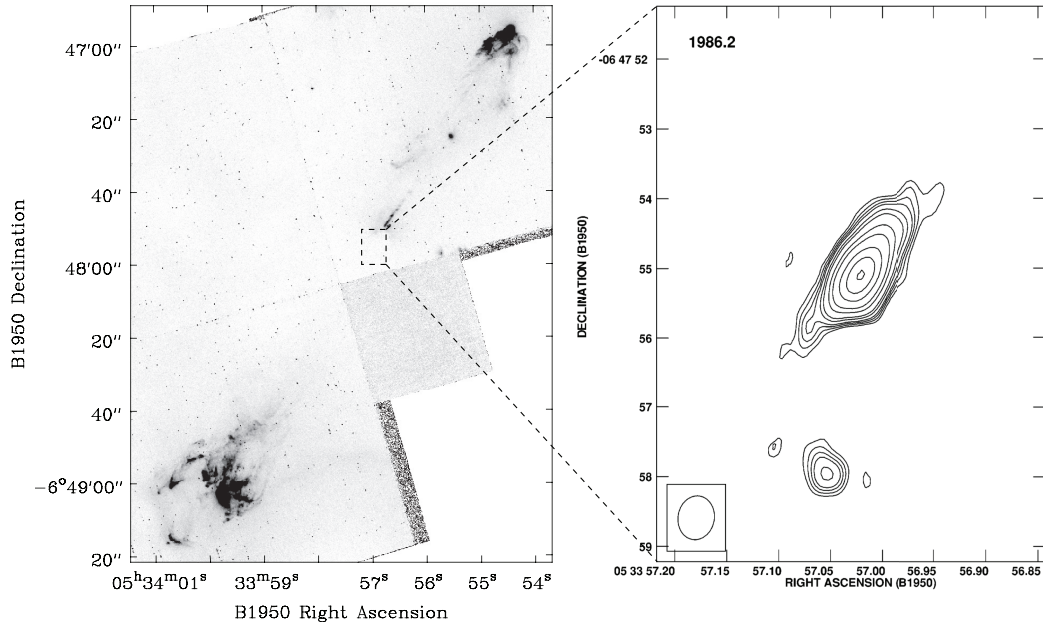


Figure 2.7.: Left: 1997 epoch *Hubble Space Telescope* image of the HH 1 – 2 system at optical wavelengths (Bally et al., 2002). Right: An insert of the radio emission tracing the source of the HH 1 – 2 jet, VLA 1 (Rodríguez et al., 2000).

or molecular outflow against the surrounding envelope could also generate a substantial radio signal (Curiel et al., 1987, 1989). In all cases, it is clear that the outflow is responsible.

Free-free emission at these wavelengths typically has a flat or positive power-law spectral index α , where the flux density $S_\nu \propto \nu^\alpha$ at frequency ν and varies from $\alpha \approx -0.1$ for optically thin emission to $\alpha \approx +2$ for optically thick emission. The classic example of an unresolved, constant velocity, fully ionised, isothermal, (standard) spherical wind has $\alpha \approx 0.6$ (Panagia & Felli, 1975). Reynolds (1986) showed that $\alpha < 0.6$ for the standard case of a collimated jet, which is the model commonly used to analyse radio observations of protostellar jets. Basic modelling of thermal bremsstrahlung from radio sources can be found in Section 3.2.

2.4.2 Thermal Dust Emission

The radio emission can also be attributed, at least at very short wavelengths ($\gtrsim 20$ GHz), to the dusty disks around these young stars (e.g Rodríguez et al., 2008b; Scaife et al., 2012a) which is heavily dominated by blackbody emission. The observed continuum flux density

from the dust emission in the Rayleigh-Jeans region and optically thin limit is characterised as

$$S_\nu \propto \nu^\beta B_\nu(T_d), \quad (2.3)$$

where β is the opacity index of the dust population and $B_\nu(T_d)$ is the Planck function for a dust temperature T_d (see [Section 3.2](#)). β depends on the dust composition and grain size distribution: smaller grains have larger opacity indices which lead to steeper spectra at longer wavelengths, whereas larger grains have lower indices and therefore flatter spectra. The opacity index can be related to the spectral index of flux density measurements as $\beta \propto (\alpha - 2)$ (e.g. [Scaife, 2013](#)). At frequencies ~ 20 GHz, there are contributions from both free-free and thermal dust emission to the radio flux densities of protostars (e.g. [Scaife et al., 2011a](#)) which need to be separated in order to accurately constrain the properties of each.

2.4.3 Non-thermal Emission

Non-thermal emission is known to arise from the more evolved and jet-less Class III YSOs ([White et al., 1992](#)). However, radio observations for a handful of low-mass Class 0–II protostars also imply non-thermal processes may be at work, such as gyro-synchrotron emission ([Ray et al., 1997](#)), suggesting the presence of at least mildly relativistic electrons spiralling along magnetic field lines. In contrast to that of free-free emission, the synchrotron spectrum has $\alpha < -0.5$ which, together with the brightness, relates to the energy spectrum of the electrons. Synchrotron radiation is the dominant source of radio emission from supernova remnants and extragalactic radio sources, such as the relativistic outflows from AGN, but there are some YSOs that have yielded spectral indices too negative to be explained by free-free emission alone, such as the Serpens MMS 1 triple radio source ([Rodríguez et al., 1989b](#); [Curiel et al., 1993](#)), suggesting that non-thermal processes must contribute.

As mentioned in [Chapter 1](#), synchrotron radiation has been detected in the jet of HH 80 – 81, a high-mass YSO ([Carrasco-González et al., 2010a](#)). This is a remarkable result as the presence of relativistic particles was previously thought to be unlikely in jets from young stars where the velocities are only of the order of hundreds of kilometres per second, in comparison with jets from AGN where the jet velocities may be a significant fraction of the speed of light. Linear polarisation has yet to be detected in low-mass protostellar jets, which is crucial for obtaining information on the magnetic field strength and distribution.

2.4.4 *The Need for Multi-scale, Multi-frequency Observations*

The jet-like structure shows that the radio emission is collimated on a scale smaller than 10 au (Shang et al., 2004), therefore extremely high angular resolution observations ($\leq 0''.07$) are required to distinguish between the competing theories of jet-launch. The observed fluxes of radio jets are weak (~ 1 mJy) making radio measurements very difficult in the past. The next generation of radio interferometers will have the improved sensitivity to image such outflows and spatial resolution ($< 0''.1$) to begin to resolve the central engine. A direct measurement of the jet at its base may favour a disk origin, where the base of the jet should be eventually resolved angularly, or a central star origin, where the base of the jet will be very small and unresolved, allowing us to directly distinguish between the D-wind and X-wind models observationally.

Multi-frequency, multi-scale investigations of YSOs are vital to obtain a complete demography of how stars like the Sun form. Data at well-sampled frequencies are crucial to precisely model and differentiate between the competing emission mechanisms, such as at the boundary between centimetre and sub-millimetre wavelengths where the flux densities have contributions from both the jet and the circumstellar material. These systems have yet to be explored at frequencies < 1 GHz, a regime in which high energy processes dominate the radio spectra of other astrophysical jets, in particular jets from AGN. In addition, radio data over a range of angular scales will shed light on the outflow properties. High spatial resolutions will allow us to peer into the depths closest to the protostar and search for the region of jet-launch. Large scale structures in these outflows can be exposed with modest spatial resolution whilst instruments with low angular resolution can detect the overall interaction of these outflows with their surroundings. All of these ingredients are vital to complete the picture of low-mass star formation.

INSTRUMENTATION: PRINCIPLES OF RADIO ASTRONOMY

Karl Jansky joined the staff of Bell Telephone Laboratories in 1928 to investigate the sources of static that might interfere with transatlantic radio voice transmissions. He constructed an antenna to detect radio waves at 20.5 MHz and, after several months, identified three types of static: nearby thunderstorms, distant thunderstorms, and an unidentified faint, steady hiss. Jansky studied the unknown signal for many months, discovering that it followed sidereal time, not solar time, and therefore must be emitted by an object distant to the solar system. He pinpointed the signal's origin to the centre of the Milky Way, in the constellation Sagittarius, and published his results (Jansky, 1933a,b). Unfortunately, Jansky's brief stint in radio astronomy ended here, as the static would not interfere with transatlantic radio communications and Bell Labs reassigned him to another project. His measurements were followed up at 160 MHz by another radio engineer, Grote Reber (Reber & Conklin, 1938), and the field of radio astronomy was born.

Today, the extent of the ground-based radio window is roughly $10\text{ MHz} \leq \nu \leq 1.5\text{ THz}$ ($30\text{ m} \leq \lambda \leq 0.2\text{ mm}$; Wilson et al., 2013) although is more generally considered to be $100\text{ MHz} \leq \nu \leq 100\text{ GHz}$. This was the first new spectral range that became available to astronomy after the near infrared–optical window, exposing radiation with non-thermal origin and where different physical mechanisms apply than in the optical wavelength range. There are many advantages to observing at radio wavelengths, the most obvious of which is that radio waves can reach ground-based instruments. The only other wavelength range that can be seen from the ground is the optical, all other wavelengths must be observed from space as they cannot penetrate the Earth's atmosphere (see Figure 3.1). Additionally, radio telescopes can observe objects or phenomena that are difficult or impossible to detect at other wavelengths, such as heavily obscured young stars, and radio emission can be used for quantitative physical diagnostics of object parameters. This chapter details the basic principles of radio astronomy.

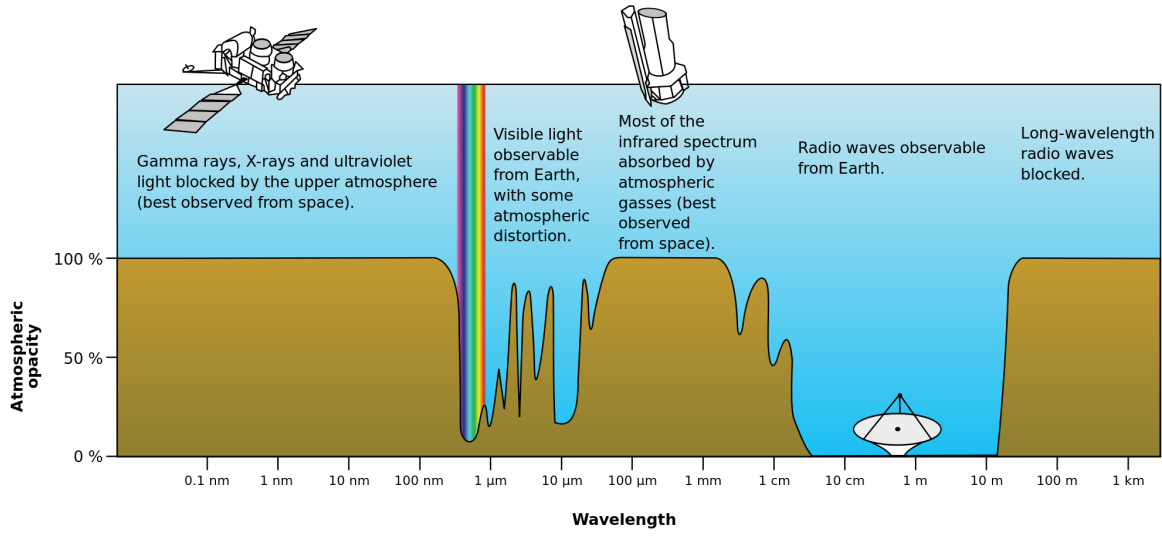


Figure 3.1.: Only optical and radio waves from space can be observed by ground-based telescopes on Earth. The atmosphere partially or completely blocks other wavelengths which only space-based telescopes can observe. Image credit: NASA/IPAC.

3.1 SOME BASIC DEFINITIONS

We consider the electromagnetic radiation to travel in straight lines or *rays*. The infinitesimal power dP intercepted by an infinitesimal projected surface $\cos \theta d\sigma$ is then defined as

$$dP = I_\nu \cos \theta d\Omega d\sigma d\nu \quad (3.1)$$

where (in SI units) dP is in W, I_ν is the brightness in $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$, Ω is the angular area subtended by an object, θ is the angle between the normal to $d\sigma$ and the direction to $d\Omega$, $d\sigma$ is in m^2 , and $d\nu$ is the infinitesimal bandwidth in Hz (Wilson et al., 2013). Equation 3.1 is the definition of the *brightness*, I_ν (energy per unit time per unit area per unit frequency per unit solid angle), also referred to as *intensity* or *specific intensity* (see Figure 3.2a).

The total flux density (energy per unit time per unit area per unit frequency) of a source can be obtained by integrating Equation 3.1 over the total solid angle Ω_s subtended by the source

$$S_\nu = \int_{\Omega_s} \frac{dP}{d\sigma d\nu} = \int_{\Omega_s} I_\nu(\theta, \varphi) \cos \theta d\Omega \quad (3.2)$$

where S_ν is measured in SI units of $\text{W m}^{-2} \text{Hz}^{-1}$. However, as the flux densities of radio sources are typically small, the commonly used flux density unit in radio astronomy is the Jansky (Jy), where $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{Hz}^{-1} = 10^{-23} \text{ erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$. S_ν has an expected

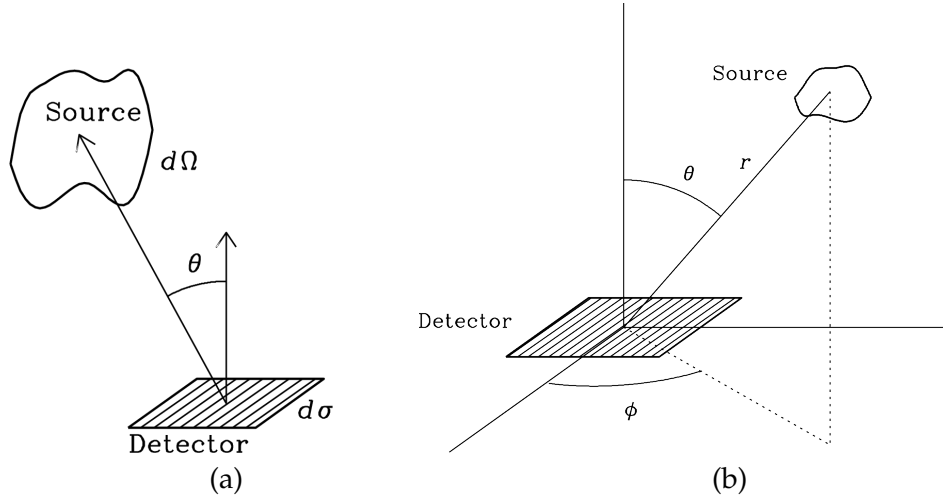


Figure 3.2.: Figures to illustrate (a) the definition of brightness (Equation 3.1; image credit: Condon & Ransom, 2010) and (b) the distance dependence of flux density (Equation 3.2; image credit: Condon & Ransom, 2010).

r^{-2} dependence on distance. Consider a sphere with radius R and uniform brightness I_ν (see Figure 3.2b). From Equation 3.2, the total flux density observed at distance r from the observer is then

$$S_\nu = \int_{\Omega_s} I_\nu(\theta, \varphi) \cos \theta \, d\Omega = I_\nu \int_0^{2\pi} \left(\int_0^{\theta_c} \sin \theta \cos \theta \, d\theta \right) d\varphi$$

where $\sin \theta_c = R/r$ defines the angle θ_c that the radius of the sphere subtends at r and $d\Omega = \sin \theta \, d\theta \, d\varphi$ (Wilson et al., 2013). Then,

$$S_\nu = \pi I_\nu \sin^2 \theta_c = I_\nu \frac{\pi R^2}{r^2} = I_\nu \Delta\Omega. \quad (3.3)$$

The *spectral luminosity* L_ν of a source is the total power per unit frequency radiated at frequency ν , and is related to the flux density,

$$L_\nu = 4\pi r^2 S_\nu \quad (3.4)$$

in SI units of W Hz^{-1} .

3.2 RADIATIVE TRANSFER

For radiation in free space, the specific intensity I_ν remains independent of the distance along a ray and will only change if radiation is emitted or absorbed (e.g. Wilson et al., 2013). This change in I_ν along the line of sight is described by the equation of transfer,

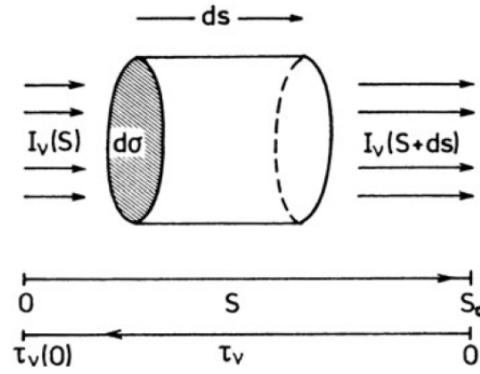


Figure 3.3.: Illustration of absorption between a source and a detector to define the quantities used in the equation of radiative transfer. Image credit: [Wilson et al. \(2013\)](#).

which is composed of a gain term, $dI_{\nu+} = \epsilon_\nu ds$ where ϵ_ν is the emissivity, and a loss term, $dI_{\nu-} = -\kappa_\nu I_\nu ds$ where κ_ν is the absorption coefficient. The change in a slab of material of thickness ds will be

$$[I_\nu(s+ds) - I_\nu(s)] d\sigma d\Omega d\nu = [\epsilon_\nu - \kappa_\nu I_\nu] d\sigma d\Omega d\nu ds \quad (3.5)$$

(see [Figure 3.3](#)) resulting in the *equation of transfer*

$$\frac{dI_\nu}{ds} = \epsilon_\nu - \kappa_\nu I_\nu. \quad (3.6)$$

If the radiation is in thermodynamic equilibrium with its surroundings, Kirchhoff's law states that the brightness distribution I_ν can be described by the Planck function $B_\nu(T)$ which is dependent only on the temperature T of the surroundings ($I_\nu = B_\nu(T)$; e.g. [Wilson et al., 2013](#)). In this case, the equation of transfer ([Equation 3.6](#)) is

$$\frac{dI_\nu}{ds} = 0 \quad (= \epsilon_\nu - \kappa_\nu I_\nu) \rightarrow I_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = B_\nu(T) \quad (3.7)$$

where

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1} \quad (3.8)$$

is Planck's law, c is the speed of light, h is Planck's constant and k_B is the Boltzmann constant. In the limit of low frequencies ($h\nu \ll k_B T$), Planck's law becomes the Rayleigh-Jeans law,

$$B_\nu(T) = \frac{2k_B T \nu^2}{c^2}, \quad (3.9)$$

and becomes Wien's law in the limit of high frequencies ($h\nu \gg k_B T$),

$$B_\nu(T) = \frac{2h\nu^3}{c^2} e^{-h\nu/k_B T}. \quad (3.10)$$

In general, I_ν will differ from $B_\nu(T)$ as full thermodynamic equilibrium is applicable only in closed systems. For the more general case of *local* thermodynamic equilibrium, consider the *optical depth*, which is defined as $d\tau_\nu = -\kappa ds$, or

$$\tau_\nu(s) = \int_{s_0}^s \kappa_\nu(s) ds. \quad (3.11)$$

Dividing Equation 3.6 by $-\kappa_\nu$ and using Kirchhoff's law (Equation 3.7), the equation of transfer then becomes

$$-\frac{1}{\kappa_\nu} \frac{dI_\nu}{ds} = \frac{dI_\nu}{d\tau_\nu} = I_\nu - B_\nu(T), \quad (3.12)$$

the solution of which is

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} B_\nu(T(\tau))e^{-\tau} d\tau. \quad (3.13)$$

Due to the definition in Equation 3.11, s and τ_ν increase in opposite directions as indicated in Figure 3.3 and integration has been performed back along the line of sight in each case. If the medium is isothermal, i.e. $T(\tau) = T(s) = T = \text{constant}$, then

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T)(1 - e^{-\tau_\nu(s)}) \quad (3.14)$$

(e.g. Wilson et al., 2013). For large optical depth ($\tau_\nu(0) \rightarrow \infty$) Equation 3.14 approaches the limit $I_\nu = B_\nu(T)$. The observed brightness, I_ν , for the optically thick case is equal to the Planck blackbody brightness distribution independent of the material.

3.2.1 Thermal Bremsstrahlung

Bremsstrahlung radiation is emitted continuously by the acceleration of electrons due to Coulomb interactions with positive ions, and is expected to be the source of radio emission from low-mass young stars. In order to model radio sources emitting bremsstrahlung, the absorption of this radiation within the medium must be taken into account and thus the transfer of radiation through the medium must be considered. Assuming an isothermal object without a background source (i.e. only radiation from the object is measured and

the background intensity $I_\nu(0)$ is negligible) and with total optical depth τ_ν , Equation 3.14 can be expressed as

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu}). \quad (3.15)$$

It follows that if $\tau_\nu \ll 1$, then $I_\nu = B_\nu(T)\tau_\nu$, and if $\tau_\nu \gg 1$, then $I_\nu = B_\nu(T)$.

If the emission coefficient ϵ_ν is known, the absorption coefficient κ_ν can be calculated from Kirchhoff's law (Equation 3.7) using the Rayleigh–Jeans approximation (Equation 3.9), and then integrated following Equation 3.11 to get τ_ν (see e.g. Wilson et al., 2013, for a full description). For bremsstrahlung,

$$\tau_\nu \approx 8.235 \times 10^{-2} \left(\frac{T_e}{\text{K}} \right)^{-1.35} \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right) \quad (3.16)$$

when $\nu \leq 20$ GHz and $T_e \geq 5000$ K (approximated by Altenhoff et al., 1960) and where EM is the *emission measure* defined as

$$\frac{EM}{\text{pc cm}^{-6}} = \int_0^s \left(\frac{n_e}{\text{cm}^{-3}} \right)^2 d \left(\frac{s}{\text{pc}} \right). \quad (3.17)$$

Following Equation 3.3 and assuming the emission is extended in comparison to the resolution of the telescope, the resulting flux density from the emission is given by

$$\left(\frac{S_\nu}{\text{Jy beam}^{-1}} \right) = 3.07 \times 10^4 \left(\frac{\nu}{\text{GHz}} \right)^2 \left(\frac{T_e}{\text{K}} \right) (1 - e^{-\tau_\nu}) \left(\frac{\Omega_b}{\text{sr}} \right) \quad (3.18)$$

where Ω_b is the beam size. The integrated flux density of a discrete source, in units of Janskys, may be found by replacing Ω_b in Equation 3.18 by Ω_s , the source size in steradians (e.g. Scaife, 2013).

Assuming a plasma of uniform density, the free–free emission will give rise to a characteristic spectrum comprised of two components: an optically thick component and an optically thin one. In the optically thick regime ($\tau_\nu \gg 1$), the optical depth term in Equation 3.18 becomes unity and the flux density $S_\nu \propto \nu^2$. In the optically thin regime ($\tau_\nu \ll 1$), the optical depth term becomes $\approx \tau_\nu$ and the flux density $S_\nu \propto \nu^{-0.1}$. Where the optically thick and thin regimes meet is the *turnover* frequency (ν_0), i.e. the frequency at which the optical depth equals unity ($\tau_\nu = 1$, see Figure 3.4).

In practice, unresolved sources can exhibit *partially* opaque spectra with spectral indices α ranging anywhere between -0.1 and 2 due to non-uniform density distributions. Partially opaque plasmas can be associated with stellar winds or ionised jets, both of which are common from young stars. In the case of a stellar wind, the “standard” geometry is that of constant velocity, fully ionised, isothermal, spherical winds with a radial density gradient

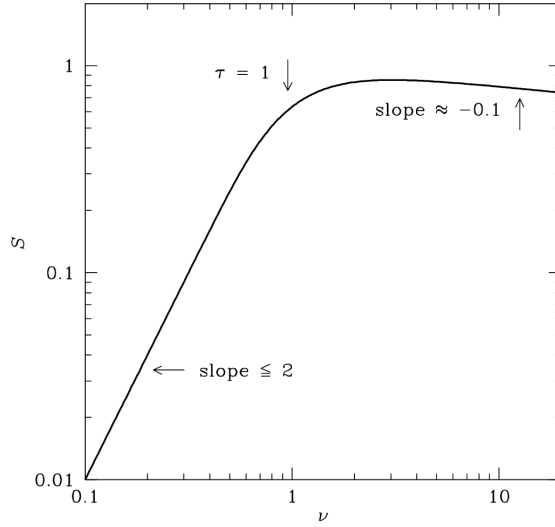


Figure 3.4.: An idealised radio spectrum (log-log plot) for a source emitting bremsstrahlung, e.g. an HII region. Image credit: [Condon & Ransom \(2010\)](#).

$n_e \propto r^{-2}$ ([Panagia & Felli, 1975](#)) and the spectrum behaves as $S_\nu \propto \nu^{0.6}$ over a wide range of frequencies.

[Reynolds \(1986\)](#) showed that well-collimated jets are much more efficient than spherical winds at producing radio flux, and mass-loss rates from such jets can be overestimated by an order of magnitude by spherical calculations. For a more general outflow where the physical conditions are parameterised by different radial dependencies (i.e. the temperature, velocity, density, ionisation fraction and optical depth are assumed to vary as r/r_0 to the powers of q_T , q_v , q_n , q_x and q_τ , respectively), the spectral index of the radio emission is of the form

$$\alpha = 2 + \frac{2.1}{q_\tau}(1 + \varepsilon + q_T) \quad (3.19)$$

where

$$q_\tau = \varepsilon + 2q_x + 2q_n - 1.35q_T \quad (3.20)$$

and ε relates to the opening angle of the jet such that $w(r) = w_0(r/r_0)^\varepsilon$ where w is the radius of the jet perpendicular to the direction of outflow. For the “standard” case of a collimated jet ($\varepsilon = \frac{2}{3}$, $q_n = -\frac{4}{3}$, $q_T = 0$, $q_v = 0$, $q_x = 0$ and $q_\tau = -2$) the spectrum behaves as $S_\nu \propto \nu^{0.25}$ ([Reynolds, 1986](#)).

3.3 APERTURE SYNTHESIS

The *angular resolution* (θ) of a single-dish radio telescope is limited by the diffraction limit of the telescope, and depends on the diameter (D) of the dish and the observing wavelength (λ):

$$\theta \approx 1.22 \frac{\lambda}{D} \quad (3.21)$$

for a circular dish and measured in radians. It is easy to see that unrealistically large diameters are needed to achieve sub-arcsecond resolution at radio wavelengths. The largest steerable, single-dish radio telescopes have diameters $D \approx 100$ m (e.g. Effelsberg and the Green Bank Telescope). For example, observations at 6 cm (5 GHz) with the Green Bank Telescope have a resolution of approximately $150''$. Because of this limited spatial resolution, single elements are combined into multi-element arrays to form a single telescope where the spatial resolution is now determined by the maximum separation between the dishes, called the *baseline* (b). These multi-element arrays are *interferometers*, and the diffraction limit becomes

$$\theta \approx \frac{\lambda}{b} \quad (3.22)$$

where the baseline can extend to many kilometres to reach sub-arcsecond resolution.

3.3.1 The Two-Element Interferometer

The simplest interferometer comprises a pair of identical radio antennae (1, 2) whose voltage outputs are *correlated*, that is, multiplied and integrated, as shown in [Figure 3.5](#) (e.g. [Condon & Ransom, 2010](#)). The antennae are separated by a baseline vector $\mathbf{b}$ observing the same monochromatic cosmic point source which is sufficiently distant that the incident wavefront can be considered to be a plane over the distance b . The angle of the pointing direction $\mathbf{s}$ from the baseline vector is θ and the projected length of the baseline on the sky is $b \sin \theta$; changing as the Earth rotates. The wavefront from the source in direction θ reaches antenna 1 at a time $\tau_g = \mathbf{b} \cdot \mathbf{s} / c = (b/c) \cos \theta$ before it reaches antenna 2, where τ_g is the *geometric delay* and c is the speed of light. See [Figure 3.5](#) for a schematic of the two-element interferometer. In the case of an interferometer with a very narrow bandwidth centred on frequency $\nu = \omega / (2\pi)$, the output voltages of antennae 1 and 2 can be written as

$$V_1(t) = V \cos[\omega(t - \tau_g)] \quad \text{and} \quad V_2(t) = V \cos(\omega t), \quad (3.23)$$

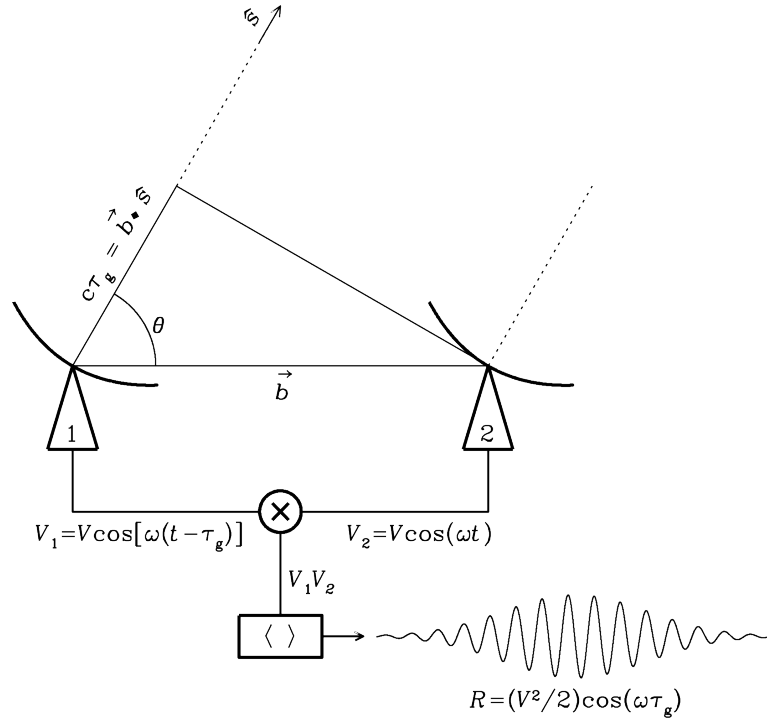


Figure 3.5.: The two-element interferometer. Image credit: [Condon & Ransom \(2010\)](#).

where t is time. The correlator first multiplies the voltages together,

$$V_1 \times V_2 = V^2 \cos(\omega t) \cos[\omega(t - \tau_g)] = \frac{V^2}{2} [\cos(2\omega t - \omega\tau_g) + \cos(\omega\tau_g)] \quad (3.24)$$

and then takes a time average long enough to remove the high frequency term from the correlator response R and keep only the slowly varying term

$$R(\tau_g) = \langle V_1 V_2 \rangle = \left(\frac{V^2}{2} \right) \cos(\omega\tau_g). \quad (3.25)$$

The response of the interferometer can be written in terms of measurable quantities ([Condon & Ransom, 2010](#)). The amplitudes V_1 and V_2 are proportional to the electric field produced by the source multiplied by the voltage gains of antennae 1 and 2, and therefore the output amplitude $V^2/2$ is proportional to the point source flux density S_ν multiplied by $A(\mathbf{s}) = (A_1 A_2)^{1/2}$, where A_1 and A_2 are the effective collecting areas of the two antennae. [Equation 3.25](#) can therefore be written as

$$R(\tau_g) = A(\mathbf{s}) S_\nu \cos(\omega\tau_g). \quad (3.26)$$

The correlator response R varies sinusoidally with the change of source direction in the interferometer frame and thus measures interference *fringes* as a function of time ([Condon](#)

& Ransom, 2010). The relative phase ϕ of the fringes is dependent on the geometric delay and the observing frequency, $\phi = \omega\tau_g = (\omega b/c) \cos \theta$, and the change in the phase as a function of θ is $d\phi/d\theta = (\omega b/c) \sin \theta = 2\pi(b \sin \theta/\lambda)$, with the instantaneous frequency being maximum when the source is at the zenith and minimum when the source is either rising or setting due to the relative change in the projected baseline. The relative phase varies with time since the delay changes as the interferometer tracks the source on the sky. A change in the phase by 2π , corresponding to the fringe period, occurs for a change in θ by $\lambda/b \sin \theta$.

The field of view is defined by the *primary beam*, which is the power reception pattern of the individual elements in the array (Condon & Ransom, 2010). The primary beam is limited by diffraction, so objects at radii $\gtrsim \lambda/D$ are strongly attenuated. If the two antennae forming the interferometer have different primary beams, the effective primary beam is the geometric mean of the two. In the current example, the antennae are identical and thus the primary beam has angular extent $\Theta \approx 1.22\lambda/D$ (in radians, Equation 3.21), which represents the *beam width between first nulls* of the receiving power pattern. The *half power beam width* (HPBW) or *full width at half maximum* (FWHM) are also commonly used, with angular extent (in radians)

$$\Theta_{\text{FWHM}} \approx \frac{\lambda}{D}. \quad (3.27)$$

Next consider a more realistic case where the antennae are tracking an extended, quasi-monochromatic source with source brightness distribution $I_\nu(\mathbf{s})$. The extended source can be treated as the sum of independent point sources and the output from the correlator becomes

$$R_c(\mathbf{b}, \mathbf{s}) = \int A(\mathbf{s}) I_\nu(\mathbf{s}) \cos(2\pi \mathbf{b} \cdot \mathbf{s} / \lambda) d\Omega \quad (3.28)$$

where $d\Omega$ is the solid angle of the source (Condon & Ransom, 2010). However, the cosine function in this response is sensitive only to the even part of the source brightness distribution and to detect the odd part a “sine” correlator (with output $R_s = (V^2/2) \sin(\omega\tau_g)$) is needed. Then,

$$R_s(\mathbf{b}, \mathbf{s}) = \int A(\mathbf{s}) I_\nu(\mathbf{s}) \sin(2\pi \mathbf{b} \cdot \mathbf{s} / \lambda) d\Omega. \quad (3.29)$$

Equation 3.28 and Equation 3.29 can be measured simultaneously with a two-correlator device called the *complex correlator*, with two different instrument delays. Using the identity $e^{i\phi} = \cos \phi + i \sin \phi$, the *complex visibility* is defined to be

$$\mathcal{V} \equiv R_c - iR_s \rightarrow \mathcal{V} = A e^{-i\phi} \quad (3.30)$$

where $A = (R_c^2 + R_s^2)^{1/2}$ is the *visibility amplitude* and $\phi = \tan^{-1}(R_s/R_c)$ is the *visibility phase* (Condon & Ransom, 2010). Thus the correlator response can be expressed in terms of a fringe pattern corresponding to that of a hypothetical point source in the direction $\mathbf{s}$. The modulus and phase of $\mathcal{V}$ are equal to the amplitude A and phase ϕ of the fringes. The response of a complex correlator to an extended source with brightness distribution $I_\nu(\mathbf{s})$ is thus

$$\mathcal{V} = \int A(\mathbf{s}) I_\nu(\mathbf{s}) e^{-i2\pi \mathbf{b} \cdot \mathbf{s} / \lambda} d\Omega \quad (3.31)$$

which has the dimensions of flux density, consistent with its Fourier transform relationship with I_ν .

Even the most elaborate interferometers with $N \gg 2$ elements can be treated as $N(N - 1)/2$ independent interferometer pairs, allowing the two-element interferometer analysis to be applied. The complex visibility function can be generalised to $\mathcal{V}_{i,j}$, measured with multiple baselines $\mathbf{b}_{i,j}$ (from antenna i to antenna j) in an array of radio telescopes and an appropriate instrumental delay τ_i (where the correlator response becomes $R(\tau) \propto \cos(\omega\tau)$ with $\tau = \tau_g - \tau_i$; Thompson et al., 2001):

$$\mathcal{V}_{i,j} = \int A(\mathbf{s}) I_\nu(\mathbf{s}) e^{-i2\pi \mathbf{b}_{i,j} \cdot \mathbf{s} / \lambda} d\Omega. \quad (3.32)$$

3.3.2 The u, v -plane

A convenient coordinate system is introduced to make use of Equation 3.31 (Thompson et al., 2001). Let the coordinates of the baseline vector measured in wavelengths, $\mathbf{b}_\lambda$, be given in a right-handed rectilinear coordinate system (u, v, w) . The w -axis is in the phase reference direction $\mathbf{s}_0$ (usually chosen to contain the target source) at an angle θ from the arbitrary direction $\mathbf{s}$. u and v will be in the projected easterly and northerly directions in the plane perpendicular to w , commonly referred to as the u, v -plane. Positions on the sky are defined in (l, m, n) , the direction cosines (where $n = \cos \theta = \sqrt{1 - l^2 - m^2}$) measured with respect to the axes u, v and w , see Figure 3.6. With this convention,

$$\mathbf{b}_\lambda \cdot \mathbf{s}_0 = w \quad (3.33)$$

$$\mathbf{b}_\lambda \cdot \mathbf{s} = ul + vm + wn = ul + vm + w\sqrt{1 - l^2 - m^2} \quad (3.34)$$

$$d\Omega = \frac{dl \, dm}{\sqrt{1 - l^2 - m^2}} \quad (3.35)$$

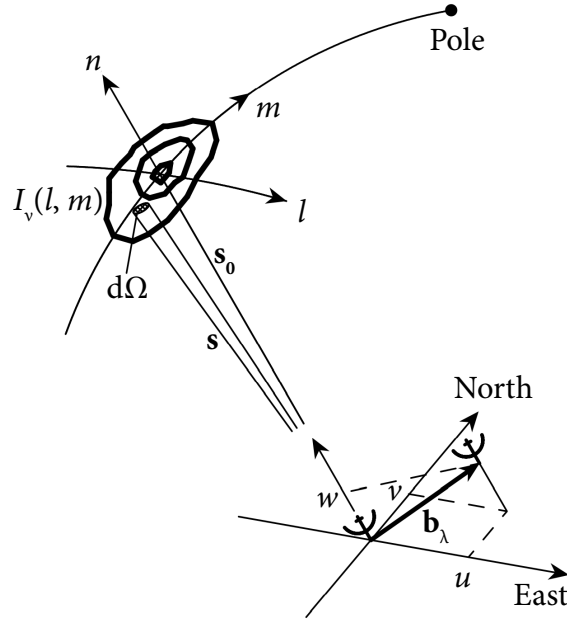


Figure 3.6.: The geometric relationship between an interferometer, a source under observation with $I_v(l, m)$ and the u, v -plane. The angle between $\mathbf{s}_0$ and $\mathbf{s}$ is θ . Image adapted from [Thompson et al. \(2001\)](#).

([Thompson et al., 2001](#)). [Equation 3.31](#) then becomes

$$\mathcal{V}(u, v, w) = \int \int A(l, m) I_v(l, m) e^{-i2\pi[ul+vm+w(\sqrt{1-l^2-m^2}-1)]} \frac{dl \, dm}{\sqrt{1-l^2-m^2}}. \quad (3.36)$$

This reduces to a two-dimensional Fourier transform relation when l and m are small enough that the term $w(\sqrt{1-l^2-m^2}-1) \approx -\frac{1}{2}(l^2+m^2)w \approx 0$. Then [Equation 3.36](#) reduces to

$$\mathcal{V}(u, v) = \int \int \frac{A(l, m) I_v(l, m)}{\sqrt{1-l^2-m^2}} e^{-i2\pi(ul+vm)} dl \, dm \quad (3.37)$$

and thus $\mathcal{V}(u, v)$ is the Fourier transform of a modified source brightness which can be inverted to give

$$\frac{A_N(l, m) I_v(l, m)}{\sqrt{1-l^2-m^2}} = \int \int \mathcal{V}(u, v) e^{i2\pi(ul+vm)} du \, dv \quad (3.38)$$

and thus the source brightness distribution can be retrieved through a sampling of the u, v -plane ([Thompson et al., 2001](#)).

3.3.3 Sensitivity

The sensitivity of an array is given by

$$\sigma_{\text{rms}} = \frac{2 k_{\text{B}} T_{\text{sys}}}{A_{\text{e}} \sqrt{N(N-1) \Delta\nu \tau}} \quad (3.39)$$

where σ_{rms} is the rms noise in Jy, A_{e} is the effective collecting area, $N(N-1)$ is the number of baselines and $\Delta\nu$ is the effective bandwidth measured in Hz (Condon & Ransom, 2010). $T_{\text{sys}} (= T_{\text{R}} + T_{\text{sky}} + T_{\text{ground}})$ is the system temperature in K, which embodies many sources of noise such as the receiver temperature T_{R} , the sky temperature T_{sky} and the ground spillover temperature T_{ground} . This equation can be rearranged to compute the required on-source integration time τ for an observation to achieve an rms noise σ_{rms} :

$$\tau = \left(\frac{2 k_{\text{B}} T_{\text{sys}}}{A_{\text{e}} \sigma_{\text{rms}}} \right)^2 \times \frac{1}{N(N-1) \Delta\nu}. \quad (3.40)$$

3.4 SPECIFIC TELESCOPES

3.4.1 AMI

The Arcminute Microkelvin Imager (AMI; Zwart et al., 2008) is located at the Mullard Radio Astronomy Observatory (MRAO), five miles south-west of Cambridge, at Lord's Bridge, and is operated by the Cavendish Laboratory. AMI comprises a pair of interferometer arrays, the Small Array (SA) and the Large Array (LA), aimed principally at Sunyaev-Zel'dovich (SZ) imaging of clusters of galaxies. Each of the AMI arrays observes using a nominal 6 GHz bandwidth centred at 15 GHz and the band is divided into eight equal bandwidth channels of 0.75 GHz. Due to interference from geostationary satellites, the two lowest frequency channels are not ordinarily used, and therefore, the six usable channels span frequencies from 13.5 – 18 GHz.

The data in Chapter 4 were taken with the AMI-LA (see Figure 3.7). The LA was originally the Ryle Telescope (5-km Telescope), designed as an east-west interferometer with eight 13 m dishes to observe individual radio sources with an angular resolution comparable to that of the large optical telescopes in the early 1970s. Four of the antennae are moveable along a railway track and the positions of the remaining antennae are fixed. All eight antennae have been arranged into a close, two-dimensional array with 28 baselines ranging from 18 – 110 m. The AMI-LA primary beam has a width at half power of 6' and an angular resolution of $\approx 30''$.



Figure 3.7.: The AMI Large Array at Lord's Bridge near Cambridge, UK. Image credit: www.mrao.cam.ac.uk.

3.4.2 *e*-MERLIN

The expanded Multi-Element Radio Linked Interferometer Network (*e*-MERLIN) synthesis telescope is a seven element interferometer with baselines of up to 217 km and connected by a new optical fibre network to Jodrell Bank Observatory near Manchester, UK (see [Figure 3.8](#)). An inhomogeneous array, *e*-MERLIN is comprised of the 76 m Lovell telescope, a 32 m dish at Cambridge, and the following 25 m antennae: Mark II, Knockin, Defford, Pickmere and Darnhall. At 5 GHz, the *e*-MERLIN primary beam has a width at half power of $5'$ with the Lovell Telescope and $7'$ without Lovell, and the resolution is better than 50 milliarcseconds, higher than that of the *HST*.

The data in [Chapter 5](#) were taken during the commissioning phase (Cycle-0, Semester 2012A) of *e*-MERLIN with only the five 25 m dishes, resulting in a primary beam of $\theta \approx 10'$. The maximum baseline was 133.7 km (between Pickmere and Defford), yielding an angular resolution of $0''.1$, and the minimum baseline was 11.2 km (between Pickmere and Mark II). A bandwidth of 0.512 GHz was observed centred around 5 GHz and divided into four equal sub-bands of 128 MHz.

The final, fully expanded array will have a bandwidth of 2 GHz per polarisation (up to 0.4 GHz at 1.4 GHz and 4 GHz bandwidth at 5 and 22 GHz), providing more than ten times the continuum sensitivity as the original MERLIN (e.g. up to $2 \mu\text{Jy beam}^{-1}$ at 5 GHz when Lovell is included). The final array will have 16×32 MHz sub-bands at 1.4 GHz



Figure 3.8.: e-MERLIN is an array of radio telescopes distributed around Great Britain, with baseline separations of up to 217 km. Image credit: www.e-merlin.ac.uk.

and 16×128 MHz sub-bands at 5 and 22 GHz. Without the Lovell telescope, sensitivity decreases by a factor of 2 – 3 and the FWHM of the primary beam is reduced.

3.4.3 GMRT

The Giant Metrewave Radio Telescope (GMRT, [Ananthakrishnan 2005](#)), is located near Khodad village, about 80 km north of Pune, India. The array consists of thirty antennae, each 45 m in diameter, and has the largest collecting area amongst the multi-element earth rotation aperture synthesis telescopes operating at metre wavelengths. Fourteen of the thirty antennae are dispersed more or less randomly in a compact central array within a square kilometre, and the remaining sixteen dishes are spread out along three arms of an approximately ‘Y’-shaped configuration, with the longest interferometric baseline of about 25 km (see [Figure 3.9](#)). Hence, a single observation with the GMRT samples the u, v -plane

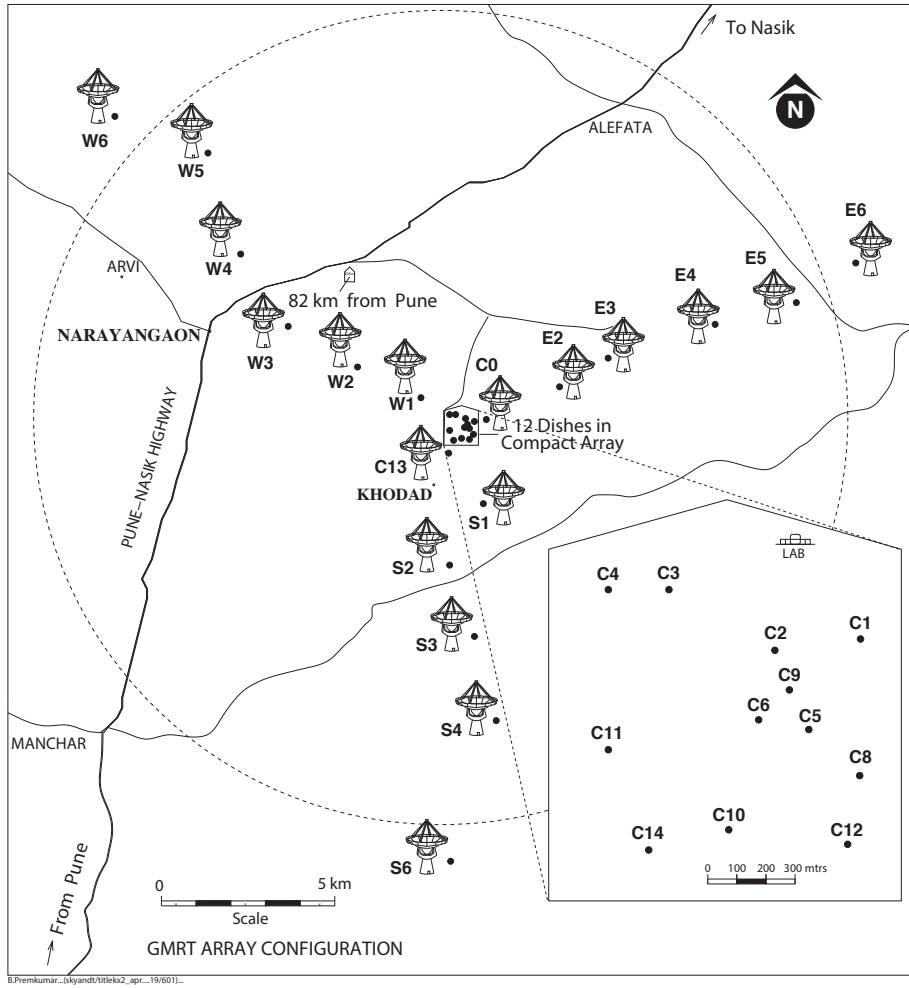


Figure 3.9.: The GMRT is an array of radio telescopes distributed in an approximate 'Y'-shaped configuration, with separations of up to 25 km. Image credit: www.gmrt.ncra.tifr.res.in.

adequately on both short and long baselines with reasonable sensitivities. The maximum instantaneous operating bandwidth at any frequency band is 32 MHz.

There is a rotating turret at the focus of each antenna on which the following feeds are mounted: 150, 325, 610/235, and the 1000 – 1450 MHz (L-band) feeds, where L-band can be subdivided into 1060, 1170, 1280 and 1390 MHz sub-bands. The reflecting surface consists of a wire mesh and the efficiency of the antennae varies from 60 – 40% from the lowest to the highest frequency. The data in [Chapter 6](#) of this thesis were taken at 325 and 610 MHz. The GMRT primary beam has a width at half power of $\approx 81'$ at 325 MHz and $\approx 43'$ at 610 MHz. The angular resolution is $\approx 9''$ at 325 MHz and $\approx 5''$ at 610 MHz.

Part II

MULTI-FREQUENCY, MULTI-SCALE INVESTIGATIONS OF LOW-MASS PROTOSTELLAR SYSTEMS

LARGE-SCALE STUDIES OF YSOS AT 16 GHz WITH AMI

In this chapter, I present 16 GHz observations of a sample of classic low-mass young stars driving outflows. These sources are selected to match the target sample for the e-MERLIN Legacy Programme at 5 GHz on the “Morphology and Time Evolution of Thermal Jets Associated with Low-mass Young Stars” (P.I. L. Rodríguez). The high spatial resolution observations provided by the e-MERLIN programme will resolve out the larger scale emission from these objects and only detect the small-scale localised emission from the central source and shocks along the length of their collimated outflows. In contrast, the data presented here will not resolve the separate components of the radio emission but will measure the integrated radio emission from these objects. This *total* radio emission at 16 GHz from YSOs has been demonstrated to show clearly defined trends with other global properties of these systems, such as bolometric luminosity, envelope mass, and outflow force (Scaife et al., 2011a,b, 2012b). If such free-free emission is to be reconciled with ionisation mechanisms arising from the impact of the molecular outflow or protostellar jet/wind on its surroundings (see Section 2.4) then it is vital to measure it in its entirety to determine quantitatively its physical correspondence to other global properties of the protostellar system. Such indirect measures of protostellar activity in the early embedded phase of YSO lifetimes may provide a window into the evolution of these objects, which is otherwise obscured.

In this chapter, I investigate the properties of the integrated radio emission from this sample of low-mass YSOs. In general, these new data confirm trends found in previous works and improve upon the statistics. I identify outliers that may provide useful targets for further study at high spatial resolution. I combine these results for the flux densities with those found in an extensive literature search to calculate the spectral indices at radio wavelengths, which are overwhelmingly consistent with free-free emission as the mechanism for the radio emission. In Section 4.1 I describe the sample of targets to be observed. In

This chapter has been published as: Ainsworth R. E., Scaife A. M. M., Ray T. P. and AMI Consortium, 2012, AMI radio continuum observations of young stellar objects with known outflows, *Monthly Notices of the Royal Astronomical Society*, 423, 1089 – 1108, doi:10.1111/j.1365 – 2966.2012.20935.x.

Section 4.2 I describe the AMI observations and the data reduction process. In Section 4.3 I comment on the results of the observations, and Section 4.4 contains detailed notes on the individual fields. In Section 4.5 I discuss the detections and non-detections, the expected contamination from extragalactic sources, the spectral energy distributions, the radio spectral indices, the derivation of physical parameters, the correlations between radio luminosity and other global properties, and, finally, evidence for variability. I summarise the results in Section 4.6.

4.1 THE SAMPLE

As detailed in Section 2.1, YSOs are divided into a number of evolutionary classes. The target sample in this work is comprised of 11 Class 0 and Class I protostars driving known outflows. The coordinates of each of these objects are listed in Table 4.1 along with their identifier. I follow the classification scheme described in Hatchell et al. (2007b) for Class 0 or Class I protostars, based on three evolutionary indicators, which for a Class I are $T_{\text{bol}} > 70 \text{ K}$, $L_{\text{bol}}/L_{\text{smm}} > 3000$, and $F_{3.6}/F_{850} > 0.003$, where $F_{3.6}$ is the flux at 3.6 cm and F_{850} is the flux at 850 μm . There are eight Class 0 and three Class I protostars in the target sample, listed in Table 4.1. A number of additional sources were detected within the AMI fields. I identify these additional sources assuming a generous threshold of 10 arcsec of a known protostellar source to allow for low signal to noise, however the maximum offset is found to be $< 4 \text{ arcsec}$. The additional sources detected are listed in Table 4.2. When combined with the original target list, these additional sources will be referred to as the “extended sample”. For the purposes of this work, all other detected sources are considered to be extragalactic and this is discussed further in Section 4.5. Physical properties of the sources including parent cloud association, distance, bolometric temperature, bolometric luminosity, envelope mass, and outflow force are listed in Table 4.3.

A number of the physical properties listed in Table 4.3 depend on the distance to the source. For example, many studies assume a distance to Perseus of 320 pc (e.g. Hatchell et al., 2007b), but here I assume a distance of $d = 250 \text{ pc}$ in order to remain consistent with the *Spitzer* “Cores to Disks” (c2d) catalogue of deeply embedded protostars (Dunham et al., 2008). Values in the literature also differ for the distance to the Taurus and Orion molecular clouds, and the values I adopt, along with their references, are listed in Table 4.3. Physical quantities from the literature have been adjusted for distance where necessary.

Table 4.1.: Sample selection and observational details. Column 1 contains the source name; 2 the protostellar evolutionary class as defined by the criteria described in [Section 4.1](#), 3 the Right Ascension in units of hours, minutes and seconds; 4 the Declination in units of degrees, minutes, and seconds; 5 the date the observation was made; 6 AMI flux calibrator; 7 AMI phase calibrator; 8 rms noise measured from recovered map; 9 major axis of AMI synthesised beam; and 10 minor axis of AMI synthesised beam.

Source	Class	RA (J2000.0)	Dec (J2000.0)	Date (dd-mm-yyyy)	1°	2°	σ_{rms} ($\mu\text{Jy beam}^{-1}$)	b_{maj} (arcsec)	b_{min} (arcsec)
L1448 IRS 3	0	03 25 36.49	+30 45 22.0	23-09-2010	3C48	J0324 + 3410	24	41.8	27.4
HH 7 – 11	I	03 29 03.73	+31 16 03.8	24-09-2010	3C48	J0324 + 3410	26	40.2	28.2
L1551 IRS 5	I	04 31 34.15	+18 08 04.8	30-09-2010	3C48	J0428 + 1732	24	50.9	27.2
L1527	0	04 39 53.87	+26 03 09.9	25-09-2010	3C48	J0440 + 2728	19	44.3	28.4
HH 1 – 2	0	05 36 22.85	–06 46 06.6	12-10-2010	3C48	J0541 – 0541	61	70.5	24.0
HH 26 IR	I	05 46 03.90	–00 14 52.5	27-08-2011	3C48	J0558 + 0044	34	78.0	28.5
HH 111	0	05 51 46.25	+02 48 29.7	06-10-2010	3C48	J0552 + 0313	31	68.7	27.4
NGC 2264 G	0	06 41 11.05	+09 55 59.2	04-10-2010	3C48	J0654 + 1004	33	54.5	26.9
Serpens SMM 1	0	18 29 49.79	+01 15 20.8	11-10-2010	3C48	J1824 + 0119	36	66.5	25.7
L723	0	19 17 53.67	+19 12 19.6	30-09-2010	3C48	J1914 + 1636	23	48.1	26.3
L1251 A	0	22 35 24.95	+75 17 11.4	25-09-2010	3C147	J2236 + 7322	25	37.6	27.8

Table 4.2.: Additional detected sources. Column 1 contains the additional source number; 2 the field the source is located in; 3 – 4 the Right Ascension and Declination of the peak flux value; 5 the AMI 16GHz combined channel flux density; 6 the spectral index α_{AMI} calculated from the AMI fluxes; 7 the associated source; and 8 the protostellar evolutionary class where applicable or object type.

AMI Source	Field	RA (J2000.0)	Dec (J2000.0)	$S_{16\text{GHz}}$ (mJy)	α_{AMI}	Associated Source	Class
1	L1448	03 25 38.9	+30 44 02	0.76 ± 0.09	-0.67 ± 0.98	L1448 C	0
2	HH 7 – 11	03 28 55.5	+31 14 35	0.39 ± 0.10	1.84 ± 0.16	NGC 1333 IRAS 2A	0
3	HH 7 – 11	03 28 57.3	+31 14 16	0.50 ± 0.10	1.65 ± 0.34	NGC 1333 IRAS 2B	I
4	L1551	04 31 44.3	+18 08 29	0.74 ± 0.09	0.61 ± 0.75	L1551 NE	0
5	L1527	04 39 49.4	+26 05 25	0.96 ± 0.09	-0.10 ± 0.92	HH 192 VLA 2	ext?
6	L1527	04 39 59.8	+26 02 06	0.88 ± 0.09	-1.25 ± 0.58	HH 192 VLA 3	ext?
7	HH 1 – 2	05 36 25.7	–06 47 16	1.00 ± 0.26	0.10 ± 1.10	HH 2	HH
8	HH 26 IR	05 46 07.4	–00 13 42	1.23 ± 0.10	1.82 ± 0.13	HH 25 MMS	0
9	HH 111	05 51 45.5	+02 50 06	0.70 ± 0.15	-0.23 ± 1.10	–	ext?
10	L1251	22 35 20.5	+75 19 44	0.71 ± 0.09	-1.20 ± 0.68	–	ext?

Table 4.3.: Source information. Column 1 contains the source name; 2 the molecular cloud association; 3 the distance to the source; 4 distance reference; 5 bolometric temperature; 6 bolometric luminosity; 7 reference for T_{bol} and L_{bol} ; 8 envelope mass calculated using the 850 μm flux from the SCUBA Legacy Fundamental Map Object Catalogue (di Francesco et al., 2008); 9 outflow force of the source; and 10 reference for the outflow force of the source.

Source	Cloud Association	d (pc)	d Ref.	T_{bol} (K)	L_{bol} ($L_{\odot}$)	Ref.	M_{env} ($M_{\odot}$)	F_{out} ($10^{-5} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$)	F_{out} Ref.
L1448 IRS 3	Perseus	250	1	53	13.7	6	16.22	$49.9 \times 10^{-2} \pm 5.29$	12
HH 7 – 11	Perseus	250	1	180	18.0	6	10.75	1.53 ± 18.0	12
L1551 IRS 5	Taurus	140	2	75	15.3	7	6.22	9.63	13
L1527	Taurus	140	2	59	2.0	8	5.89	0.79 ± 0.13	17
HH 1 – 2	Orion	420	3	–	23	9	42.46	–	–
HH 26 IR	Orion	420	3	–	25.1	10	4.68	36.1	13
HH 111	Orion	420	3	49	19.2	11	13.90	4.57	13
NGC 2264 G	Mon OB1	800	4	25	12	4	11.59	300	13
Serpens SMM 1	Serpens	260	14	56	17.3^a	15	28.17	2.8	16
L723	–	300	4	50	3	4	5.14	26	13
L1251 A	Cepheus Flare	320	5	–	2.24	5	14.83	8.6	13
L1448 C	Perseus	250	1	49	3.9	6	5.1	$16.3 \times 10^{-2} \pm 1.9$	12
NGC 1333 IRAS 2A	Perseus	250	1	58	13.9	6	2.81^b	$56.8 \times 10^{-2} \pm 5.6$	12
NGC 1333 IRAS 2B	Perseus	250	1	106	5.3	15	0.74^b	–	–
L1551 NE	Taurus	140	2	56	4.2	11	5.6	–	–
HH 25 MMS	Orion	420	3	34	5.2	4	43.96	–	–

References: (1) Dunham et al. 2008; (2) Kenyon et al. 1994; (3) Menten et al. 2007; (4) André et al. 2000; (5) Kun et al. 2009; (6) Hatchell et al. 2007b; (7) van Kempen et al. 2009; (8) Jørgensen et al. 2009; (9) Fischer et al. 2010; (10) Nisini et al. 2002; (11) Froebrich 2005; (12) Hatchell et al. 2007a; (13) Anglada 1995; (14) Straizys et al. 1996; (15) Enoch et al. 2009b; (16) Graves et al. 2010; (17) Bontemps et al. 1996.

^a Enoch et al. 2009a

^b Enoch et al. 2009b

4.2 OBSERVATIONS AND DATA REDUCTION

The data in this work were taken with the Arcminute Microkelvin Imager (AMI) Large Array at the Mullard Radio Astronomy Observatory near Cambridge, UK (Zwart et al., 2008). AMI is comprised of eight 13 m dishes, operating between 13.5 and 17.9 GHz with eight 0.75 GHz bandwidth channels. The channels 1 – 3 were not used due to a poorer response in this frequency range and interference due to geostationary satellites. The FWHM of the primary beam of the AMI is ≈ 6 arcmin at 16 GHz. See Section 3.4 for more information.

AMI data reduction is performed using the local software tool `REDUCE`. This applies both automatic and manual flags for interference, shadowing and hardware errors. `REDUCE` Fourier transforms the lag correlator data to synthesise frequency channels and performs phase and amplitude calibration before output to disk in *uv* FITS format. Flux (primary) calibration is performed using 3C48 for all fields except for L1251 where 3C147 was used, and assumed flux densities can be found in Table 4.4. Phase (secondary) calibration is carried out using the bright point sources listed in Table 4.1. Absolute calibration is typically accurate to 5% but an increased absolute calibration error of 10% is applied to flux densities from channel 8 in order to reflect the poorer phase stability of this channel relative to the others.

Table 4.4.: AMI frequency channels and primary calibrator flux densities measured in Jy.

Channel No.	4	5	6	7	8
Freq. [GHz]	14.62	15.37	16.12	16.87	17.62
3C48	1.75	1.66	1.58	1.50	1.43
3C147	2.62	2.50	2.40	2.30	2.20

Reduced data were imaged using the National Radio Astronomy Observatory’s (NRAO) Common Astronomy Software Applications package (CASA)¹. Multiple data sets were concatenated, additional baseline flagging was carried out, and the `CLEAN` task was used for deconvolution to produce the combined frequency image as well as the separate spectral channel images. Primary beam correction and fitting Gaussian models to radio sources in order to extract flux densities were performed in NRAO’s Astronomical Image Processing System (AIPS)². All errors quoted are 1σ .

¹ <http://casa.nrao.edu>

² <http://aips.nrao.edu>

4.3 RESULTS

Maps were made using naturally-weighted visibilities to ensure optimal signal-to-noise levels, except in the case of HH 1 – 2 in which uniform weighting was used to improve resolution. As HH 1 – 2 is the lowest-declination source, the beam would otherwise have been very extended. The dimensions of the synthesised beam for each source are listed in [Table 4.1](#). Source detection for these data was performed in the un-primary-beam-corrected maps, where I identified all objects within the FWHM of the AMI primary beam with a peak flux density $> 5\sigma_{\text{rms}}$, where σ_{rms} is the rms noise determined from the maps. σ_{rms} for each target field is listed in [Table 4.1](#). Integrated flux densities for detected sources were then extracted from the primary-beam-corrected maps using `IMFIT` and are listed in [Table 4.5](#). The errors on the flux densities are calculated as $\sigma = \sqrt{(0.05S_\nu)^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{rms}}^2}$, where σ_{fit} is the fitting error returned from `IMFIT` and $0.05S_\nu$ is a conservative 5% absolute calibration error (except for channel 8 where I use a 10% absolute calibration error, $0.1S_\nu$). Including σ_{fit} provides an over-estimation to the total error.

Extracted flux densities are listed in [Table 4.5](#), and column 8 of [Table 4.5](#) lists the spectral indices α_{AMI} calculated over the AMI channels. The uncertainties of these values are large due to the short frequency coverage of AMI. Spectral indices are discussed further in [Section 4.5](#). In two cases, HH 26 IR and NGC 2264, the flux density was extracted only from the 16 GHz combined-channel image. For these objects, the flux density in the combined-channel image is $< 5\sqrt{n}\sigma$, where n is the number of combined channels, indicating that the sources would be detected at $< 5\sigma$ in the individual channel maps. Combined-channel maps for each source may be found in [Appendix A](#) with the exception of L1448 IRS 3 which is shown in [Figure 4.1](#) for illustration purposes.

Table 4.5.: Integrated flux densities. Column 1 contains the source name; 2 the combined-channel 16 GHz flux density for that source; 3 – 7 contain the AMI integrated flux densities for each source from AMI channels 4 – 8; and 8 contains the spectral index α_{AMI} calculated from the AMI fluxes.

Source	$S_{16\text{ GHz}}$ (mJy)	AMI Channel Number						α_{AMI}
		4 [14.62 GHz] (mJy)	5 [15.37 GHz] (mJy)	6 [16.12 GHz] (mJy)	7 [16.87 GHz] (mJy)	8 [17.62 GHz] (mJy)		
L1448 IRS 3	2.39 ± 0.16	2.40 ± 0.25	2.34 ± 0.26	2.41 ± 0.37	2.26 ± 0.24	2.62 ± 0.37	0.20 ± 0.73	
HH 7 – 11	3.63 ± 0.24	3.43 ± 0.20	3.10 ± 0.18	3.91 ± 0.22	3.43 ± 0.19	3.83 ± 0.41	0.70 ± 0.41	
L1551 IRS 5	4.97 ± 0.27	4.74 ± 0.25	4.37 ± 0.24	4.79 ± 0.28	4.82 ± 0.29	5.48 ± 0.57	0.79 ± 0.40	
L1527	1.33 ± 0.10	1.04 ± 0.11	1.04 ± 0.14	1.12 ± 0.12	1.20 ± 0.16	1.38 ± 0.19	1.15 ± 0.57	
HH 1 – 2	1.70 ± 0.27	1.30 ± 0.28	1.53 ± 0.30	1.34 ± 0.18	1.33 ± 0.14	-	-0.17 ± 1.02	
HH 26 IR	0.39 ± 0.08	-	-	-	-	-	-	
HH 111	2.49 ± 0.20	3.11 ± 0.53	2.68 ± 0.28	2.39 ± 0.26	2.86 ± 0.30	2.51 ± 0.40	-0.40 ± 0.85	
NGC 2264 G	0.30 ± 0.22	-	-	-	-	-	-	
Serpens SMM 1	7.32 ± 0.41	8.21 ± 0.77	7.66 ± 0.55	7.04 ± 0.43	6.77 ± 0.44	7.30 ± 0.83	-0.73 ± 0.56	
L723	0.58 ± 0.09	0.58 ± 0.09	0.52 ± 0.06	0.65 ± 0.08	0.66 ± 0.07	0.52 ± 0.11	0.42 ± 0.82	
L1251 A	1.05 ± 0.12	0.86 ± 0.18	0.98 ± 0.14	1.00 ± 0.20	0.76 ± 0.16	1.10 ± 0.25	0.06 ± 0.99	

4.4 NOTES ON INDIVIDUAL FIELDS

L1448

L1448 IRS 3 is made up of the L1448 North group of Class 0 protostars: NA, NB, and NW (Curiel et al., 1990; Terebey & Padgett, 1997). AMI does not resolve the separate sources, so the data at 16 GHz (see Figure 4.1) represents the integrated radio emission from the three protostars and appears mostly point-like with respect to the beam, but exhibits slight extension in a north–south direction, with another slight bulge to the west. The spectral energy distribution of this source is shown in Figure 4.2, and includes the observed radio spectra over the AMI frequency channels 3 – 8 combined with flux densities from the literature. Spectral energy distributions and spectral indices are discussed in Section 4.5.

L1448 NA and NB are in a $7''$ separation protobinary system (Curiel et al., 1990) and L1448 NW lies approximately $20''$ northwest of L1448 NA (Terebey & Padgett, 1997) in the Perseus Molecular Cloud. The outflows in this region have been discussed extensively by Wolf-Chase et al. (2000). Only redshifted gas associated with the outflow of L1448 NA is detected in their CO maps, with a position angle (PA, measured from north through east) of $\approx 150^\circ$ and a total length of at least 0.7 pc (at their assumed distance of 300 pc). They suggest that the lack of blueshifted CO emission from L1448 NA could be due to the likelihood that the cloud boundary has been reached in this direction and that the flow has broken out of the molecular cloud. The outflow associated with L1448 NB has a PA $\approx 129^\circ$ and $6'$ to the northwest along the outflow axis lie the blueshifted optical emission knots of HH 196 (Bally et al., 1997). L1448 NB is confirmed as the exciting source for HH 196 from the CO maps of Wolf-Chase et al. (2000), where the true extent of the L1448 NB CO outflow is demonstrated for the first time. They determine that the most conservative length for the L1448 NB outflow, where the major axis is taken from the HH 196 knots through the lower end of the redshifted lobe, is $\sim 12'$. The directions of these outflows are illustrated in Figure 4.1.

L1448 C is also detected within the primary beam, which is the driving source of the high velocity outflow in L1448 (Bachiller et al., 1990). The northern (blueshifted) lobe is highly collimated within $10''$ of the source (Guilloteau et al., 1992) with bow shaped knots pointing to the northwest (PA = 159° , see Figure 4.1; Bachiller et al., 1995) before being deflected through a total angle of $\sim 32^\circ$ due to a possible collision with the core containing L1448 NA and NB (Davis & Smith, 1995; Curiel et al., 1999). The southern (redshifted) knots begin to appear after a gap of $30''$ and the jet is deflected by $\sim 20^\circ$ from its initial direction abruptly near the position of the CO “bullet” known as R3 (Bachiller et al., 1990).

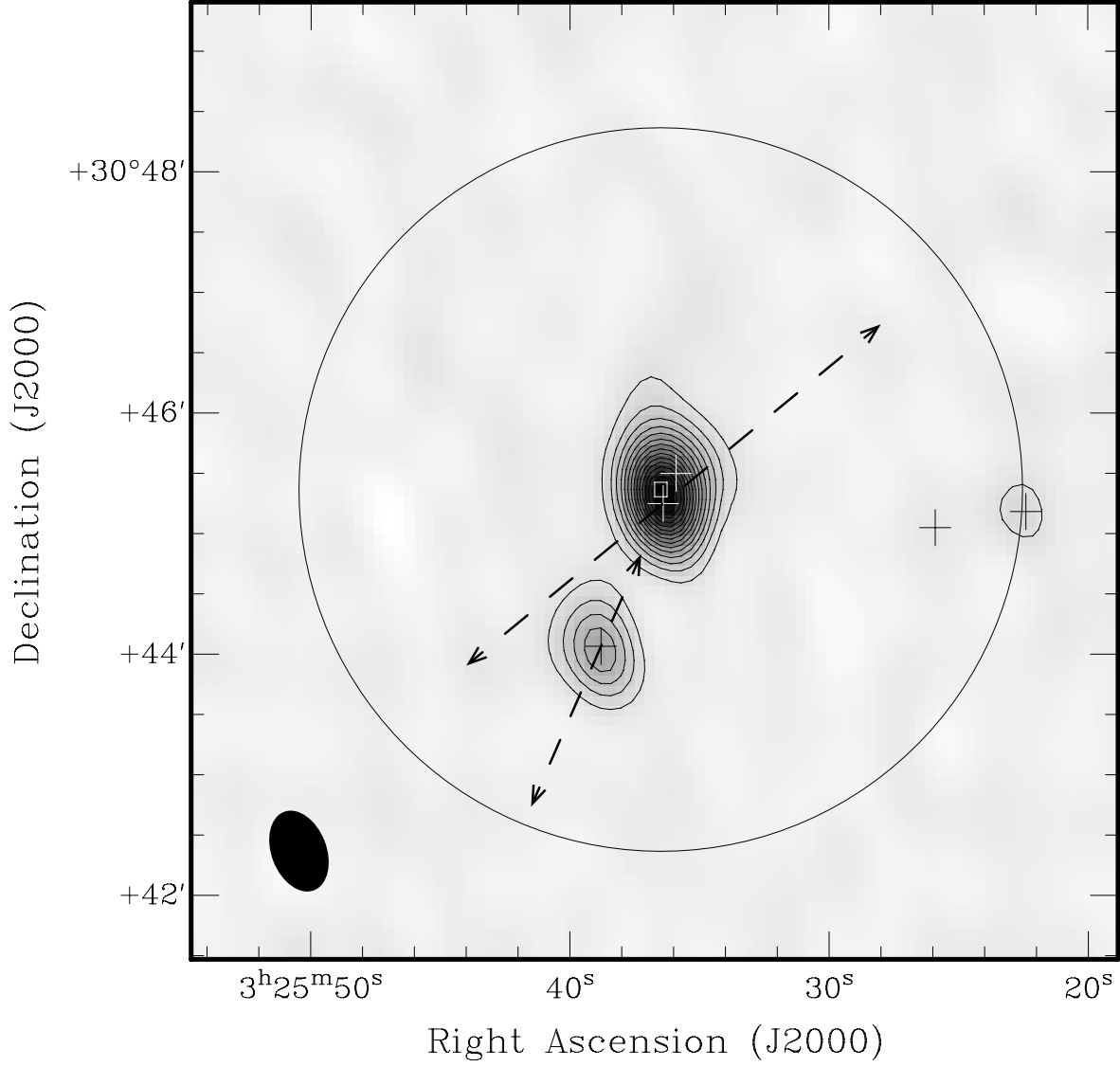


Figure 4.1.: The AMI 16 GHz combined channel map uncorrected for the primary beam response for L1448. The positions of known Class 0 YSOs are indicated as crosses (+) from [Hatchell et al. \(2007b\)](#). The dashed black lines indicate the outflow axes for L1448 NB (northern axis) and L1448 C (southern axis) from [Wolf-Chase et al. \(2000\)](#), details in [Section 4.4](#). The half power point of the primary beam is plotted as a solid circle (≈ 6 arcmin at 16 GHz) and the synthesised beam as the filled ellipse in the bottom left corner (see [Table 4.1](#)). Contours at 5, 10, 15, 20 σ_{rms} etc, where $\sigma_{\text{rms}} = 24 \mu\text{Jy beam}^{-1}$.

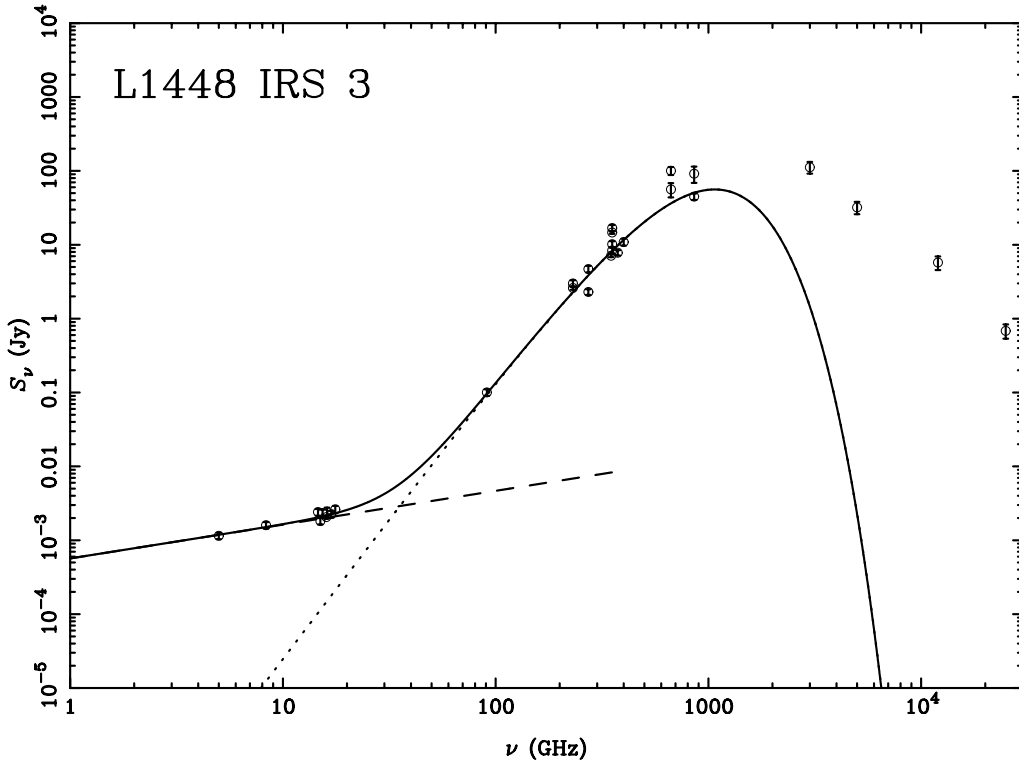


Figure 4.2.: The SED for L1448 IRS 3 with the observed radio spectra over the AMI frequency channels 3 – 8 combined with flux densities from the literature. The dashed line represents the power-law with index α' tracing the jet and the dotted line represents the modified blackbody model of the envelope/disk, with the parameters listed in [Table 4.8](#).

HH 7 – 11

The AMI 16 GHz data presented here (see [Appendix A](#)) shows emission extended in a direction almost perpendicular to the direction of the HH 7 – 11 outflow, but consistent with the distribution of objects detected with the Very Large Array (VLA) by [Rodríguez et al. \(1999\)](#), almost all of which are associated with YSOs.

HH 7 – 11 SVS 13 is a designated Class I object in NGC 1333 within the Perseus Molecular Cloud, and is generally believed to be the driving source of the chain of HH 7 – 11 knots to the southeast. However, using high-resolution VLA data, [Rodríguez et al. \(1997\)](#) propose that VLA 3, detected $\sim 6''$ southwest of SVS 13 (VLA 4), is instead the driving source of the HH 7 – 11 outflow. VLA 3 is better aligned with the HH 7 – 11 knots and the elongation of the source is approximately along the axis of the HH and molecular flows. [Rodríguez](#)

et al. (1997) suggest that SVS 13 is the driving source of a much smaller, nearby chain of HH objects to the east.

NGC 1333 *IRAS* 2A and 2B are also detected within the primary beam, which were first detected by Jennings et al. (1987) as *IRAS* 2, and subsequently by Sandell et al. (1994) who detected a quadrupolar outflow centred on the source suggesting that it might be a binary. The two sources, *IRAS* 2A and 2B, were detected at 3.6 and 6 cm by Rodríguez et al. (1999, VLA 7 and 10 respectively) who suggest that the quadrupolar outflow may originate from *IRAS* 2A and which therefore itself may be a binary.

L1551

L1551 IRS 5 is a deeply embedded multiple protostellar Class I source in the Taurus Molecular Cloud that drives a binary jet (Rodríguez et al., 2003a). At 16 GHz (see Appendix A) this source appears point-like and it has been suggested that the emission for this source near 1 cm arises from nearly equal contributions of dust emission from the disks and free-free emission from the ionised ejecta (Rodríguez, 1998).

Rodríguez et al. (2003b) have shown that the emission at centimetre wavelengths is produced by a pair of closely aligned (within $\approx 12^\circ$) bipolar ionised jets, which themselves are aligned with the larger scale bipolar molecular outflow. Lim & Takakuwa (2006) determined that L1551 IRS 5 is a triple protostellar system by identifying two main (N and S) components, separated by $\simeq 0''.3$, each comprised of a circumstellar dust disk and bipolar ionised jet, and a third component lying $\approx 0''.09$ southeast of the N component as another circumstellar dust disk.

The Class 0 source L1551 NE (Moriarty-Schieven et al., 1995) is detected to the east of IRS 5 at 1.9 cm, but is not resolved. L1551 NE has a molecular outflow and is likely to drive the HH objects 28, 29, and 454 (Devine et al., 1999). Radio continuum observations at 3.5 cm identified L1551 NE as a binary source with separation $0''.5$ (Reipurth et al., 2002).

L1527

L1527, or *IRAS* 04368 + 2557, is detected at 16 GHz as a point-source (see Appendix A). This object is an embedded Class 0 (Melis et al., 2011) protostar in the Taurus Molecular Cloud with a compact accretion disk and a $\approx 0''.2$ binary companion (Loinard et al., 2002). The HH 192 outflow associated with this object has an east-west orientation (Gomez et al., 1997) with an edge-on disk perpendicular to the outflow axis (Tobin et al., 2010) that is infalling onto the central source (Ohashi et al., 1997). Scaife et al. (2012a) found an opacity index $\beta = 0.32 \pm 0.04$ for this source, consistent with the presence of large dust grains, or *pebbles*, in the disk.

HH 192 VLA 2 and 3 (Rodríguez & Reipurth, 1998) are also detected at 16 GHz. There are no other references to these objects in the literature. A spectral index of $\alpha_{\text{AMI}} = -0.10$ is found for VLA 2 consistent with optically thin free-free emission and $\alpha_{\text{AMI}} = -1.25$ for VLA 3 which is inconsistent with free-free emission and suggests that it could be extragalactic. For the purposes of this work, VLA 2 and 3 are considered to be extragalactic sources (see Section 4.5) although the emission from VLA 2 could be consistent with an HII region.

HH 1 – 2

At 16 GHz, the HH 1 – 2 driving source is detected as a point source (see Appendix A). HH 1 and 2 are considered to be the prototypes of the HH phenomena, displaying two bright bow shocks which expand as a part of a bipolar outflow moving away from the central source that drives a finely collimated jet (see Figure 2.7; Rodríguez et al., 2000). The Class 0 driving source of HH 1 and 2, VLA 1, was detected as a centimetre continuum radio source by Pravdo et al. (1985), and subsequent observations have shown that the source powers a small thermal radio jet along the axis of the HH flow (see Figure 2.7; Rodríguez et al., 1990). Another source, VLA 2, was found 3'' from VLA 1, producing the HH 144 flow which is at a large angle to the HH 1 flow axis. AMI does not resolve the two sources VLA 1 and 2 and the combined thermal emission is approximately point-like.

The Herbig–Haro objects HH 1 and HH 2 themselves have been previously detected at centimetre wavelengths (e.g. Rodríguez et al., 1990, 2000) and HH 2 is detected but HH 1 is not at 16 GHz. Rodríguez et al. (1990) find a flux density of 0.78 mJy at 2 cm for HH 1, however I constrain an upper flux density limit of 0.34 mJy, suggesting that this source is variable. Radio continuum emission from other HH objects has been found to be time variable (Rodríguez et al., 2008a; Carrasco-González et al., 2010b). Rodríguez et al. (1990) find flux densities of 1.75 mJy for the central source and 0.98 mJy for HH 2, for which these data are consistent.

HH 26 IR

HH 26 IR is detected weakly at 16 GHz (see Appendix A), and is a Class I protostar (Davis et al., 1997) located within the L1630 cloud in Orion that drives a molecular outflow. L1630 is rich in star formation activity and has a complex morphology. Two embedded Class 0 protostars, HH 24 MMS and HH 25 MMS, are also in this star formation region and both have compact jets, while HH 26 IR drives a more extended outflow (Gibb & Heaton, 1993). H₂ knots HH 26A, B, C, and D exist along the axis of the HH 26 IR outflow which is

approximately orthogonal to the HH 25 outflow (Davis et al., 1997). HH 25 MMS is also detected within the AMI primary beam to the northeast of HH 26 IR.

HH 111

At 16 GHz, HH 111 (see Appendix A) is significantly extended along an approximate north–south direction, perpendicular to the known outflow direction. The driving source is IRAS 05491 + 0247, a suspected Class I binary source (Yang et al., 1997) that drives a bipolar molecular outflow. The outflow was first discovered in the optical by Reipurth (1989). However, based on the classification criterion defined in Section 2.1 and Section 4.1, this source has a bolometric temperature consistent with a Class 0 object and this is discussed further in Section 4.5. The jet is well-collimated, aligned approximately in the east–west direction, and has knots with velocities ranging from 300 to 600 km s^{−1} for different parts of the jet complex (Reipurth et al., 1992). It was found that the optical jet is part of a giant HH complex extending over 7.7 pc (Reipurth et al., 1997).

Near-infrared observations (Gredel & Reipurth, 1994) revealed a second bipolar flow, HH 121, emerging from around the same position as the optical outflow and is aligned approximately in the north–south direction, consistent with the extension observed here. Such a quadrupolar outflow is indicative of a binary companion. 3.6 cm (Reipurth et al., 1999) and 7 mm (Rodríguez et al., 2008b) VLA observations suggest a common origin within $\approx 0''.1$. It has been suggested that the most viable interpretations for the structure are that the observations are of two orthogonal disks around separate protostars or a disk with a perpendicular jet (Rodríguez et al., 2008b).

NGC 2264

Emission from NGC 2264 G is detected at $5\sigma_{\text{rms}}$ in the AMI combined-channel map (see Appendix A). The NGC 2264 G molecular outflow was one of nine discovered in a CO survey of the Monoceros OB1 cloud conducted by Margulis & Lada (1986) and was found to have very high velocity emission and a well-collimated, bipolar morphology (Margulis et al., 1988). It is centred on IRAS 06384 + 0958 and extends ≈ 1.6 pc in an approximately east–west direction (Caratti o Garatti et al., 2006). Lada & Fich (1996) show that the outflow is S-shaped and symmetric with respect to the driving source, VLA 2, which was detected by Gómez et al. (1994) using VLA ammonia observations. They obtained a spectral index for the outflow of $\alpha \simeq 0.3 \pm 0.2$ which is consistent with optically thin free–free emission of a thermal jet, and their 3.6 cm VLA images show VLA 2 to be elongated in the direction of the outflow. Subsequent observations of VLA 2 by Ward-Thompson et al. (1995) using the

James Clerk Maxwell Telescope (JCMT) obtained a ratio of sub-millimetre and bolometric luminosity indicative of a Class 0 protostar.

Serpens

At 16 GHz, AMI does not resolve the triple radio source SMM 1 but measures the integrated radio emission. The emission is oriented in an approximate north–south direction (see [Appendix A](#)), despite the outflow orientation of northwest–southeast which could be due to the presence of multiple objects in this region. The Serpens Molecular Cloud is a nearby star formation region containing clusters of low-mass protostars as well as several HH objects and outflows. The most luminous and most deeply embedded object in the Serpens cloud core is the triple radio source SMM 1, comprised of a central source, a NW component, and a SE component, and is a known Class 0 source associated with a highly collimated radio continuum jet ([Rodríguez et al., 1989b](#)).

[Curiel et al. \(1993\)](#) presented high-sensitivity, multi-frequency VLA radio continuum observations of the triple radio source, showing a one-sided radio jet morphology, but did not detect a counter jet. These authors show that the central source is extended at 3.6 cm, but the difference between the direction of the major axis and the orientation of the radio jet appear to be significant, suggesting that the central source is precessing or nutating. They find that the central source has a spectral index $\alpha \simeq 0.15 \pm 0.09$, consistent with the value of $\alpha \simeq 0.1 \pm 0.1$ obtained by [Rodríguez et al. \(1989b\)](#), while the NW and SE components have spectral indices $\alpha \simeq -0.05 \pm 0.05$ and $\alpha \simeq -0.30 \pm 0.04$ respectively. These results suggest a thermal origin for the emission associated with the central source and the NW component, and a borderline thermal/non-thermal origin for the SE component. [Scaife et al. \(2012b\)](#) present evidence for radio variability in SMM 1, as previously suggested by [Enoch et al. \(2009a\)](#) who detect a high mass disk around the source. Here I adopt a bolometric luminosity of $L_{\text{bol}} = 17.3 L_{\odot}$ ([Enoch et al., 2009a](#)), however I note that significantly higher luminosities have been reported for this object (e.g. $46 L_{\odot}$ from [Hurt & Barsony, 1996](#)).

L723

L723, also known as *IRAS 19156 + 1906*, appears point-like at 16 GHz (see [Appendix A](#)). L723 is a designated low-mass, Class 0 object ([Lee et al., 2002](#)). The associated outflow consists of a pair of bipolar lobes aligned along the east–west direction and another pair of bipolar lobes aligned roughly in the north–south direction, with *IRAS 19156 + 1906* located at their common centre ([Lee et al., 2002](#)). VLA observations at 3.6 cm reveal two sources, VLA 1 and VLA 2, toward the centre of the outflow ([Anglada et al., 1991](#)), although VLA 1

is likely a background source (Anglada et al., 1996; Girart et al., 1997). VLA 2 has a jet-like morphology and partially optically thick free-free emission, characteristic of a thermal radio jet, and was first identified as the powering source of the east–west pair of molecular lobes by Anglada et al. (1996). Recent VLA observations by Carrasco-González et al. (2008) at 3.6 cm and 7 mm resolve VLA 2 into several components and the two brightest sources at 3.6 cm, VLA 2A and 2B, are separated by $\approx 0''.29$.

L1251

The emission at 16 GHz of L1251 A is detected as a point-source (see Appendix A). L1251 A is a star-forming region toward Cepheus, and is centred on the bright source *IRAS* 22343 + 7501 which is associated with a large-scale ($\sim 10'$) molecular outflow (Sato & Fukui, 1989; Schwartz et al., 1988). VLA observations (Meehan et al., 1998; Beltrán et al., 2001; Reipurth et al., 2004) show several radio sources (VLA 6, 7, and 10) within this region that could possibly drive the molecular outflow. Reipurth et al. (2004) show two sources with clear extensions, VLA 7 and 10, and suggest that VLA 10 could drive the molecular outflow found by Sato & Fukui (1989), which extends for $10'$ in the approximate northeast–southwest direction. However, VLA 7 is consistent with the outflow found by Schwartz et al. (1988) that has an outflow direction in an almost perpendicular direction, and the emission detected with AMI is consistent with this. AMI does not resolve these sources, but measures the integrated radio emission.

4.5 DISCUSSION

4.5.1 Detections and Non-detections

100% of the objects in the target sample are detected with AMI at 16 GHz, which includes eight Class 0 and three Class I protostars based on the classification scheme described in Section 2.1 and Section 4.1. Four additional Class 0 and one additional Class I sources are detected within the AMI primary beam of these fields.

In the L1448 field there is one Class 0 source (31; Hatchell et al., 2007b) that is not detected, in the HH 7 – 11 field there is one Class 0 (62; Hatchell et al., 2007b) and one Class I (50; Hatchell et al., 2007b) that are not detected, and in the Serpens field there is one Class 0 (VLA 5; Scaife et al., 2012b) and two Class I (VLA 9, 16; Scaife et al., 2012b) sources that are not detected.

I identify AMI 7 as the radio counterpart to HH 2, but HH 1 is not detected at 16 GHz even though it has been previously detected at centimetre wavelengths. Additionally, none

Table 4.6.: Summary of detection statistics. The original sample includes only objects listed in Table 4.1. The extended sample includes all objects listed in Table 4.1 and Table 4.2, inclusive of the original sample.

Class	Present	Detected	%
<i>Original Sample:</i>			
Class 0	8	8	100
Class I	3	3	100
<i>Extended Sample:</i>			
Class 0	15	12	80
Class I	7	4	57

of the HH 192 objects are detected in the L1527 field which lie within the AMI primary beam.

Detection statistics for the original and extended samples divided by evolutionary class are listed in Table 4.6. It is not surprising that 100% of the target sample is detected as all sources have been previously detected at centimetre wavelengths and have known radio jets. Therefore, the original sample is biased, and for these reasons it is difficult to draw strong statistical conclusions from this sample. Detection rates for Class 0 objects in the extended sample is typical compared to Scaife et al. (2011b, 2012b) but high for Class I. This is likely due to the small sample size or the fact that a majority of the extended sample consists of the original sample which was chosen on the basis that these objects have been detected at these wavelengths before.

4.5.2 Expected Contamination by Extragalactic Radio Sources

At 16 GHz, a certain number of extragalactic radio sources are expected to be seen within each of the fields. Following Scaife et al. (2011a,b, 2012b), I quantify this number using the 15 GHz source counts model from de Zotti et al. (2005) scaled to the 10C survey source counts (Davies et al., 2011). The average rms noise from these data is $\simeq 30 \mu\text{Jy beam}^{-1}$ and therefore this model predicts that there should be $0.043 \text{ sources arcmin}^{-2}$, or $\simeq 2$ radio sources within a 6 arcmin FWHM primary beam above a $5\sigma_{\text{rms}}$ flux density of $150 \mu\text{Jy}$. Accounting for the radial attenuation of the primary beam, $\approx 10 \pm 3$ extragalactic radio sources are therefore expected within the target fields. Making the assumption that all sources which cannot be identified with a previously known protostellar object are extragalactic, there are 4 radio sources, lower than predicted but consistent at the 2σ level. The low number of extragalactic sources detected in these fields compared to the model may represent an over-estimation from the 15 GHz source counts, which are extrapolated

from a completeness limit of 0.5 mJy and is high compared with the detection limit of 0.15 mJy. One break in the observed source counts is already known at mJy flux density levels (Davies et al., 2011) and it is possible that a further break exists below 0.5 mJy.

4.5.3 Spectral Energy Distributions

I conducted an extensive literature search for unresolved, integrated flux densities to include in the spectral energy distribution for each source. It should be noted that Wendker (1995) was a useful reference. High resolution data that were highly discrepant due to flux loss or data with high uncertainties (e.g. 450 μm data from di Francesco et al., 2008) were not included. Spectral energy distributions are shown in Figure 4.2, Figure 4.3, and Appendix B, with the maximum likelihood models from Table 4.8 overlaid. The list of archival data used in the spectral energy distributions can be found in Appendix C. Where uncertainties were not provided, an error of 10% was used in the model fittings and this is indicated by a [†] in Appendix C. Only data $\nu < 3 \text{ THz}$ ($\lambda > 100 \mu\text{m}$) were included in the fit, but IRAS data $\nu > 3 \text{ THz}$ are included in the plots for illustration.

Maximum Likelihood SED Fitting

Power-law spectral indices, α_{AMI} , were fitted to the AMI channel data alone for each object, see Table 4.2 and Table 4.5, using the Markov Chain Monte Carlo based Maximum Likelihood algorithm METRO (Hobson & Baldwin, 2004). The fit is of the form:

$$S_\nu \propto \nu^{\alpha_{\text{AMI}}} \quad (4.1)$$

where S_ν is the flux density measured at frequency ν .

METRO was then used to fit a combined radio power-law, with spectral index α' , and blackbody model to the larger dataset for each source. This fit utilised data at wavelengths longer than 100 μm and had the form:

$$S_{\text{total}} = S_1 + S_2 = K_1 \left(\frac{\nu}{\nu_1} \right)^{\alpha'} + K_2 \frac{\nu^\beta B_\nu(T_d)}{\nu_2^\beta B_{\nu_2}(T_d)}, \quad (4.2)$$

where β is the dust opacity index, B_ν is the Planck function for a dust temperature T_d , K_1 is the normalised flux density at $\nu_1 = 16 \text{ GHz}$ and K_2 is the normalised flux density at $\nu_2 = 300 \text{ GHz}$. Fitting was performed in two scenarios to obtain the maximum likelihood values for the spectral index α' of each source. These two scenarios are:

- (i) fixing the dust temperature based on evolutionary class, and
- (ii) allowing the dust temperature to be fitted as a free parameter.

It can be seen that when $\nu = \nu_1$, S_1 equals K_1 , the normalised flux density at 16 GHz and when $\nu = \nu_2$, S_2 equals K_2 , the normalised flux density at 300 GHz, and we define these parameters as S_{16}^{norm} and S_{300}^{norm} respectively. Uniform and separable priors were used for all parameters, with ranges

$$\Pi = \Pi_\alpha(-2, 2)\Pi_\beta(0, 3)\Pi_{T_d}(5, 45). \quad (4.3)$$

The Greybody Contribution

When $\nu = \nu_1 = 16$ GHz, the free-free component should dominate the total flux density S_{total} , however at 16 GHz there is also expected to be a small contribution to the radio flux density of protostars due to the long wavelength tail of the thermal dust emission from the envelopes around these objects (e.g. [Scaife et al., 2012a](#)).

It is important to separate the greybody component from the free-free emission and I calculate this predicted contribution to the 16 GHz flux density in the following way:

$$S_{\text{gb},16} = f(K_2, \beta, T_d) = K_2 \frac{\nu^\beta B_{16}(T_d)}{\nu_2^\beta B_{300}(T_d)}, \quad (4.4)$$

with an associated error

$$\sigma_{S,16}^2 = \left(\frac{\partial f}{\partial K_2} \sigma_{K_2} \right)^2 + \left(\frac{\partial f}{\partial \beta} \sigma_\beta \right)^2 + \left(\frac{\partial f}{\partial T_d} \sigma_{T_d} \right)^2, \quad (4.5)$$

where $\nu = 16$ GHz, $\nu_2 = 300$ GHz, and σ_{K_2} , σ_β and σ_{T_d} are the uncertainties on K_2 , β and T_d respectively and listed in [Table 4.7](#) and [Table 4.8](#). In all cases, I find that the error, $\sigma_{S,16}$, is dominated by the uncertainty on β . For example, in the case of L1448 IRS 3: $\sigma_{S,16}^2 = 4.39^2 + 75.8^2 + 14.3^2 \mu\text{Jy}^2$.

The value of $S_{\text{gb},16}$ is subtracted from the measured 16 GHz flux density to remove the contribution of thermal dust emission and obtain values of only the radio emission due to the outflow component at 16 GHz, $S_{\text{rad},16}$. This is to ensure that the values used do not include contributions from the thermal dust tail which varies greatly between sources and which might therefore influence any conclusions being drawn from the correlations examined in a later section of this chapter. I compute the radio luminosity $S_{\text{rad},16} d^2$ using the greybody-subtracted radio flux densities and the distance values listed in [Table 4.3](#) to use in the correlations in [Section 4.5.6](#). If the greybody subtracted flux density is not distinct from zero by $> 3\sigma$, I consider the radio luminosity consistent with zero (see [Table 4.7](#) and [Table 4.8](#)).

Table 4.7.: Model results for fixed T_d . Column 1 contains the source name; 2 the spectral index; 3 the opacity index; 4 the dust temperature, where 15 K was used for Class 0 sources and 20 K for Class I; 5 the normalised flux density at 16 GHz; 6 the normalised flux density at 300 GHz; 7 the predicted greybody contribution at 16 GHz; and 8 the radio luminosity measured at 16 GHz with the predicted thermal dust contribution subtracted. “UC” is used to indicate that the parameter is unconstrained.

Source	α'	β	T_d (K)	S_{16}^{norm} (mJy)	S_{300}^{norm} (Jy)	$S_{\text{gb},16}$ (μJy)	$S_{\text{rad},16}d^2$ (mJy kpc ²)
L1448 IRS 3	0.37 ± 0.09	1.48 ± 0.05	15	1.88 ± 0.09	4.96 ± 0.15	297.47 ± 52.50	0.131
HH 7 – 11	1.12 ± 0.04	1.92 ± 0.02	20	3.03 ± 0.08	5.30 ± 0.19	77.96 ± 4.83	0.222
L1551 IRS 5	0.10 ± 0.04	1.52 ± 0.14	20	3.90 ± 0.17	4.47 ± 0.43	214.58 ± 130.38	0.093
L1527	0.17 ± 0.08	0.96 ± 0.10	15	0.85 ± 0.05	0.49 ± 0.02	134.94 ± 52.75	0.023
HH 1 – 2	0.23 ± 0.04	2.38 ± 0.08	15	1.49 ± 0.07	0.99 ± 0.02	4.33 ± 1.25	0.299
HH 26 IR	UC	0.62 ± 0.07	20	0.04 ± 0.06	0.56 ± 0.03	372.00 ± 101.97	–
HH 111	0.88 ± 0.07	1.66 ± 0.07	15	2.16 ± 0.09	0.90 ± 0.02	31.95 ± 8.81	0.434
NGC 2264 G	-0.29 ± 0.24	1.44 ± 0.39	15	0.50 ± 0.10	0.54 ± 0.65	37.06 ± 192.75	–
Serpens SMM 1	-0.06 ± 0.02	1.47 ± 0.05	15	6.89 ± 0.14	5.22 ± 0.20	327.71 ± 56.62	0.473
L723	-0.26 ± 0.09	1.83 ± 0.07	15	0.58 ± 0.03	0.93 ± 0.05	20.04 ± 5.15	0.050
L1251 A	1.79 ± 0.15	2.92 ± 0.27	15	0.91 ± 0.07	0.32 ± 0.07	0.29 ± 0.51	0.107
L1448 C	1.12 ± 0.12	2.10 ± 0.04	15	0.53 ± 0.02	1.64 ± 0.04	16.25 ± 2.41	0.046
NGC 1333 IRAS 2A	2.42 ± 0.07	2.01 ± 0.05	15	0.43 ± 0.02	1.52 ± 0.10	19.33 ± 3.67	0.023
NGC 1333 IRAS 2B	1.31 ± 0.05	1.95 ± 0.09	20	1.02 ± 0.04	0.53 ± 0.04	7.16 ± 2.69	0.031
L1551 NE	-0.13 ± 0.31	1.41 ± 0.03	15	0.60 ± 0.09	1.83 ± 0.02	136.09 ± 11.08	0.012
HH 25 MMS	2.13 ± 0.04	1.68 ± 0.16	15	0.97 ± 0.07	0.83 ± 0.10	27.82 ± 22.30	0.212

Table 4.8.: Model results for variable T_d . Column 1 contains the source name; 2 the spectral index; 3 the opacity index; 4 the dust temperature; 5 the normalised flux density at 16 GHz; 6 the normalised flux density at 300 GHz; 7 the predicted greybody contribution at 16 GHz; and 8 the radio luminosity measured at 16 GHz with the predicted thermal dust contribution subtracted. “UC” is used to indicate that the parameter is unconstrained.

Source	α'	β	T_d (K)	S_{16}^{norm} (mJy)	S_{300}^{norm} (Jy)	$S_{\text{gb},16}$ (μJy)	$S_{\text{rad},16}d^2$ (mJy kpc ²)
L1448 IRS 3	0.46 ± 0.09	1.81 ± 0.12	10.77 ± 0.95	2.02 ± 0.09	5.13 ± 0.12	145.74 ± 77.31	0.140
HH 7 – 11	1.28 ± 0.04	3.00 ± 0.08	12.53 ± 0.90	3.24 ± 0.07	6.21 ± 0.27	4.92 ± 1.59	0.227
L1551 IRS 5	0.09 ± 0.03	1.46 ± 0.05	26.74 ± 2.07	3.87 ± 0.09	4.54 ± 0.17	233.58 ± 43.54	0.093
L1527	0.20 ± 0.08	0.81 ± 0.11	44.86 ± 1.57	0.86 ± 0.06	0.44 ± 0.03	138.81 ± 60.00	0.023
HH 1 – 2	0.21 ± 0.04	2.18 ± 0.19	16.93 ± 1.80	1.46 ± 0.07	1.01 ± 0.02	7.35 ± 7.38	0.299
HH 26 IR	UC	0.66 ± 0.16	17.36 ± 5.25	0.04 ± 0.09	0.59 ± 0.04	368.59 ± 300.38	–
HH 111	0.84 ± 0.07	1.55 ± 0.17	17.33 ± 3.68	2.11 ± 0.10	0.90 ± 0.02	41.31 ± 35.89	0.366
NGC 2264 G	-0.31 ± 0.11	1.71 ± 0.13	18.30 ± 1.88	0.49 ± 0.06	0.36 ± 0.02	10.02 ± 5.59	0.186
Serpens	-0.07 ± 0.02	1.25 ± 0.04	28.54 ± 1.54	6.74 ± 0.14	4.85 ± 0.18	451.87 ± 71.01	0.464
L723	-0.29 ± 0.09	1.59 ± 0.13	17.56 ± 1.31	0.56 ± 0.04	0.92 ± 0.04	37.73 ± 20.70	0.049
L1251 A	1.70 ± 0.14	2.27 ± 0.41	20.85 ± 4.36	0.86 ± 0.07	0.38 ± 0.06	1.98 ± 7.84	0.107
L1448 C	1.17 ± 0.15	2.22 ± 0.11	12.70 ± 1.25	0.54 ± 0.03	1.69 ± 0.04	12.88 ± 5.99	0.047
NGC 1333 IRAS 2A	2.56 ± 0.03	2.76 ± 0.19	9.85 ± 1.10	0.46 ± 0.02	1.17 ± 0.07	2.22 ± 2.20	0.024
NGC 1333 IRAS 2B	1.40 ± 0.05	2.89 ± 0.26	9.55 ± 1.90	1.06 ± 0.03	0.57 ± 0.06	0.76 ± 1.28	0.031
L1551 NE	UC	0.78 ± 0.05	40.64 ± 3.29	0.17 ± 0.07	1.69 ± 0.02	585.75 ± 0.05	–
HH 25 MMS	UC	0.55 ± 0.09	41.27 ± 3.65	0.004 ± 0.18	1.51 ± 0.09	1021.76 ± 352.26	–

Comparison of the Two Scenarios

In Scenario (i), METRO was run by fixing T_d to 15 K for Class 0 objects and to 20 K for Class I objects, and allowing the other parameters to be fitted as free parameters to determine their maximum likelihood values. Overall, fixing the dust temperature provided reasonable fits to the spectral energy distributions, with the exception of L1527, NGC 2264 G, Serpens SMM 1, and L1551 NE where it provided a poor fit to the greybody peaks. The results for the maximum likelihood values of α' , β , S_{16}^{norm} and S_{300}^{norm} in each case are listed in [Table 4.7](#), along with the dust temperature used (columns 2 – 6), the greybody contribution at 16 GHz (column 7), and the radio luminosity at 16 GHz with the greybody contribution subtracted out (column 8). A weighted average spectral index of $\bar{\alpha}' = 0.20 \pm 0.41$ is found for the original sample, consistent with free–free emission from a collimated jet, and a dust opacity index of $\bar{\beta} = 1.75 \pm 0.36$ consistent with the value for the interstellar medium (ISM). Quoted errors represent the standard deviation of the distribution of values, rather than the standard error on the mean.

In Scenario (ii), I do not fix T_d and allow the algorithm to determine the maximum likelihood value for this parameter along with α' , β , S_{16}^{norm} and S_{300}^{norm} . The results for these parameters along with $S_{\text{gb},16}$ and $S_{\text{rad},16}d^2$ are listed in [Table 4.8](#). Again, a weighted average spectral index of $\bar{\alpha}' = 0.20 \pm 0.46$ is found for the original sample consistent with free–free emission from a collimated jet. An opacity index of $\bar{\beta} = 1.52 \pm 0.56$ and a dust temperature $\bar{T}_d = 18.46 \pm 9.77$ K are found for the original sample.

In the first scenario, with fixed T_d , 80% of the sources in the original sample for which the spectral indices could be constrained had maximum likelihood values of $-0.1 < \alpha' < 2$, consistent with free–free emission. In the second scenario, with T_d varying, again 80% of the sources in the original sample had α' consistent with free–free emission. In both cases, NGC 2264 G and L723 have spectral indices $\alpha' < -0.1$, inconsistent with free–free emission and suggestive of non-thermal emission. The one source for which an accurate value of α' is unconstrained in the original sample is HH 26 IR, due to insufficient low-frequency data. Unconstrained parameters are indicated in [Table 4.7](#) and [Table 4.8](#) by “UC”. Since α' is unconstrained for HH 26 IR, the algorithm attributes all the flux density at 16 GHz to thermal dust emission, resulting in a value of $S_{\text{rad},16}d^2 \approx 0$ when subtracted from the AMI flux density. Consequently, it does not appear in the correlations in [Section 4.5.6](#).

A spectral index of $\alpha > 2$ is generally considered un-physical for free–free emission, and is attributed to dust emission. In the cases where the likelihood distribution pushed the upper limit of the prior range, I increased the prior range to $\Pi_\alpha(-2, 3)$. In the extended sample, NGC 1333 IRAS 2A has $\alpha' > 2$ in both model scenarios, suggesting that the lower frequency data is an extension of the greybody emission and that there is no free–free component. This will not be reflected accurately in the calculation of the greybody emission at 16 GHz since the algorithm constrains a separate α' component, and this will in

turn affect the radio luminosity calculated for this source and the correlations discussed in Section 4.5.6. When T_d is fixed in Scenario (i), HH 25 MMS also has $\alpha' > 2$, suggesting that it is purely greybody emission. This will have the same consequences as for NGC 1333 IRAS 2A. However, α' is unconstrained for HH 25 MMS when T_d is allowed to vary in Scenario (ii) and this will have the reverse affect on the radio luminosity. Examining the SED plot (see Appendix B), it is possible that HH 25 MMS has a free-free component based on one or two data points, but the model is unable to constrain it without more low-frequency data.

For L1551 NE, α' is constrained in Scenario (i) but not in Scenario (ii). Consequently, the calculated radio luminosities differ significantly between the two scenarios and this will affect the correlations in Section 4.5.6. Specifically, $S_{\text{rad},16}d^2$ is a factor of 4.3 higher when T_d is allowed to vary than when it is fixed to 15 K (see Table 4.7 and Table 4.8). When T_d is fixed for this source, the peak of the greybody is constrained by the given dust temperature (and does not fit the higher frequency data), allowing the algorithm to determine α' using the two low-frequency data points (see Figure 4.3a). However, when T_d is allowed to vary, the AMI data point at 16 GHz is fit as part of the greybody emission and α' is left unconstrained, as there is only one remaining low-frequency data point (see Figure 4.3b). This results in a more significant greybody contribution at 16 GHz. Therefore the radio luminosity will be significantly lower when $S_{\text{gb},16}$ is subtracted in this scenario compared to that when the dust temperature is fixed, and this will drastically change its position on the correlation plots between the two scenarios. The same situation is also found in the case of HH 25 MMS.

4.5.4 Dust Temperatures

In Scenario (ii), where T_d varies, the results for T_d range between 9 – 45 K. Values in the literature for the dust temperatures associated with Class 0 and I sources are found to range between 10 – 40 K (Reipurth et al., 1993; Dent et al., 1998; Shirley et al., 2002; Young et al., 2003; Hatchell et al., 2007b). Dent et al. (1998) find that their sample of Class 0 protostars can be fitted with optically thin emission, opacity indices between 1 – 1.5, and dust temperatures between 20 – 30 K. For their Class I sources, these authors derive opacity indices between 1 – 2 and dust temperatures of ~ 30 K, with which the results in this work are consistent.

For Class 0 sources, I find weighted average values of $\bar{\beta} = 1.35 \pm 0.29$ and $\bar{T}_d = 20.1 \pm 10.89$ K, and for Class I sources I find $\bar{\beta} = 1.81 \pm 0.74$ and $\bar{T}_d = 14.85 \pm 5.15$ K. These results are reversed from what is expected based on the first SED scenario, but this is likely to be due to the low number of Class I sources in our sample compared to Class 0. Scaife et al. (2012a) find $\beta = 0.3$ for L1527 by fitting data from 5 GHz to 350 GHz jointly using the sum

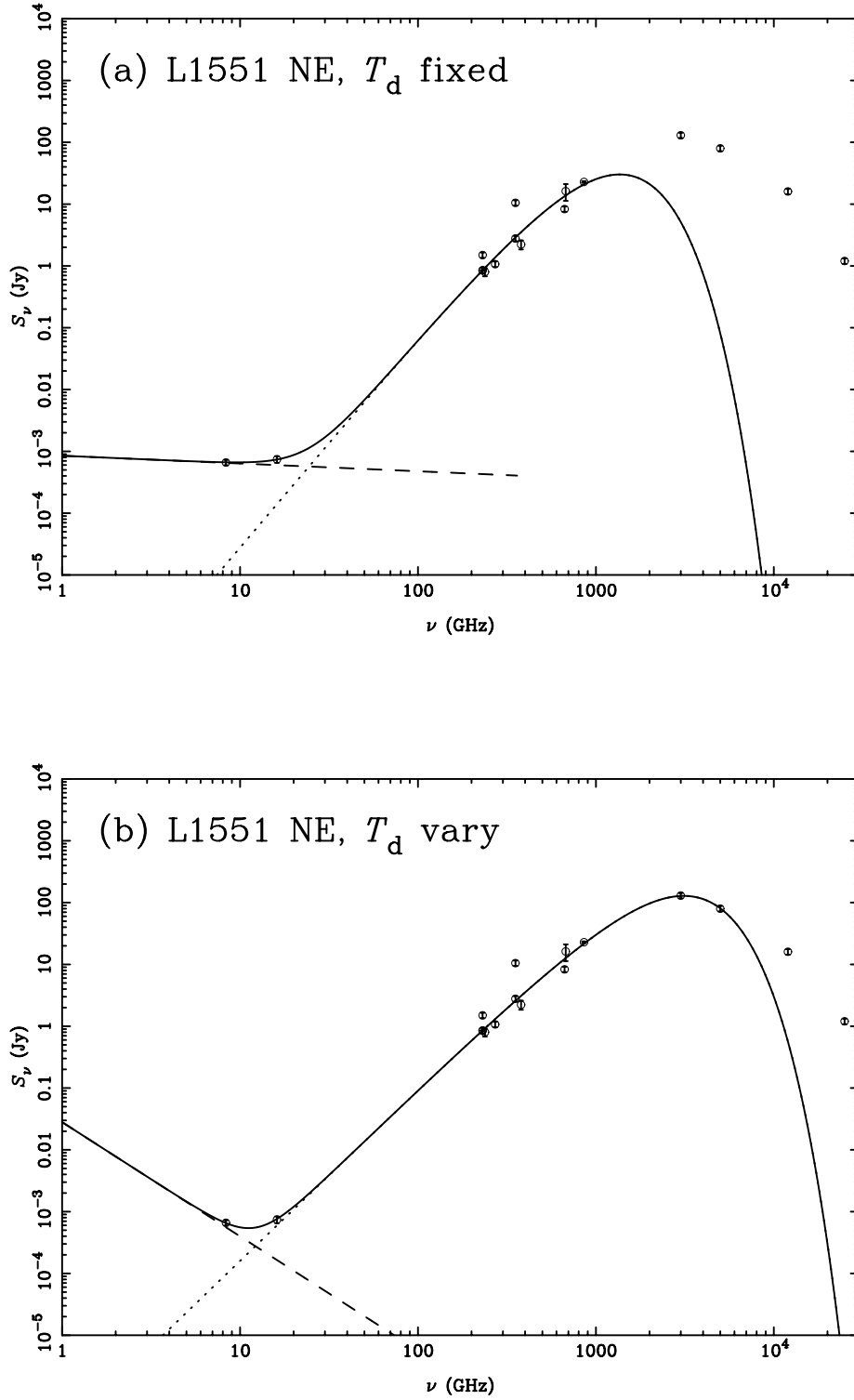


Figure 4.3.: The spectral energy distribution fits for L1551 NE when (a) $T_d = 15$ K, and (b) when T_d is allowed to vary. In the first case, the method determines α' for the two low-frequency data points, but in the second case the AMI data point is fit as greybody emission and α' is unconstrained. The same situation is also found in the case of HH 25 MMS but no other sources suffer from this discrepancy between the two scenarios.

of two power-laws, which is slightly shallower than the value of $\beta = 0.81 \pm 0.11$ found in this work. However, both are consistent with the value of $\beta \leq 1$, indicating the presence of large dust grains.

4.5.5 Radio Spectral Indices

Typically, the radio emission detected at centimetre wavelengths for Class 0 and I protostars is observed to possess a flat or rising spectrum, indicating that it occurs as a consequence of free-free radiation from ionised gas (see [Section 2.4](#) and [Section 3.2](#)). Unresolved sources can exhibit partially opaque spectra with spectral indices in the range $-0.1 \leq \alpha \leq 2$, where a value of -0.1 indicates optically thin free-free emission and a value of $+2$ indicates optically thick. For the case of a “standard”, spherical wind, the spectral index $\alpha = 0.6$. Shallower spectral indices ($\alpha < 0.6$) are expected for unresolved, well-collimated, constant velocity, isothermal, fully ionised (“standard collimated”) jets, and similar values are expected for fully ionised, adiabatic jets ([Reynolds, 1986](#)). In this section I compare the results for α_{AMI} ([Table 4.2](#) and [Table 4.5](#)) and α' from the spectral energy distribution scenario (ii) where T_d is allowed to vary ([Table 4.8](#)).

Across the AMI band, 7/9 (78%) of the target sources, where the spectral index α_{AMI} could be constrained, are within the range $-0.1 \leq \alpha_{\text{AMI}} \leq 2$ indicating free-free emission (see [Table 4.5](#)). When including the additional protostellar sources detected in these fields (see [Table 4.2](#)), 11/14 (79%) of the sources have α_{AMI} within this range. The three sources that lie outside this range, HH 111, Serpens SMM 1 and L1448 C, have $\alpha_{\text{AMI}} < -0.1$, suggesting that another emission mechanism is at work. Spectral indices inconsistent with free-free emission have been found previously for Serpens SMM 1 ([Rodríguez et al., 1989b](#); [Curiel et al., 1993](#)). The weighted average spectral index of the original sample calculated from the AMI fluxes is $\overline{\alpha_{\text{AMI}}} = 0.42 \pm 0.59$, consistent with a standard, collimated jet. The flux densities for HH 26 IR and NGC 2264 could only be extracted from the 16 GHz combined-channel map, so it was not possible to measure α_{AMI} for these sources. For the extended sample, $\overline{\alpha_{\text{AMI}}} = 1.52 \pm 0.64$, still consistent with free-free emission although quite steep. The steep $\overline{\alpha_{\text{AMI}}}$ could result from fitting only the AMI data from which the greybody contribution had not been subtracted. $\overline{\alpha'}$ does not suffer from this which will be shown in the next paragraph. The large uncertainties of α_{AMI} in [Table 4.5](#) are due to the short frequency coverage of AMI.

For comparison, 8/10 (80%) of the original sample have $-0.1 \leq \alpha' \leq 2$ when including archival data (again, excluding HH 26 IR, see [Table 4.8](#)). For the extended sample, 10/13 (77%) of the sources (excluding L1551 NE and HH 25 MMS) have α' within this range. The values for α' that lie outside this range are NGC 2264 and L723 ($\alpha' < -0.1$) and NGC 1333 IRAS 2A ($\alpha' > 2$). The original sample has a weighted average spectral index

$\overline{\alpha'} = 0.20 \pm 0.46$ and the extended sample has $\overline{\alpha'} = 0.37 \pm 0.63$, both consistent with free-free emission and a well-collimated flow. This is a much more accurate representation of the radio emission arising from the jet, as the dust contribution from the envelope/disk has been taken into account.

In the case of NGC 2264 G, there are two known radio continuum sources in this outflow region: VLA 1, which was proposed as the driving source by [Rodríguez & Curiel \(1989\)](#), and VLA 2, which is suggested to be the driving source source by [Gómez et al. \(1994\)](#). [Gómez et al. \(1994\)](#) find a spectral index $\alpha \simeq -1.3 \pm 0.4$ for VLA 1 and a significantly lower flux density than [Rodríguez & Curiel \(1989\)](#), suggesting that it appears to be highly variable and an extragalactic nature cannot be ruled out. For VLA 2, these authors find a spectral index $\alpha \simeq 0.3 \pm 0.2$, consistent with free-free emission. The negative spectral index $\alpha' = -0.31 \pm 0.11$ obtained here for NGC 2264 G is likely contaminated by VLA 1 as the sources are unresolved by AMI. Additional high resolution observations are needed to confirm the non-thermal component.

L723 is like NGC 2264 G, i.e. there is a nearby source, VLA 1, with a spectral index $\alpha \leq -0.1$ that could be contaminating the SED for the prospective driving source, VLA 2. [Anglada et al. \(1996\)](#) find a spectral index $\alpha = -0.3 \pm 0.2$ for VLA 1, and discuss the possibility that the source is a radio-emitting, optically obscured T Tauri star. These authors find a spectral index $\alpha = 0.5 \pm 0.2$ for VLA 2, consistent with free-free emission, and the results of [Carrasco-González et al. \(2008\)](#) for the spectral index of VLA 2 are also indicative of free-free emission. I find $\alpha_{\text{AMI}} = 0.42 \pm 0.82$ for L723, consistent with free-free emission from a canonical jet even though these sources are not resolved. The negative spectral index $\alpha' = -0.29 \pm 0.09$ obtained is likely affected by both VLA 1 and insufficient low-frequency data to better constrain α' .

From the data presented here, L1527 is found to have a spectral index $\alpha_{\text{AMI}} = 1.15 \pm 0.57$, which agrees with the value of $\alpha_{\text{AMI}} = 1.17 \pm 0.42$ found by [Scaife et al. \(2012a\)](#). A spectral index of $\alpha > 0.8$ can be easily produced by velocity gradients or the recombination that might be expected for rapidly diverging flows ([Reynolds, 1986](#)). For consistency purposes, I have used the same archival data as in [Scaife et al. \(2012a\)](#) for the SED, who find $\alpha' = -0.11 \pm 0.09$. However, I find $\alpha' = 0.70 \pm 0.06$ in this work. I attribute this difference to the fact that the data is fit with multiple greybody components in [Scaife et al. \(2012a\)](#). L1527 has a known disk ([Loinard et al., 2002](#); [Tobin et al., 2010](#)) which dominates the SED at sub-millimetre frequencies, while the envelope contribution dominates at far-infrared frequencies. The single greybody model used in this work does not provide the best fit to both the envelope and disk. However, in both scenarios the SED model here predicts $\beta \leq 1$, consistent with the presence of large dust grains in the disk ([Scaife et al., 2012a](#)).

Overall, the values for the spectral indices are not unexpected as all sources listed in [Table 4.5](#) and the protostellar sources listed in [Table 4.8](#) have known outflows. In the cases

of NGC 2264 G and L723, higher spatial resolution data can help constrain the emission mechanism for the driving sources of these outflows and identify non-thermal components.

4.5.6 Correlations

Radio luminosity has been shown to correlate with global properties such as bolometric luminosity, envelope mass, and outflow force (Scaife et al., 2011a,b, 2012b). I combine these data with the previous work to redraw the correlations, see Figure 4.4 and Figure 4.5. I use the radio luminosity ($S_{\text{rad},16}d^2$) results calculated by subtracting the predicted greybody contribution at 16 GHz ($S_{\text{gb},16}$) from the measured flux density ($S_{16\text{GHz}}$), in the correlations that follow to ensure that the values used are representative of only the outflow component of the radio emission. I compare the correlations between both SED scenarios and examine the relation of this sample to existing correlations.

Note on Classification

Scaife et al. (2011b) found that when comparing bolometric temperatures determined using *IRAS* data (Hatchell et al., 2007b) and those found from fluxes calculated using *Spitzer* SEDs (Dunham et al., 2008), the *IRAS* temperatures were, on average, a factor of 1.6 higher than the corresponding *Spitzer* values. Bolometric temperature is one of the indicators for protostellar class and within this sample, one of the sources with $70 \leq T_{\text{bol}} \leq 150$ K (HH 111) will change from Class I to 0 when the *Spitzer* temperature is used.

Correlation between Radio Luminosity and Bolometric Luminosity

The correlation of radio luminosity with bolometric luminosity for low-mass protostars was first shown by Anglada (1995) using 3.6 cm emission, and more recently by Shirley et al. (2007) with the inclusion of 6 cm emission. The correlation is believed to arise as a consequence of the correlation between outflow force and bolometric luminosity as the degree of shock ionisation is expected to be larger for more powerful outflows from higher luminosity sources (Shirley et al., 2007). Scaife et al. (2011b) find the correlation between 16 GHz radio luminosity and bolometric luminosity to be

$$\log[L_{\text{rad}}(\text{mJy kpc}^2)] = -(1.74 \pm 0.18) + (0.51 \pm 0.26) \log[L_{\text{bol}}(L_{\odot})]. \quad (4.6)$$

Figure 4.4a shows the correlation of radio luminosity with bolometric luminosity for Scenario (i), where T_{d} is fixed, and Figure 4.4b for Scenario (ii), where T_{d} varies. These new data extend the trend into higher luminosities. Note that the bolometric luminosity for the Serpens SMM 1 source used here is $L_{\text{bol}} = 17.3 L_{\odot}$ (Enoch et al., 2009a), however significantly higher luminosities have been reported for this object in the literature which

could explain the offset from the trend (see [Section 4.4](#)). The value of α' is unconstrained for HH 26 IR due to insufficient low-frequency data. As a result, this method calculates a significant value for $S_{\text{gb},16}$, resulting in a value of $S_{\text{rad},16}d^2$ consistent with zero due to the low flux density detected by AMI. HH 26 IR is therefore not included in the plots. Data below 8 GHz is needed to constrain the spectral index of this source and establish an accurate measure of the radio luminosity.

Two sources, L1551 NE and HH 25 MMS, have their location change significantly between [Figure 4.4a](#) and [Figure 4.4b](#), due to the large difference in their radio luminosities between the two SED scenarios (as discussed extensively in [Section 4.5.3](#)). Larger radio luminosities were calculated for both sources in the case where T_d is fixed. However, the lower radio luminosity calculated from the scenario where T_d is allowed to vary for HH 25 MMS is in better agreement with the trend than the higher value from the scenario where T_d is fixed. The opposite is true for L1551 NE, and the radio luminosity calculated for this source from Scenario (i) is in better agreement with the trend than the one calculated from Scenario (ii). Like HH 26 IR, L1551 NE deviates from the trend due to a radio luminosity $S_{\text{rad},16}d^2 \approx 0$ when T_d varies, and more observations at these frequencies are needed to constrain the spectral index and establish the radio luminosity.

I use a two sample Kolmogorov-Smirnov (KS) test to determine whether the sample from this work is consistent with the known correlation. I reject the null hypothesis of no difference between the datasets if the probability is less than the standard cutoff value of $p = 0.05$. I find p-values of $p = 0.021$ and $p = 0.037$ for Scenarios (i) and (ii) respectively, indicating that the sample from this work is statistically different from the previous sample in both scenarios.

I attribute this discrepancy to the values of the bolometric luminosity, rather than the radio luminosity, as no similar effect is seen in the correlation with envelope mass (see next section). There are a number of possible explanations. The dataset from previous papers (open circles in [Figure 4.4](#)) has bolometric luminosity values dominated by a single catalogue ([Hatchell et al., 2007b](#)), whereas the current sample has values from a much wider range of references. A larger degree of scatter in the current dataset might therefore be expected due to differences in methodology. Alternatively, it is possible that the bolometric luminosities derived in [Hatchell et al. \(2007b\)](#) which dominate the archival dataset have themselves a systematic offset from those found more generally in the literature, however this seems unlikely as it has not been noted in previous comparisons. A further possibility is that the current sample is (on average) biased towards sources with high ratios of bolometric luminosity to envelope mass. Since these sources are preferentially selected to be well known radio protostars, it is likely that this effect is present at some level. I therefore suggest that the underlying cause of the discrepancy is a combination of both this last possibility and the first.

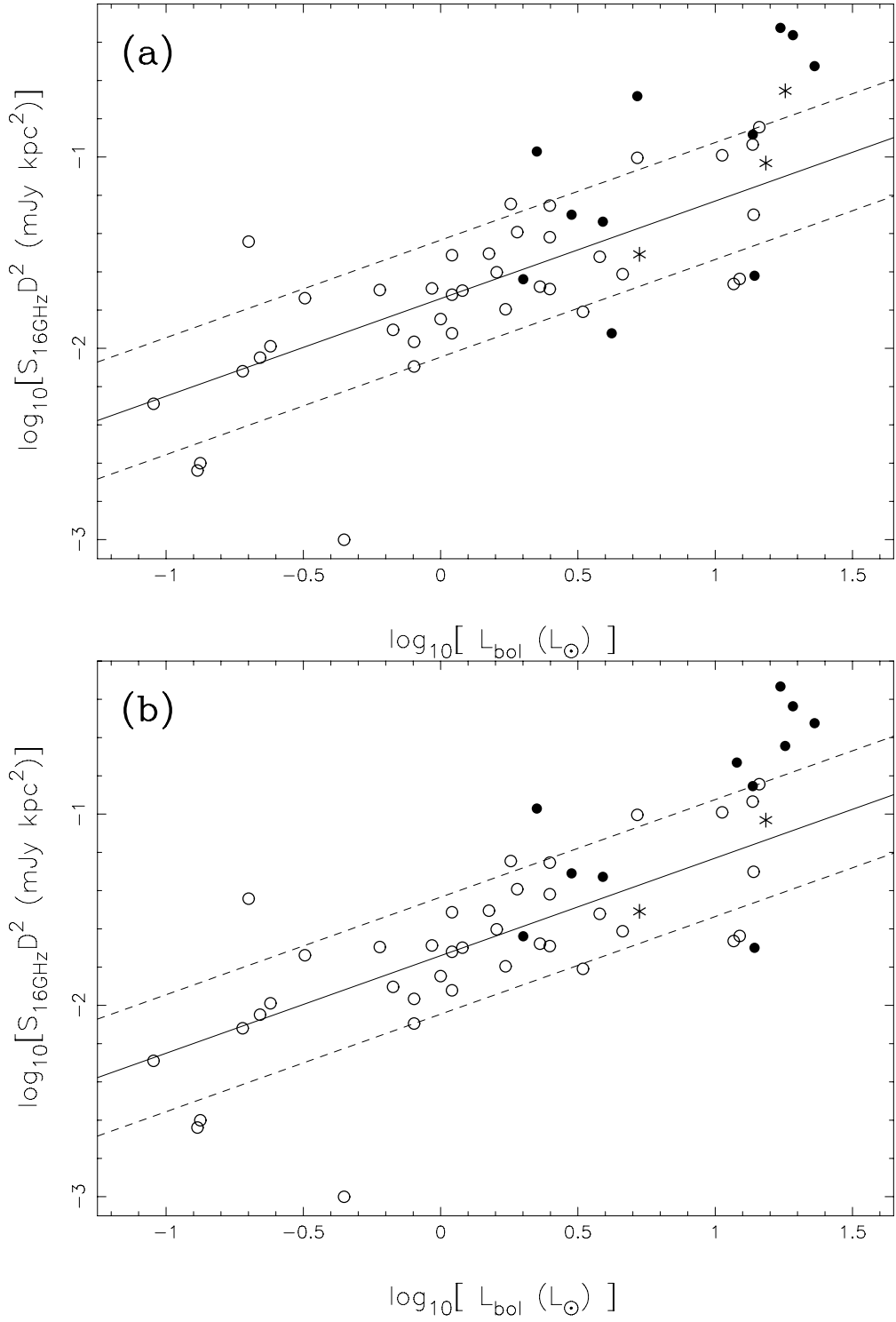


Figure 4.4.: (a) Correlation of 16 GHz radio luminosity with bolometric luminosity for Scenario (i) where T_d is fixed to 15 K for Class 0 objects and 20 K for Class I objects, and (b) for Scenario (ii) where T_d is fitted as a free parameter. Filled circles represent Class 0 sources from this sample, stars are Class I, and unfilled circles are previous data. Best fitting correlations from [Scaife et al. \(2011b\)](#) are shown as solid lines (see [Equation 4.6](#)) and the dashed lines are the 1σ limits on the distribution.

Correlation between Radio Luminosity and Envelope Mass

Figure 4.5 shows the correlation between radio luminosity and envelope mass. The envelope masses listed in column 8 of Table 4.3 were determined using the 850 μm flux densities from the Sub-millimetre Common-User Bolometer Array (SCUBA) Legacy Fundamental Map Object Catalogue (di Francesco et al., 2008) in the following way:

$$M_{\text{env}} = \frac{S_\nu d^2}{\kappa_\nu B_\nu(T_d)} \quad (4.7)$$

where κ_ν is the opacity, $B_\nu(T_d)$ is the Planck function at a dust temperature T_d and the scaling factor $[\kappa_\nu B_\nu(T_d)]^{-1}$ uses the scaled value from Hatchell et al. (2007b), applied in Scaife et al. (2012b). This scales the envelope masses by a factor of 0.33 in order to compare them directly with the mass values obtained from the Bolocam catalogue of Enoch et al. (2009b). This factor is the average ratio of envelope masses for the sources from the Perseus region studied in Scaife et al. (2011b) when measured with Bolocam (Enoch et al., 2009b) and with SCUBA (Hatchell et al., 2007b), accounting for differences in the assumed T_d and κ_ν after correcting for the assumed distance between these works when calculating mass values. Distances used are listed in column 3 of Table 4.3. Froebrich (2005) finds that a lower dust temperature of 15 K e.g., as suggested by Motte & André (2001) and Hatchell et al. (2007b), would lead to envelope masses that are a factor of 1.6 higher, however this should not affect these results as I maintain consistency within the sample. The SCUBA (di Francesco et al., 2008) 850 μm flux density is unresolved for NGC 1333 IRAS 2A and B, and so I use the values from Enoch et al. (2009b) for these objects.

The data from this work are combined with those from Scaife et al. (2011a,b) to examine the correlation of radio luminosity with envelope mass. It can be seen from Figure 4.5 that the data from this work are consistent with those from the literature. A best-fitting correlation using the combined dataset is found to be,

$$\log[L_{\text{rad}}(\text{mJy kpc}^2)] = (-1.83 \pm 0.25) + (0.96 \pm 0.41) \log[M_{\text{env}}(M_\odot)]. \quad (4.8)$$

Uncertainties on the envelope mass have contributions from the assumed opacity and temperature in addition to a 20 – 30% uncertainty from the sub-millimetre flux density (Scaife et al., 2012b).

As protostars evolve through the Class 0–I stages, both the envelope mass and the average mass-loss rate in the outflow decrease (see Section 2.1; Bontemps et al., 1996). The observed correlation of L_{rad} with M_{env} could also be interpreted as a correlation with mass-loss rate. Models of radio emission arising from ionised spherical stellar winds (see

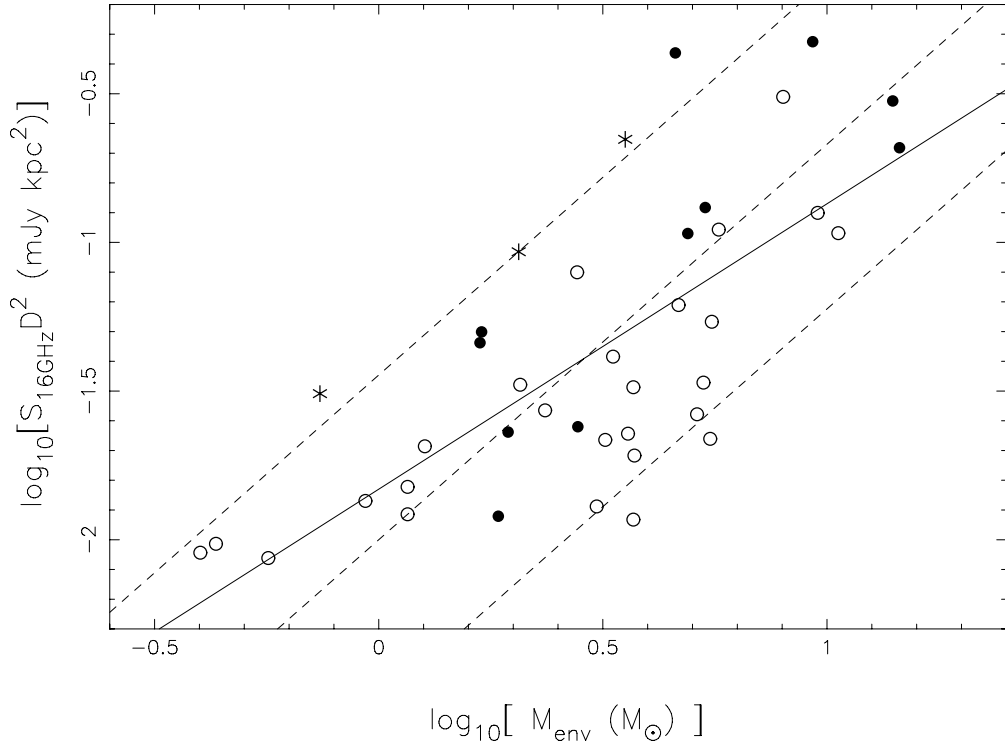


Figure 4.5.: Correlation of envelope mass with 16 GHz radio luminosity, where the solid line indicates the best fitting correlation using the combined data set, the dashed lines indicate a slope of 1.33 and the 1σ limits on the distribution of data relative to this slope. Filled circles represent Class 0 sources from this sample, stars are Class I, and unfilled circles are previous data.

Section 3.2; Panagia & Felli, 1975) predict a correlation between the radio luminosity and the mass-loss rate

$$\left(\frac{S_\nu d^2}{\text{mJy kpc}^2} \right) = 5.12 \left(\frac{\nu}{10 \text{ GHz}} \right)^{0.6} \left(\frac{T_e}{10^4 \text{ K}} \right)^{0.1} \left(\frac{\mu}{1.2} \right)^{-4/3} \left(\frac{v_*}{10^3 \text{ km s}^{-1}} \right)^{-4/3} \bar{Z}^{-2/3} \left(\frac{\dot{M}}{10^{-5} M_\odot \text{ yr}^{-1}} \right)^{4/3}, \quad (4.9)$$

where μ is the mean atomic weight per electron, v_* is the velocity, and $\bar{Z}$ is the average ionic charge. Collimated jet models (Reynolds, 1986) also predict the relationship $L_{\text{rad}} \propto \dot{M}^{4/3}$ with weak dependencies on ionisation fraction, collimation, temperature and outflow inclination. Figure 4.5 compares the data to this power-law with index $4/3 = 1.33$, shown as a dashed line. Note that the fitted correlation is consistent with this index at the 1σ level.

Class I sources are expected to have smaller envelope masses than Class 0 by definition (see Section 2.1) but from these data there is no evident deviation from the trend based on evolutionary class. In fact, the Class I sources in this sample are all found along the $+1\sigma$ level line of the correlation.

From the KS test I find p-values of $p = 0.374$ and $p = 0.54$ for Scenarios (i) and (ii) respectively, indicating that the sample from this work is consistent with the correlations found from the previous sample in both scenarios. .

Note that the correlation fitted directly to the data shown in [Figure 4.5](#) will be subject to an observational bias due to the low significance end of the data. This form of Eddington bias causes the slope of the fitted correlation to be artificially shallow due to the increased data scattered above the correlation, relative to that scattered below the correlation which will be missed due to the detection limit. Such a bias can be corrected statistically, and following the method of [Herranz et al. \(2006\)](#) I use a maximum likelihood estimator for the slope, m , to recover a value of $\hat{m} = 1.01$.

The correlation with bolometric luminosity will also be subject to a similar bias. However, I do not correct the fit in this case as the detection limit is not the only criterion for detection of a radio counterpart in this case, as shown in [Scaife et al. \(2011b\)](#).

Correlation between Radio Luminosity and Outflow Force

One of the models discussed in [Section 2.4](#) for producing the free-free emission is shock induced ionisation through the impact of a neutral stellar wind or molecular outflow against the surrounding envelope ([Curiel et al., 1987, 1989](#)), where the radio luminosity

$$\left(\frac{S_\nu d^2}{\text{mJy kpc}^2} \right) = 3.98 \times 10^{-2} \left(\frac{\dot{M}}{10^{-7} \text{M}_\odot \text{yr}^{-1}} \right) \left(\frac{v_*}{100 \text{ km s}^{-1}} \right)^{0.68} \times \left(\frac{T}{10^4 \text{ K}} \right)^{0.45} \left(\frac{\Omega}{4\pi} \right) \left(\frac{\nu}{5 \text{ GHz}} \right)^{-0.1} \quad (4.10)$$

and $(\Omega/4\pi)$ represents the fraction of the stellar wind being shocked. The correlation between radio luminosity and outflow force might therefore be expected: $L_{\text{rad}} \propto \dot{M} v_* = F_{\text{out}}$. The 16 GHz radio luminosity data presented here are consistent with the loose correlation with outflow force measured in [Scaife et al. \(2011a,b\)](#), see [Figure 4.5](#). The solid line indicates the shock ionisation model of [Curiel et al. \(1989\)](#) with a temperature of $T_e = 10^4 \text{ K}$. The upper (lower) dashed line indicates the same model with a temperature of $T_e = 3000 \text{ K}$ (10^5 K ; [Scaife et al., 2011b](#)).

From the [Reynolds \(1986\)](#) model, the correlation $F_{\text{out}} \propto L_{\text{rad}}^{2.1/2(2-\alpha)}$ is predicted. In the case of a spherical stellar wind with $\alpha = 0.6$, $F_{\text{out}} \propto L_{\text{rad}}^{0.75}$, and in the case of a collimated jet with $\alpha = 0.25$, $F_{\text{out}} \propto L_{\text{rad}}^{0.6}$ (see [Scaife et al., 2011a](#)). The lack of a well defined correlation in this case may be due to the errors inherent in measurements of outflow force. Class 0 objects are generally considered to have more energetic outflows than Class I, but there is no clear evolutionary division in the correlation presented here.

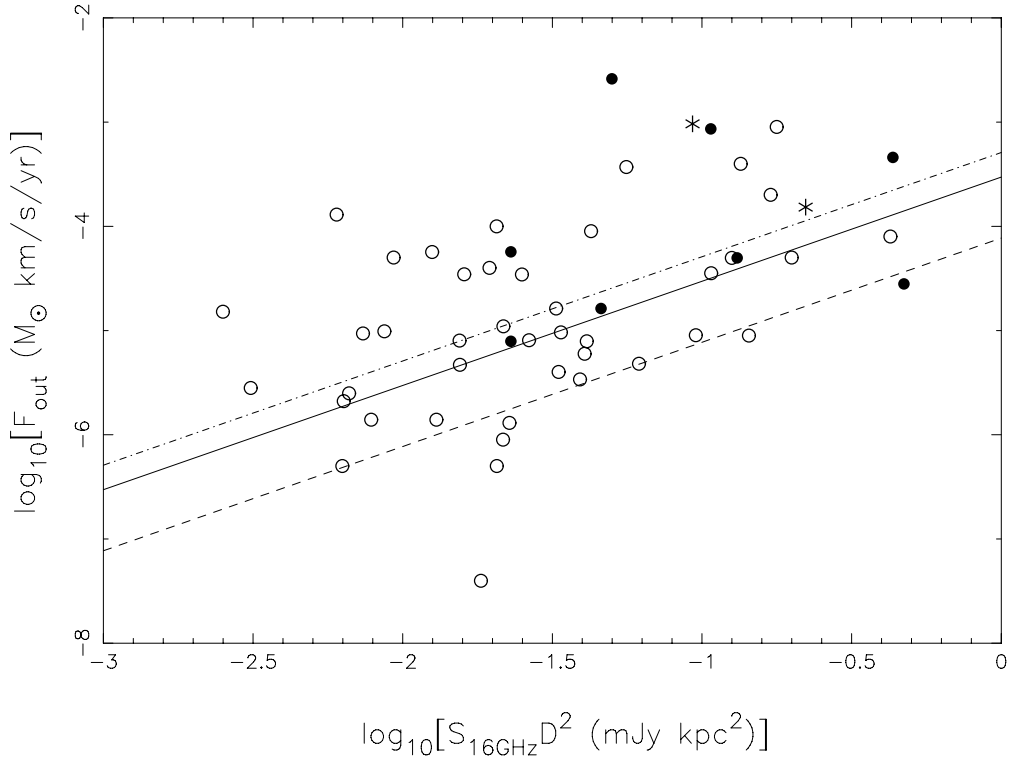


Figure 4.6.: Correlation of 16 GHz radio luminosity with outflow force, where the solid line indicates the best fitting correlation using the combined data set, the dashed lines indicate a slope of 1.33 and the 1σ limits on the distribution of data relative to this slope. The solid line indicates the shock ionisation model of [Curiel et al. \(1989\)](#) with a temperature of $T_e = 10^4$ K. The upper (lower) dashed line indicates the same model with a temperature of $T_e = 3000$ K (10^5 K). In both plots, filled circles represent Class 0 sources from this sample, stars are Class I, and unfilled circles are previous data.

As discussed in [Scaife et al. \(2011a\)](#), there are many uncertainties in outflow force measurements and variations in how F_{out} is estimated. For example, some estimates are derived from the total momentum observable in the outflow lobes and divided by a measure of the outflow dynamical time. [Bontemps et al. \(1996\)](#) use a measure of the force derived within an annulus around the outflow origin which provides a better measurement for outflows that have only been partially mapped. Values for F_{out} may vary even whilst using the same method to calculate it depending on which velocity is used. Many studies increase their outflow forces by a factor of 10 to account for optical depth and inclination effects, following [Bontemps et al. \(1996\)](#). From the current sample, only two of the values for outflow force from the literature have been corrected in this way: L1527 and Serpens SMM 1 (see [Table 4.3](#)). As the majority of the data included in [Figure 4.6](#) has this correction implemented, I apply the same adjustment to the values in [Table 4.3](#) for the purposes of the plot. For a large enough sample of protostars, the trends should still be apparent but may have large scatter ([Scaife et al., 2011a](#)). Due to the considerable uncertainties in outflow

force measurements and estimations, we do not include error bars for F_{out} measurements in [Figure 4.6](#).

4.5.7 Variability

Radio variability might be expected for Class 0 and I sources due to episodic accretion rates and mass ejection in the outflows ([Kenyon & Hartmann, 1995](#)). However, only two sources, L1551 IRS 5 and Serpens SMM 1, show strong signs of variability based on examination of their spectral energy distributions (see [Appendix B](#)). This could be due to the fact that there is a comparatively larger amount of archival data for these sources, and it is likely that a majority of the sources in this sample possess variable natures but more observations at multiple epochs are needed to confirm this. In the case of NGC 2264 G, evidence for variability has been shown ([Gómez et al., 1994](#)) for an object in the same region as the driving source of this outflow which will affect the results of unresolved data.

L1551

[Rodríguez et al. \(2003a\)](#) have compiled measurements of L1551 IRS 5 at 2 cm from 1983 to 1998 to determine the proper motion of the multiple sources, and by comparing different epochs they found that the S component underwent a major ejection event during the late 1980s and showed considerable elongation in the east–west direction.

By comparing data at 5 and 15 GHz taken at different epochs (see [Appendix C](#)) there is clear evidence of variability. The flux densities measured at 5 GHz range by a factor of ≈ 1.7 over all epochs, while the flux densities measured at 15 GHz range by a factor of ≈ 2.2 . In addition, the VLA observations of [Keene & Masson \(1990\)](#) were measured in September 1988, and their flux density at 15 GHz is a factor of ≈ 1.7 higher than the flux density measured in this work at a similar frequency. [Lim & Takakuwa \(2006\)](#) detect three circumstellar dust disks in this region, and therefore luminosity variations might be expected. These authors have discussed that the flux of the N jet (see [Section 4.4](#)) is typically higher than the flux of the S jet, except during the epoch of the major ejection event of the S jet.

Serpens

Evidence for variability has been shown for Serpens SMM 1 by [Scaife et al. \(2012b\)](#) and references therein. [Curiel et al. \(1993\)](#) suggest that the knotty structure in the NW and SE components is the result of a discrete ejection of material (“bullets”) from the source, which could account for the radio flare event in the archival data ([Scaife et al., 2012b](#)) that appear to have faded. The observations at 16 GHz for SMM 1 presented in this work were taken 11 October 2011 and the flux density (see [Table 4.5](#)) is a factor of ≈ 1.5 higher than that

presented in [Scaife et al. \(2012b\)](#) who measure a flux density of 4.736 ± 0.237 mJy with AMI observations taken between December 2010 and January 2011. Our measured flux density is within the uncertainty limits of the 15 GHz flux density of 10 ± 3 mJy found by [Snell & Bally \(1986\)](#). [Enoch et al. \(2009a\)](#) detect a high mass disk around this source which should be unstable and therefore exhibit luminosity variations.

HH 1

The Herbig–Haro object HH 1 has been previously detected at centimetre wavelengths (e.g. [Rodríguez et al., 1990, 2000](#)) however, here HH 1 is not detected at 16 GHz. I calculate a flux density upper limit of 0.34 mJy for this object, inconsistent with the value of 0.78 mJy at 2 cm found by [Rodríguez et al. \(1990\)](#). However, [Pravdo et al. \(1985\)](#) also failed to detect HH 1 in the radio, suggesting that this source is variable. Indeed, multi-wavelength observations of this object have been discussed by [Raga et al. \(2011\)](#), and HH 1 has been shown to be variable at radio wavelengths. Future observations with AMI and e-MERLIN at the same epoch will provide a better picture of the variability of these objects.

4.6 SUMMARY

In this chapter, I have presented 16 GHz observations made with AMI of a sample of low-mass young stars driving jets. The main results are as follows:

- The data presented in this work provide support for free–free emission as the dominant mechanism for producing the radio luminosity from these YSOs at 16 GHz. Across the AMI channel bands, 80% of the detected protostellar sources in the target sample have spectral indices $-0.1 \leq \alpha_{\text{AMI}} \leq 2$ consistent with free–free emission and I find an average spectral index $\overline{\alpha_{\text{AMI}}} = 0.42 \pm 0.59$ consistent with the value for a collimated, ionised jet. Although the flux densities integrated over the whole of the source are in general indicative of free–free emission, it could be possible that subcomponents within the source show non-thermal (i.e. negative) spectra.
- I have also presented and examined spectral energy distributions for each detected protostellar source, combining the AMI data with available archival data from an extensive literature search. Two scenarios were tested to obtain maximum likelihood values for the spectral indices, dust opacity indices, and dust temperatures. In Scenario (i), T_d is fixed for each source based on protostellar evolutionary class and 80% of the objects in the target sample are found to have spectral indices consistent with free–free emission, with an average spectral index $\overline{\alpha'} = 0.20 \pm 0.41$ also consistent with the value for a well collimated outflow. In Scenario (ii), T_d is not fixed, and

the same average value for the spectral index is found. These values for the spectral indices are consistent with expectations as all target sources drive known outflows.

- I examined the errors associated with determining the radio luminosity and found that the dominant source of error is the uncertainty on the opacity index, β .
- In both scenarios, NGC 2264 G and L723 have $\alpha' \leq -0.1$, inconsistent with free-free emission. For these two sources there are other objects within close proximity (i.e. within the synthesised beam) that have non-thermal spectral indices that may affect the integrated flux densities. Higher spatial resolution data can help constrain the emission mechanism for the driving sources of these outflows. I also find $\alpha' > 2$ in some cases (e.g. NGC 1333 IRAS 2A) suggesting that the lower frequency data is an extension of the greybody emission and that there is no free-free component detectable in these data.
- I examined the correlations between the radio luminosity and bolometric luminosity, envelope mass, and outflow force and found that these data are broadly consistent with correlations found by previous samples. There is a slight bias in the correlation with bolometric luminosity towards higher values of L_{bol} .
- Evidence for variability has been shown for L1551 IRS 5 and Serpens SMM 1 by close inspection of their SEDs. It is apparent from their histories that they have undergone radio flare events, supporting non-steady accretion models of protostellar evolution. I also find variability in the Herbig-Haro object HH 1.

SUB-ARCSECOND STUDIES OF YSOS AT 5 GHz WITH E-MERLIN

Moving to lower frequency and much higher spatial resolution, this chapter presents observations taken of the CTTS DG Tau at 5 GHz with e-MERLIN as part of the Legacy Programme on the “Morphology and Time Evolution of Thermal Jets Associated with Low-mass Young Stars” (P.I. L. Rodríguez), of which the data acquisition, reduction and analysis were to form the basis of this thesis. At the CTTS stage of protostellar evolution, most of the original core has already been accreted, resulting in lower accretion rates through the surrounding accretion disk onto the YSO and the system becomes optically visible (see [Section 2.1](#); [Pudritz et al., 2007](#)). CTTSs are a perfect laboratory for studying the jet launching and collimation mechanisms as their proximity (140 pc to the nearest star forming regions) and lack of obscuring envelope give access to the inner jet regions within 20 – 200 au, where the outflow structure might not yet be significantly disturbed by interaction with the ambient medium ([Ray, 2007](#); [Agra-Amboage et al., 2011](#)). Observations with radio interferometers of YSO outflows have the advantage that their spatial resolution can be comparable or better than the *HST*. Moreover, the new class of radio interferometers, such as e-MERLIN and the Jansky Very Large Array (JVLA) in the US, have vastly improved sensitivity to detect the central jet engine.

In this chapter, I present the highest resolution radio images made to date of DG Tau and its nearby cousin, DG Tau B. In previous, lower spatial resolution radio observations, both DG Tau and DG Tau B exhibit compact and elongated morphologies in the known direction of their outflows ([Cohen et al., 1982](#); [Bieging et al., 1984](#); [Rodríguez et al., 2012](#)) and possess positive spectral indices, α , typical of free-free emission. Radio SEDs for these sources are presented in [Scaife et al. \(2012a\)](#) and [Lynch et al. \(2013\)](#) and show evidence for variability. In [Section 5.1](#) I present details of these new e-MERLIN observations, and the results in [Section 5.2](#). In [Section 5.3](#) I discuss the implications of these findings, compare

This chapter has been published as: Ainsworth R. E., Ray T. P., Scaife A. M. M., Greaves J. S., and Beswick R. J., 2013, Subarcsecond high-sensitivity measurements of the DG Tau jet with e-MERLIN, *Monthly Notices of the Royal Astronomical Society: Letters*, **436**, L64–L68, doi:10.1093/mnrasl/slt114

them with previous data and mock observations, and derive jet parameters such as the jet opening angle and mass-loss rate of DG Tau. In [Section 5.4](#) I summarise the main results.

5.1 OBSERVATIONS AND DATA REDUCTION

The e-MERLIN synthesis telescope is a seven element interferometer with baselines of up to 217 km and connected by a new optical fibre network to Jodrell Bank Observatory near Manchester, UK. The data in this work were taken during the commissioning phase of e-MERLIN with only the five 25 m dishes, resulting in a primary beam of $\theta \approx 10'$, a maximum baseline of 133.7 km (between Pickmere and Defford), and a minimum baseline of 11.2 km (between Pickmere and Mark II). See [Section 3.4.2](#) for more details.

DG Tau was observed at 5 GHz for ≈ 22 hrs by e-MERLIN between 1 and 4 August 2011 (average epoch 2011.58), with 4×128 MHz sub-bands of 512 spectral channels each, yielding a total bandwidth of 512 MHz. Data were reduced and analysed using AIPS. Data were initially edited with SPFLG and IBLED, averaged to 64 channels per intermediate frequency (IF) channel, and concatenated with DBCON before further editing was conducted. FRING was used to derive delay and rate corrections for the calibrator sources, and CALIB was used to derive time-dependent phase, and then amplitude and phase solutions.

Flux calibration was performed using short observations of 3C286 at the beginning and end of each run, and the flux density scale was calculated with SETJY ([Perley & Butler, 2013](#)). The flux density for each IF was then reduced by 4% to account for the resolution of the e-MERLIN shortest spacing (see The MERLIN User Guide¹). Calibrator flux densities are listed in [Table 5.1](#). Bandpass calibration was performed using the bright point sources J0555 + 398 and J1407 + 284, and the phase was calibrated using interleaved observations of J0429 + 2724. Visibilities were re-weighted to take into account the different sensitivity of each dish, and the target source data was SPLIT for imaging with the calibration applied. Absolute calibration is expected to be accurate to about 10% for commissioning data.

Table 5.1.: e-MERLIN frequency channels and calibrator flux densities measured in Jy.

Channel No.	1	2	3	4
Freq. [GHz]	4.41	4.54	4.70	4.80
3C286	7.63	7.50	7.37	7.25
J0555 + 398	5.46	5.47	5.36	5.55
J1407 + 284	2.44	2.43	2.43	2.38

¹ www.e-MERLIN.ac.uk

5.2 RESULTS

Deconvolution and imaging were performed with IMAGR. Naturally weighted visibilities were used to ensure optimal signal-to-noise ratio (SNR) levels. Primary beam correction was applied with PBCOR. The combined channel map centred at 4.67 GHz (hereafter referred to as 5 GHz) for DG Tau is shown in Figure 5.1, and DG Tau B is also detected within the primary beam at $4\sigma_{\text{rms}}$ (see Figure 5.2). The dimensions of the synthesised beam are 0.11×0.10 arcsec with a position angle (PA) of $317^\circ.1$. The root-mean-square (rms) noise was measured in AIPS using IMEAN, and the values recovered are $24 \mu\text{Jy beam}^{-1}$ for the DG Tau map and $25 \mu\text{Jy beam}^{-1}$ for the DG Tau B map.

At epoch 2011.58, DG Tau is detected at J2000.0 coordinates $\alpha = 04^{\text{h}}27^{\text{m}}04^{\text{s}}.693$, $\delta = +26^\circ06'15''.82$. The optical position of this source corrected for proper motion (Zacharias et al., 2013) is plotted as a cross in Figure 5.1, where the errors are indicated by the size of the cross, and the radio detection with e-MERLIN is in agreement within the errors. This signifies that the emission is stationary and coincides with the source and is not a faster moving knot of emission.

Due to the high resolution of e-MERLIN, I am unable to identify the $4\sigma_{\text{rms}}$ source to the north in Figure 5.1, although I suspect it may be extragalactic. In the absence of further data at similar resolution and sensitivity, I cannot say definitively and therefore do not discuss it further in this work.

Flux densities were extracted from the primary beam corrected maps using JMFIT. Errors on the flux densities are calculated as $\sigma = \sqrt{(0.1S_{5\text{GHz}})^2 + \sigma_{\text{rms}}^2 + \sigma_{\text{fit}}^2}$, where $0.1S_{5\text{GHz}}$ is 10% absolute calibration error on the total 5 GHz flux density $S_{5\text{GHz}}$, σ_{rms} is the rms noise and σ_{fit} is the fitting error returned from JMFIT. All errors are quoted to 1σ .

5.3 DISCUSSION

5.3.1 DG Tau

At 5 GHz, DG Tau is detected at $6\sigma_{\text{rms}}$, and at such high spatial resolution the source exhibits an asymmetric, compact and slightly elongated morphology consistent with the known direction of the outflow axis. DG Tau has a total flux density $S_{\text{t},5\text{GHz}} = 312 \pm 78 \mu\text{Jy}$ and a peak flux density $S_{\text{p},5\text{GHz}} = 160 \pm 38 \mu\text{Jy}$.

DG Tau is a highly active CTTS located at a distance of 140 pc in the Taurus Molecular Cloud, and was one of the first T Tauri stars to be associated with an optical jet (HH 158, Mundt & Fried, 1983). The optical outflow is observed to have an onion-like kinematic structure within 500 au of the star, with faster and more collimated gas bracketed by wider and slower material, and the flow becomes gradually denser and of higher excitation close

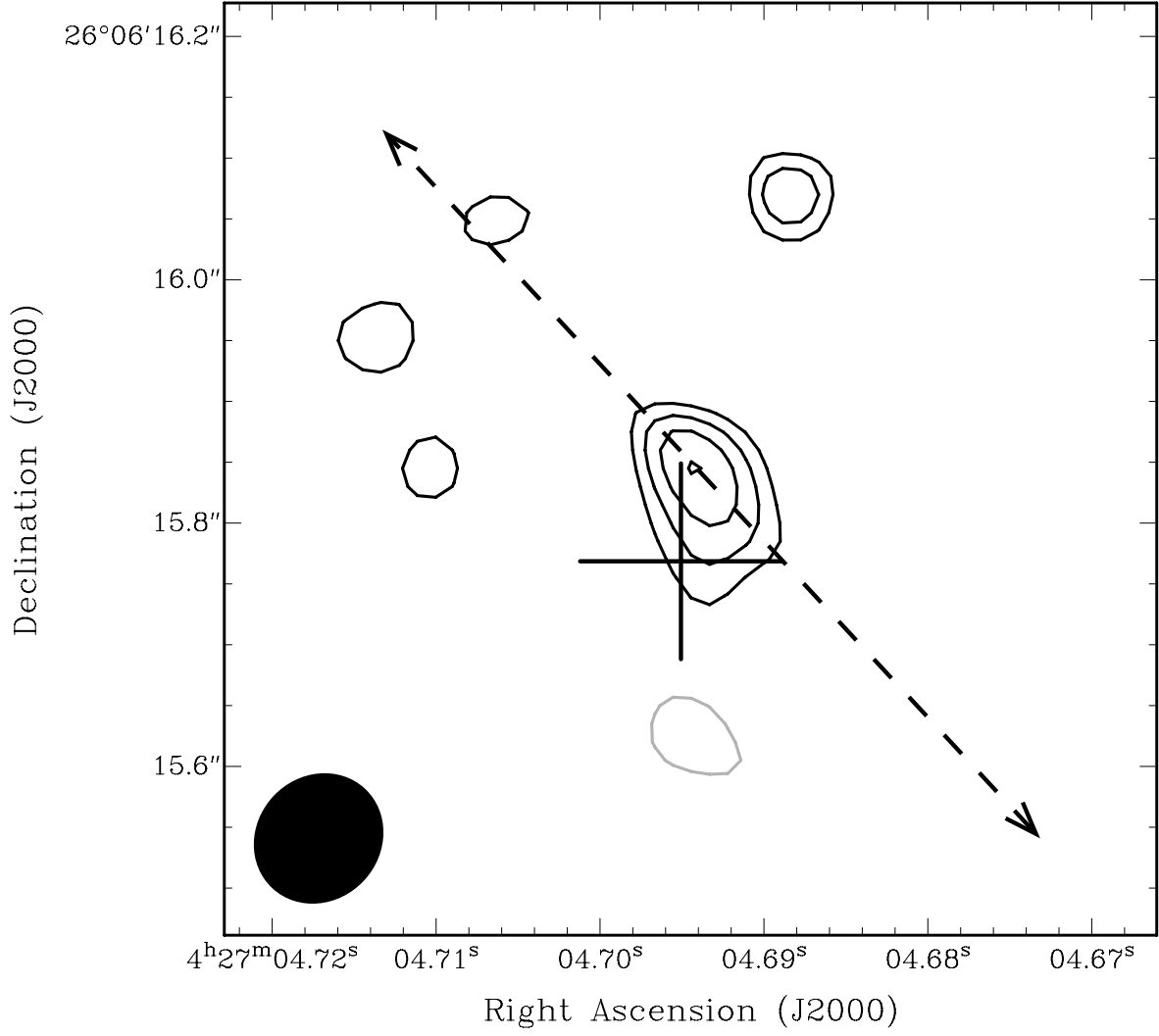


Figure 5.1.: e-MERLIN map at 5 GHz for DG Tau with contours at -3 (grey), 3 , 4 , 5 , and $6\sigma_{\text{rms}}$, where $\sigma_{\text{rms}} = 24 \mu\text{Jy beam}^{-1}$. The known outflow direction is shown as a dashed line, and the optical position for DG Tau is shown as a cross (see [Section 5.2](#)).

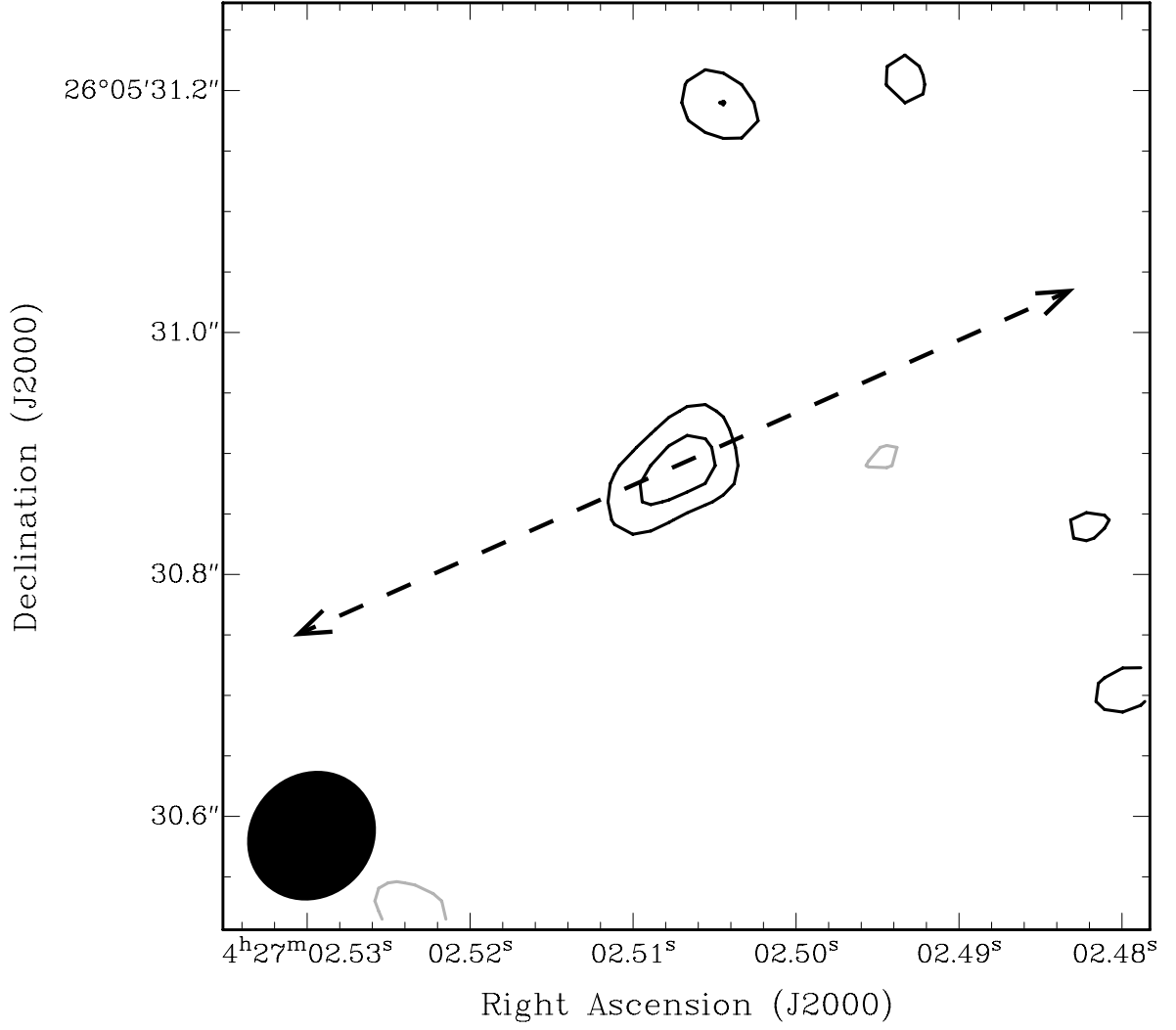


Figure 5.2.: e-MERLIN map at 5 GHz for DG Tau B with contours at -3 (grey), 3 , 4 , 5 , and $6\sigma_{\text{rms}}$, where $\sigma_{\text{rms}} = 25 \mu\text{Jy beam}^{-1}$. The known outflow direction is shown as a dashed line.

to the central axis (Bacciotti et al., 2000). This behaviour is naturally expected if the wind is launched from a broad range of disk radii (Agra-Amboage et al., 2011). Signatures of jet rotation have been observed (Bacciotti et al., 2002; Coffey et al., 2004, 2007), supporting a magneto-centrifugal jet launch scenario (Pudritz et al., 2007) and the disk has also been shown to rotate in the same direction as the jet (Testi et al., 2002). The HH 158 jet has a PA of 223° (Bacciotti et al., 2002) with an inclination angle $i \approx 38^\circ$ with respect to the line of sight (Eislöffel & Mundt, 1998), and has been traced out to a total projected distance of ≈ 0.5 pc (McGroarty et al., 2007). Radial velocities in the jet have been found to range up to $\sim 350 \text{ km s}^{-1}$ with average velocities of $\sim 200 \text{ km s}^{-1}$ (Dougados et al., 2000). Extended X-ray emission has also been detected along the outflow (Güdel et al., 2007, 2008).

This source has been seen to possess a slightly rising radio spectrum with $\alpha \approx 0.6$ (Scaife et al., 2012a; Lynch et al., 2013), typical of collimated thermal jets or spherical stellar winds (Reynolds, 1986). However, when the total flux density from this work is compared with the nearly coeval JVL A-configuration observations (epoch 2011.46) at 8.5 GHz from Lynch et al. (2013), a spectral index $\alpha_5^{8.5} = 2.4 \pm 0.5$ is found. Within the error this spectral index is possibly consistent with free-free emission, however $\alpha > 2$ is generally considered unphysical for free-free emission. Although variability is expected to cause some difference in the measured flux densities between different observation epochs, this is likely not the case here. In particular, the transit time across the source at maximum jet velocity is ≈ 4 months, which is longer than the amount of time between the JVL A and e-MERLIN epochs (1 month) and is therefore not the cause of the discrepancy. The unphysical spectral index in this case likely arises predominantly from the mismatch in angular scales recovered by the two arrays. The longer baselines of the e-MERLIN array compared to those of the JVL A will reduce the sensitivity to larger scale structure. Source components $\geq \lambda/D_{\min}$ radians (~ 1 arcsec for a minimum baseline of $D_{\min} = 11.2$ km) will be attenuated by more than 50% of their flux, and therefore undetected. As a result, extrapolating between the e-MERLIN and JVL A data will give an inaccurate spectral index, which is indeed the case.

To cross-check the commissioning data, I simulated the observations with the CASA simulator toolkit using a simple Gaussian flux distribution model of the JVL A data (Lynch et al., 2013) as the sky model (deconvolved dimensions provided by Christene Lynch, private communication 2013). Running SIMOBSERVE, I find that the angular scale and general morphology of DG Tau from the simulated visibilities is in agreement with the observations. Additional observations with e-MERLIN at different frequencies are needed to constrain the spectral index on this scale, although with the improved sensitivity provided by the Lovell telescope and the full bandwidth of 2 GHz, it may be possible to extract an instantaneous e-MERLIN spectral index from this source in the future with the fully upgraded array.

5.3.2 DG Tau B

Located $\approx 55''$ to the southwest of DG Tau is DG Tau B, the driving source of the asymmetrical optical jet HH 159 (Mundt & Fried, 1983) and not thought to be related to DG Tau except by projected proximity (Jones & Cohen, 1986). DG Tau B is a low-luminosity, deeply embedded Class I source ($L_{\text{bol}} = 0.7 L_{\odot}$, Watson et al., 2004). It drives a narrow optical jet (Mundt et al., 1991) and a collimated, redshifted CO outflow (Mitchell et al., 1994), both of which are well aligned at a PA of $\approx 294^\circ$. PAs between $116 - 122^\circ$ have been found for the blueshifted jet (McGroarty & Ray, 2004; Mundt et al., 1991). The total projected length of the DG Tau B outflow is ≈ 0.5 pc (McGroarty & Ray, 2004). A circumstellar disk has been observed at mm-wavelengths and is perpendicular to the outflow axis (Looney et al., 2000).

DG Tau B is detected at $4\sigma_{\text{rms}}$ within the e-MERLIN primary beam, with $S_{\text{t},5\text{GHz}} = 150 \pm 63 \mu\text{Jy}$ and $S_{\text{p},5\text{GHz}} = 113 \pm 38 \mu\text{Jy}$. The morphology is jet-like and has a deconvolved PA of 125° , consistent with the known jet axis (Mundt et al., 1991). A variable free-free component is suggested by the SED of DG Tau B, which could be explained by non-steady accretion/ejection (e.g. Kenyon & Hartmann, 1995). There is contribution to the radio emission from the dust disk at higher radio frequencies (Scaife et al., 2012a), however the contribution at 5 GHz for both DG Tau and B should be negligible.

5.3.3 Jet Opening Angle

The strongest constraints on the jet collimation scale come from measurements of nearby T Tauri stars with *HST* (Ray et al., 1996) and ground-based adaptive optics, including DG Tau (Dougados et al., 2000, see Figure 2.5). These authors show that jets from protostars appear resolved transversely and collimated as close as 35 – 50 au from the central star, with initial opening angles of $\theta_0 \approx 20 - 30^\circ$ which drop to only a few degrees beyond 50 au. However, if the jet originates from a region within 1 au of the star, it must have $\theta_0 \geq 45^\circ$ to reach the observed width, and then undergo strong recollimation within 35 – 50 au (Cabrit, 2002).

I used this e-MERLIN commissioning data to estimate the jet opening angle in the following way. I defined the direction of the line of brightest emission to be the e-MERLIN jet direction of DG Tau, which is consistent with that found in the optical. I made one dimensional cuts perpendicular to that direction with the AIPS task *SLICE* to determine the initial opening angle $\theta_{\text{e-MERLIN}}$ found with the e-MERLIN data. Each slice was fitted with a Gaussian using *SLFIT* and the FWHM of the Gaussian is then deconvolved from the synthesised beam to determine the FWHM of the jet at that distance. The peak of the emission in the 5 GHz map (Figure 5.1) was assumed to be the base of the jet, and the last slice of the jet was made at a distance of $0''.07$ from this point and has a FWHM of $0''.09$ (12.6 au).

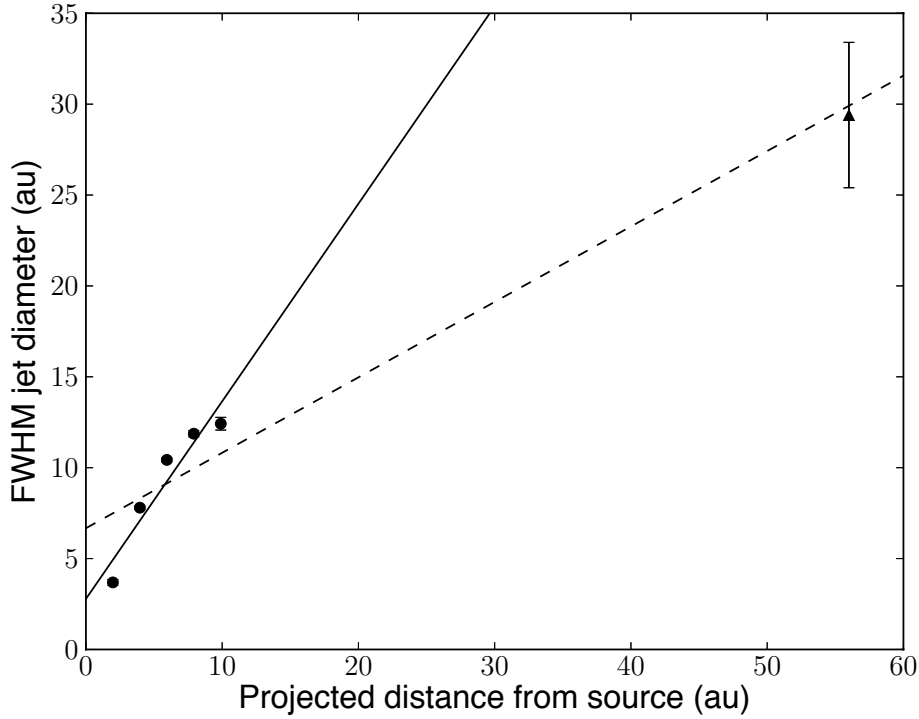


Figure 5.3.: Deconvolved FWHM of the DG Tau jet as a function of distance from the source. The measurements from these e-MERLIN data are shown as filled circles and the errors are of order or smaller than the circles. The optical measurement at 56 au from [Dougados et al. \(2004\)](#) is shown as a triangle, and the error is an overestimate based on the range of optical measurements from these authors. The best-fitting regression to only the e-MERLIN measurements is shown as a solid line, and the dashed line represents the best fit when including the FWHM measurement at 56 au.

As the emission at 5 GHz terminates at this point, it was assumed to be the unity optical depth surface ($\tau_v = 1$, see [Section 3.2.1](#)) and used the radius of the jet measured here to compute the mass-loss rate, see [Section 5.3.4](#).

In [Figure 5.3](#), the FWHM of the jet is plotted as a function of distance from the star, and an optical measurement at 56 au from [Dougados et al. \(2004\)](#) is included in the plot along with the radio measurements. I fit two linear regressions: (1) to only the five e-MERLIN data points, and (2) to the e-MERLIN and 56 au optical data points to calculate the average, constant opening angle for these ranges. From the linear fit to the e-MERLIN data I find an average, constant opening angle $\theta_{\text{e-MERLIN}} = 71^\circ$ (for distances $\simeq 10$ au), and when the optical point at 56 au is included I find an angle of 30° . For comparison, the average opening angle on scales of $\simeq 100$ au is $\approx 14^\circ$ based on data from [Dougados et al. \(2004\)](#).

If the opening angles are derived from only the first and last slices, $\theta_{\text{e-MERLIN}} = 86^\circ$ at 2 au from the source and $\theta_{\text{e-MERLIN}} = 64^\circ$ at 10 au. Many studies have shown that the

initial opening angle is much larger than the average opening angle θ_a further down the jet (e.g. Mundt et al., 1991; Raga et al., 1991), indicating that jets are often only partially collimated on scales of tens of au and that a significant amount of collimation is achieved over the length of the jet. DG Tau itself has also been shown to have a wider θ_a compared with other CTTS, and it has been suggested that it is due to precession or contribution from strong bow-shock wings (Dougados et al., 2000). Mundt & Fried (1983) find an opening angle of 10° for a jet length of 8 arcsec, showing further collimation on large scales. The measurement of $\theta_{e\text{-MERLIN}}$ is much larger than that found further along the jet, suggesting that the DG Tau jet starts initially as a poorly collimated wind close to the star and is recollimated further down the flow, in agreement with both D-wind (Ferreira et al., 2006) and X-wind (Shang, 2004) theories.

I note that these measurements used to derive the jet opening angle are not independent of each other due to the fact that they were made within the same beam. This method was used to illustrate the potential capabilities of the fully upgraded e-MERLIN which, with the inclusion of the Lovell and Cambridge dishes, may have sufficient sensitivity and resolution to resolve the base of these plasma outflows. If resolved along both directions, the jet opening angle can be measured close to the base of the jet directly and compared with current theories of MHD jet launch. The improved future observations made within the Morphology and Time Evolution of Thermal Jets Associated with Low Mass Young Stars Legacy Programme can further constrain these parameters through comparison with models of different jet geometries.

5.3.4 Mass-loss Rates

The mass-loss rate ($\dot{M}_j$) is a vital parameter to derive as the mass ejection-to-accretion rate ratio is a constraining parameter for MHD launching models (see Section 2.3). The mass-loss rate for the blueshifted DG Tau jet has been estimated by various authors using different techniques. Mass-loss rates ranging between $8 \times 10^{-9} - 3 \times 10^{-7} M_\odot \text{ yr}^{-1}$ have been estimated from observations at optical wavelengths (Hartigan et al., 1995; Lavalley-Fouquet et al., 2000; Bacciotti et al., 2002; Coffey et al., 2008; Agra-Amboage et al., 2011; Maurri et al., 2014). These estimates show discrepancies of almost two orders of magnitude depending on the adopted method for calculating $\dot{M}_j$ due to high uncertainties on physical properties (e.g. jet radius) and extinction (Cabrit, 2007; Agra-Amboage et al., 2011).

Using *Herschel*/Photoconductor Array Camera and Spectrometer (PACS) observations, Podio et al. (2012) estimate $\dot{M}_j = 1.1 \times 10^{-7} M_\odot \text{ yr}^{-1}$ from the [OI] $63 \mu\text{m}$ luminosity. If the ejected material is moving fast enough to produce a dissociated J-shock, then [OI] emission will be the dominant coolant in the postshock gas for temperatures of $100 - 5000 \text{ K}$ and is therefore a direct tracer of the mass flow into the shock.

To directly compare $\dot{M}_j$ found using these new e-MERLIN data with recent JVL A results, I follow the method described in [Lynch et al. \(2013\)](#) to compute the mass-loss rate. Free-free emission depends on the observing frequency, the plasma temperature, and the linear emission measure (see [Section 3.2](#)). The optical depth at a given location in the jet can be estimated from source structure and the plasma temperature is known from optical line observations, therefore the emission measure can be calculated and further the electron density in the jet at that particular location. As the entire detected radio jet is the optically thick surface for the spatial resolution of e-MERLIN, I identify the observed termination of the radio jet with the unity optical depth surface ($\tau = 1$) at 5 GHz. I measure a distance of ~ 0.07 arcsec (9.8 au projected for a distance of 140 pc, see [Section 5.3.3](#)) from the base of the jet to the $\tau = 1$ surface. Assuming a mean temperature of $T = 5000$ K, the emission measure at 0.07 arcsec is $EM = 3.5 \times 10^7 \text{ pc cm}^{-6}$ (see [Equation 3.17](#)). This yields an electron density of $n_e = 8.6 \times 10^5 \text{ cm}^{-3}$ at this location in the jet.

I then use a simple jet density and cross-section model to compute $\dot{M}_j$ in the ionised component (see [Section 2.2.2](#)). For a jet of density ρ_j , cross-section A_j , and velocity v_j , $\dot{M}_j = \rho_j A_j v_j$. Assuming a circular cross section of radius r_j and complete ionisation in the flow such that $\rho_j = \mu m_p n_e$ (where $\mu = 1.2$ is the mean atomic weight and m_p is the proton mass), the mass-loss rate can be re-written as

$$\left(\frac{\dot{M}_j}{M_\odot \text{ yr}^{-1}} \right) = 2.2 \times 10^{-11} \left(\frac{n_e}{10^5 \text{ cm}^{-3}} \right) \left(\frac{r_j}{\text{au}} \right)^2 \left(\frac{v_j}{100 \text{ km s}^{-1}} \right). \quad (5.1)$$

For an estimated jet radius of 6.3 au at 0.07 arcsec and an average radial velocity of 200 km s^{-1} , the mass-loss rate $\dot{M}_j = 1.5 \times 10^{-8} M_\odot \text{ yr}^{-1}$, within a factor of 3 of that found by [Lynch et al. \(2013\)](#). This is an underestimate of the total mass-loss rate as it is only a measure of the ionised component. An ionisation fraction of $\sim 14\%$ is found when comparing this value for $\dot{M}_j$ with the total mass-loss rate from [Podio et al. \(2012\)](#), which is consistent with previous measurements (e.g. [Coffey et al., 2008](#)).

As jets are ultimately powered by accretion (e.g. [Cabrit et al., 1990](#); [Hartigan et al., 1995](#)), the mass ejection to mass accretion ratio is therefore a key parameter to constrain the jet acceleration mechanism and launch site ([Cabrit, 2007](#)). [Hartigan et al. \(1995\)](#) inferred a mean one-sided ratio $\dot{M}_j / \dot{M}_{\text{acc}} \simeq 0.01$, however recent accretion rate estimates ([Agra-Amboage et al., 2011](#)) are an order of magnitude lower on average and therefore provide a ratio 10 times higher.

[Podio et al. \(2012\)](#) find a possible range for the mass accretion rate $\dot{M}_{\text{acc}} = 0.5 - 2 \times 10^{-6} M_\odot \text{ yr}^{-1}$ for DG Tau when comparing different estimates of this rate by different authors, and find $\dot{M}_j / \dot{M}_{\text{acc}} = 0.05 - 0.2$ for the mass ejection to mass accretion ratio in the [OI] emitting flow. The mass-loss rate derived in this work for the ionised component is consistent with this ratio when incorporated into the non-ionised component, compatible

with the range of $0.01 < \dot{M}_j/\dot{M}_{\text{acc}} < 0.1$ predicted by MHD models for D-winds (Ferreira et al., 2006) and $\dot{M}_j/\dot{M}_{\text{acc}} < 0.3$ for X-winds (Shu et al., 2000).

5.4 SUMMARY

In the case of DG Tau, these results suggest that the jet starts initially as a poorly collimated wind and becomes collimated on scales of 50 au, in line with MHD D-wind theory. I find a large initial opening angle of 86° within 2 au of the base of the jet which becomes smaller further out, a mass-loss rate of $\dot{M}_j = 1.5 \times 10^{-8} M_\odot \text{ yr}^{-1}$ for the ionised component, and a mass ejection to mass accretion ratio of $\dot{M}_j/\dot{M}_{\text{acc}} = 0.05 - 0.2$. These results are in accord with predictions of MHD jet-launching models.

The improved sensitivity of e-MERLIN has provided the highest resolution images of the CTTS DG Tau and the nearby Class I protostar DG Tau B at cm-wavelengths. This work gives a preview on how e-MERLIN will contribute to the study of low-mass YSOs and their outflows, as observations of the inner 20 au are needed to test different jet-launching scenarios. I have already probed these objects with a new level of angular resolution and sensitivity with e-MERLIN during the commissioning phase, and they will be further improved with the final array.

INTERMEDIATE-SCALE STUDIES OF YSOS AT 325 AND 610 MHz WITH THE GMRT

The study of low-mass YSOs at radio wavelengths has been predominantly constrained to frequencies > 1 GHz due to their weakness (~ 1 mJy), the sensitivity limitations of radio telescopes, and the fact that their spectra typically rise with frequency. For these reasons, historical radio measurements have been biased towards powerful, well-known objects. More recent studies of larger and less biased samples of low-mass, low-luminosity YSOs have provided clear evidence for distinct trends in the behaviour of the radio luminosity of these sources when compared with their bolometric and infrared luminosities (Scaife et al., 2011a, see also Chapter 4), similar to trends seen in higher luminosity sources (e.g. Anglada, 1995).

I conducted a pathfinder project with the Giant Metrewave Radio Telescope (GMRT) to observe a sample of three low-mass YSOs with known radio emission previously measured at gigahertz frequencies: L1551 IRS 5, T Tau and DG Tau. All three reside in the Taurus Molecular Cloud at a distance of 140 pc (e.g. Kenyon et al., 1994). The goal of these low frequency investigations was to determine the frequency at which the free-free emission from these YSOs becomes optically thin (see Section 3.2.1). This frequency is required to break the degeneracy between source size and gas density inherent within the characteristic property of emission measure (Equation 3.17) in these objects. Once the physical size of the emitting region is constrained, the total mass of the ionised gas around the YSO can be determined.

In this chapter I present the first investigations of YSOs at frequencies < 1 GHz. At 325 and 610 MHz, the GMRT has angular resolutions in between those of AMI and e-MERLIN which therefore allows structures on intermediate scales to be studied. I compile the spectral energy distributions for each source, and find that these new GMRT data show a continuation of the free-free spectrum extrapolated from gigahertz frequencies, and that

Part of this chapter has been published as: Ainsworth R. E., Scaife A. M. M., Ray T. P., Taylor A. M. Green D. A. and Buckle J. V., 2014, Tentative Evidence for Relativistic Electrons Generated by the Jet of the Young Sun-like Star DG Tau, *Astrophysical Journal Letters*, 792, L18–L22, doi:10.1088/2041 – 8205/792/1/L18.

the frequency at which the emission becomes optically thin has not yet been reached. In [Section 6.1](#) I present details of the observations and data reduction. I present the results in [Section 6.2](#) and discuss them in [Section 6.3](#). I summarise the conclusions in [Section 6.4](#).

6.1 OBSERVATIONS AND DATA REDUCTION

The observations were made using the GMRT ([Ananthakrishnan, 2005](#)), which consists of thirty 45 m dishes and is located about 80 km north of Pune, India. Fourteen of the thirty dishes are dispersed more or less randomly in a compact central array within a square kilometre, and the remaining sixteen dishes are spread out along three arms of an approximately “Y”-shaped configuration, with the longest interferometric baseline of about 25 km. See [Section 3.4.3](#) for more details.

Observations of the young stars L1551 IRS 5, T Tau and DG Tau were made at 325 and 610 MHz between 6 – 14 December 2012 (average epoch 2012.95). At 325 MHz, observations were taken for 7 hours per night over the course of three nights for a total of 21 hours and observations at 610 MHz were taken for 10 hours in a single run. See [Table 6.1](#) for number of hours on-source for each target. A total bandwidth of 32 MHz was observed, which was split into 256 spectral channels. The sample integration time was 16.9 s. The primary beam of the GMRT has a width at half power of approximately 85' at 325 MHz and 44' at 610 MHz. The observational details can be found in [Table 6.1](#).

The flux density scale was set through observations of 3C48 at the beginning and end of each observing run. For the cases where 3C48 set before the end of the run, 3C147 or 3C286 were observed. The flux densities were calculated using the AIPS task SETJY and were found to be 45.6 Jy at 325 MHz and 29.4 Jy at 610 MHz for 3C48, 55.1 Jy at 325 MHz for 3C147, and 20.8 Jy at 610 MHz for 3C286. Each target source was observed for a series of interleaved 10 min scans so as to maximise the uv coverage for imaging, and the nearby phase calibrator, J0431 + 206, was observed for 3 min after every two scans so as to monitor the phase and amplitude fluctuations of the telescope. The AIPS task GETJY retrieved flux densities of 2.78 ± 0.02 Jy at 325 MHz and 3.05 ± 0.05 Jy at 610 MHz for J0431 + 206.

Flagging of baselines, antennas, channels, and scans that suffered heavily from interference was performed for each night’s observation using standard AIPS tasks. Bandpass calibration was applied to each antenna using the flux calibrator sources. Five central frequency channels were then combined together with the task SPLAT and antenna-based phase and amplitude calibration was performed with CALIB. This calibration was then applied to the original data and averaged into 24 separate spectral channels. Target source data was then extracted from the larger datasets via the SPLIT task and the observations from each run were concatenated with DBCON for imaging. The specific tasks used and general pipeline for reducing this data is presented in [Appendix D](#).

Table 6.1.: Column 1 contains the source name; 2 the protostellar evolutionary class, 3 the Right Ascension in units of hours, minutes and seconds; 4 the Declination in units of degrees, minutes, and seconds; 5 the observing frequency; 6 the on-source observing time; 7 the measurements of the synthesised beam; 8 the integrated flux density; 9 the rms noise measured from the recovered map and 10 the spectral index extrapolated between the two GMRT observations for each source (see Section 6.2 for details).

Source	Class	J2000.0 Coordinates		ν (MHz)	Obs. time (hrs.)	HPBW, PA ($'' \times ''$, $^\circ$)	S_ν (mJy)	σ_{rms} ($\mu\text{Jy beam}^{-1}$)	α_{GMRT}
L1551 IRS 5	I	α ($^{\text{h}}$ $^{\text{m}}$ $^{\text{s}}$)	δ ($^\circ$ $'$ $''$)	325	6	11.4×9.5 , -88.5	1.19 ± 0.33	152	0.20 ± 0.47
				610	2	6.2×4.9 , 76.5	1.35 ± 0.13	51	
T Tau	II	04 21 59.4	+19 32 06	325	3	10.8×9.5 , -81.6	3.83 ± 0.31	106	0.13 ± 0.16
				610	2	6.0×5.0 , 83.8	4.16 ± 0.23	46	
DG Tau	II	04 27 04.7	+26 06 16.3	325	6	11.6×9.2 , 79.6	0.73 ± 0.15	146	-0.84 ± 0.48
				610	2	6.5×5.2 , 74.0	0.43 ± 0.10	89	

6.2 RESULTS

Due to the large primary beam of the GMRT, I followed [Garn et al. \(2007\)](#) and conducted wide-field imaging using facets. The task SETFC was used to create a list of facet positions for use in IMAGR. Each field was divided into 61 smaller facets for the 325 MHz data and into 31 facets for the 610 MHz data, and arranged in a hexagonal grid. In each case the area covered is large compared with the GMRT primary beam, allowing bright sources well outside of the observed region to be cleaned from the images. The faceting technique avoids the introduction of phase errors due to the non-planar nature of the sky ([Garn et al., 2007](#)). Each field went through several iterations of self-calibration and re-imaging, improving the noise levels up to 30% and significantly reducing the residual side lobes around bright sources. The resulting facets were then stitched together and corrected for the primary beam using FLATN. To illustrate the quality of the data, the central facet from the L1551 IRS 5 region is shown in [Figure 6.1](#) and the full, FLATN images for each source at each frequency are presented in [Appendix E](#).

Images of each field were produced with ROBUST set to 0 within IMAGR to optimise the trade-off between angular resolution and sensitivity. Combined channel maps at 325 and 610 MHz for each source are shown in [Figure 6.2](#), [Figure 6.3](#) and [Figure 6.4](#). Target sources were identified within the central facet with a peak flux density $> 3\sigma_{\text{rms}}$, where σ_{rms} is the rms noise determined from the maps and listed in [Table 6.1](#). Flux densities were extracted with JMFIT (with the exception of DG Tau, see [Section 6.3.5](#)). Errors on the flux densities are calculated as $\sigma = \sqrt{(0.05S_\nu)^2 + \sigma_{\text{rms}}^2 + \sigma_{\text{fit}}^2}$, where $0.05S_\nu$ is an assumed 5% absolute calibration error on the flux density S_ν , σ_{rms} is the rms noise and σ_{fit} is the fitting error returned from JMFIT. All errors are 1σ . Integrated flux densities, along with the dimensions of the synthesised beam for each source, are listed in [Table 6.1](#).

A visual inspection of the overall target fields suggests that a systematic displacement might be present. I have fit a number of bright, compact (presumably extragalactic) sources in each field using JMFIT in AIPS at both 325 and 610 MHz to compare the absolute positions. In the majority of cases, the positions at 325 MHz differ from those at 610 MHz by approximately $0''.86$ in declination for L1551 IRS 5, $0''.17$ for T Tau and $2''$ for DG Tau. The shift is understandable due to the difference of ionosphere with declination between the target and phase calibrator (up to $\approx 6^\circ$ separation for DG Tau), which will be worse at 325 MHz than 610 MHz. The positions at 610 MHz are in general consistent with those from the NRAO VLA Sky Survey (NVSS, [Condon et al., 1998](#)) to within an average of $0''.5$, making them more reliable than the positions at 325 MHz. However, due to a lack of low frequency radio surveys at higher resolution for this patch of the sky (NVSS has a spatial resolution of around $45''$) the absolute coordinates may have a residual uncertainty of around $0''.5$, although this should not have a significant impact as the GMRT spatial resolu-

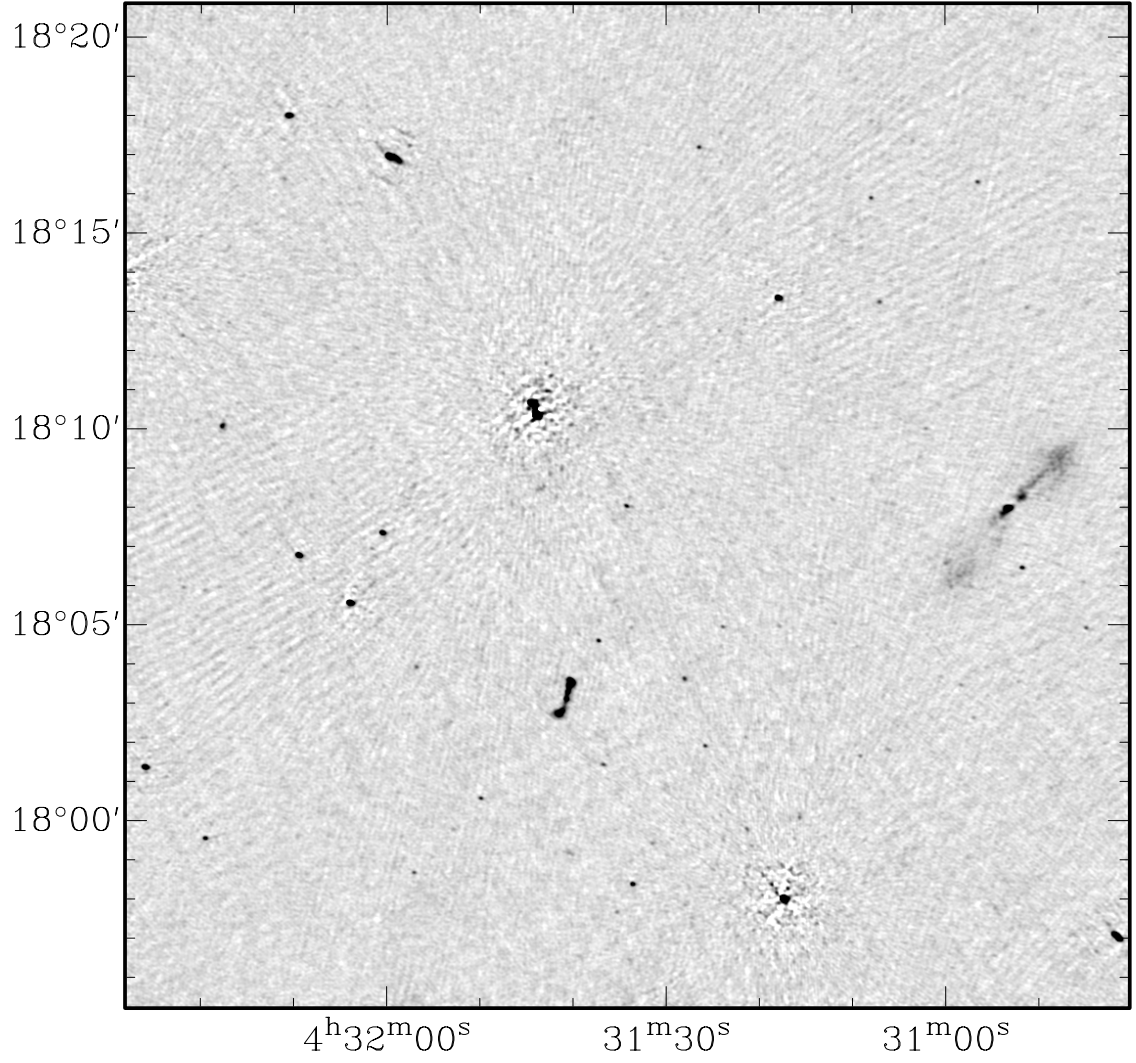


Figure 6.1.: The central facet of the GMRT combined channel map for the L1551 field at 610 MHz to illustrate the quality of the data. The grey-scale ranges between -0.2 and 1 mJy beam^{-1} , and the resolution of the image is $6''.2 \times 4''.9$, PA $76^\circ.5$. All coordinates are J2000.0.

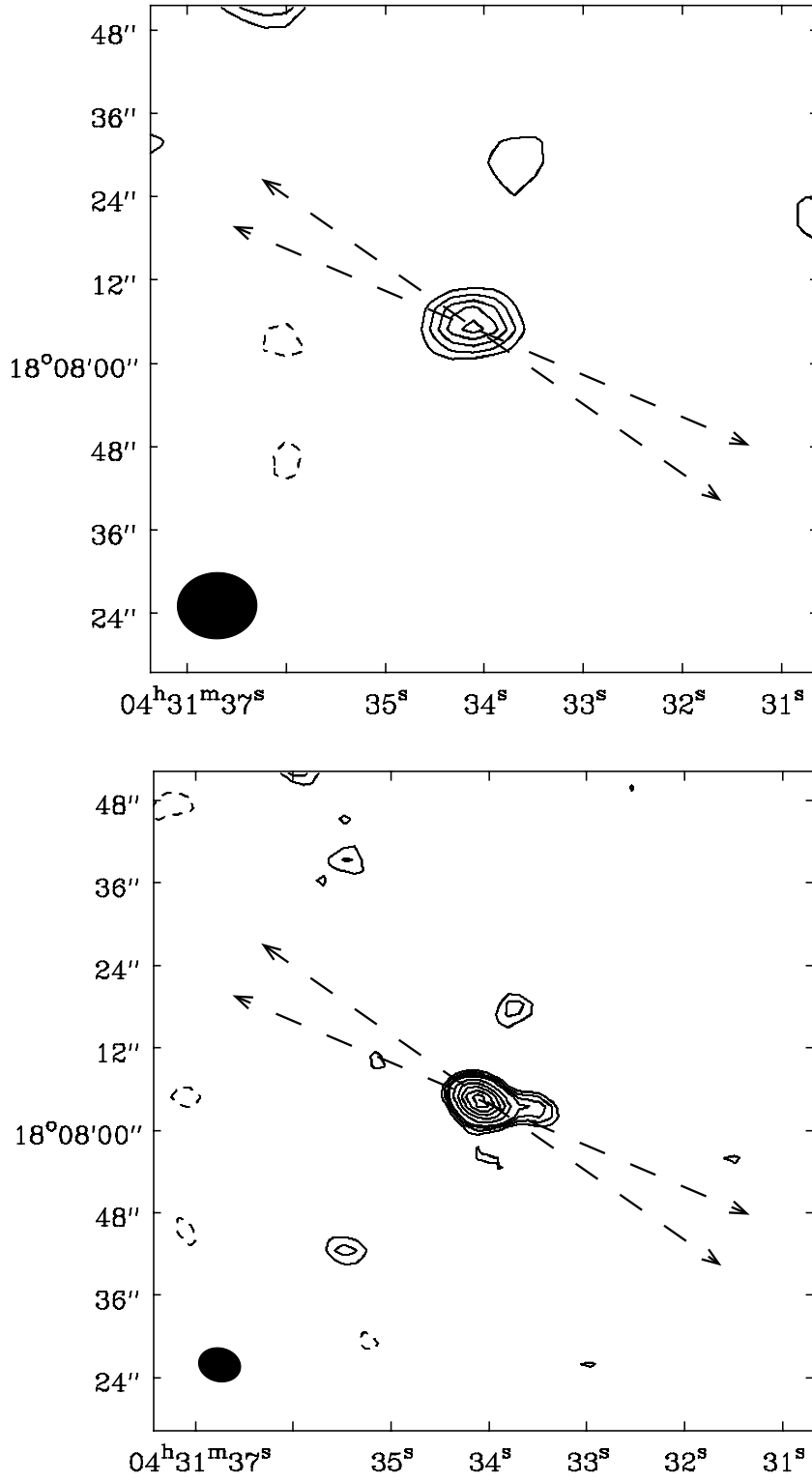


Figure 6.2.: The GMRT combined channels maps for L1551 IRS 5 (*top*) at 325 MHz with contour levels $-3, 3, 4, 5, 6, 7 \times \sigma_{\text{rms}}$ and (*bottom*) at 610 MHz with contour levels $-3, 3, 4, 5, 6, 9, 12, 15, 18, 21 \times \sigma_{\text{rms}}$. The values for σ_{rms} for each frequency are listed in [Table 6.1](#). All coordinates are J2000.0, the synthesised beam is shown as a filled ellipse in the bottom left corner of each map and the two known outflow axes (see [Section 6.3.1](#)) are denoted by the dashed lines.

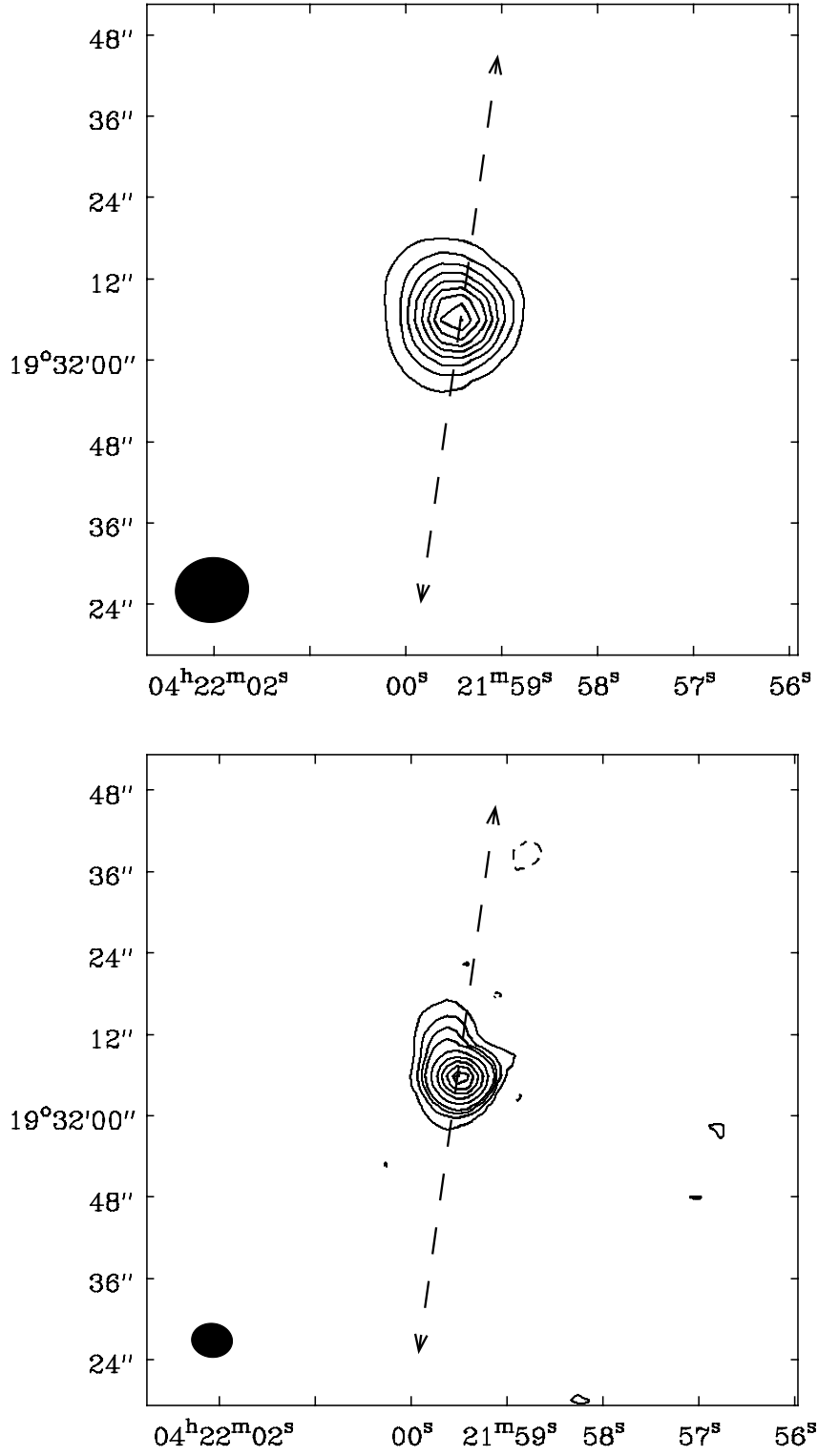


Figure 6.3.: The GMRT combined channels maps for T Tau (*top*) at 325 MHz with contour levels $-3, 3, 6, 9, 12, 15, 18, 21, 24, 27 \times \sigma_{\text{rms}}$ and (*bottom*) at 610 MHz with contour levels $-3, 3, 6, 9, 12, 20, 30, 40, 50, 60, 65 \times \sigma_{\text{rms}}$. The values for σ_{rms} for each frequency are listed in [Table 6.1](#). All coordinates are J2000.0, the synthesised beam is shown as a filled ellipse in the bottom left corner of each map and the known outflow axis is denoted by the dashed line.

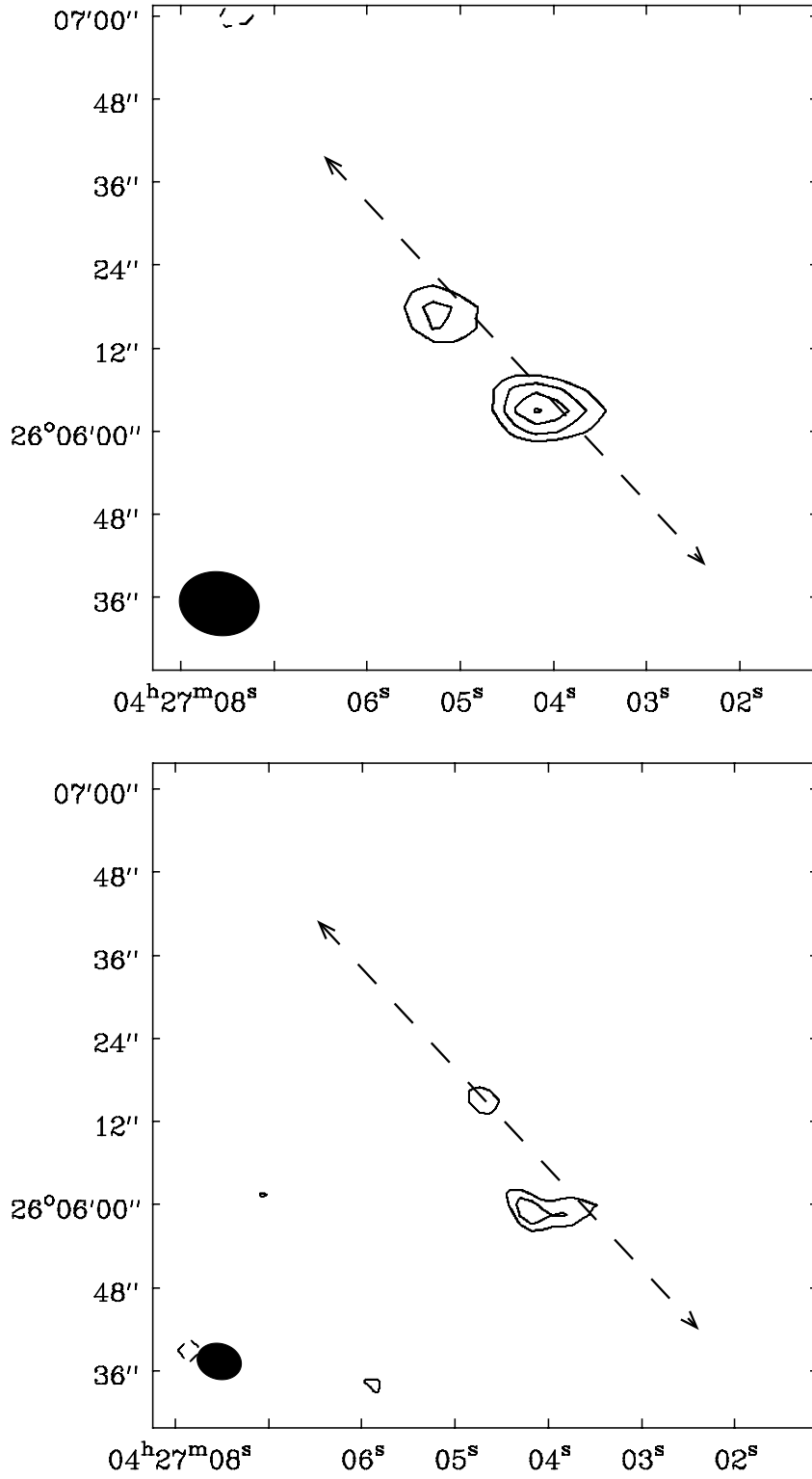


Figure 6.4.: The GMRT combined channels maps for DG Tau (*top*) at 325 MHz with contour levels $-3, 3, 4, 5, 6 \times \sigma_{\text{rms}}$ and (*bottom*) at 610 MHz with contour levels $-3, 3, 4 \times \sigma_{\text{rms}}$. The values for σ_{rms} for each frequency are listed in [Table 6.1](#). All coordinates are J2000.0, the synthesised beam is shown as a filled ellipse in the bottom left corner of each map and the known outflow axis is denoted by the dashed line.

ution is of order $5 - 10''$. I have therefore shifted the 325 MHz maps by $0''.86$ to the south in declination for L1551 IRS 5 and $2''$ to the south in declination for DG Tau to make them consistent with the 610 MHz images. I do not shift the 325 MHz map in the case of T Tau as this target was closest in position to the phase calibrator and does not suffer heavily from this problem.

The spectral index between the GMRT frequencies observed was calculated for each source using

$$\alpha_{\text{GMRT}} = \frac{\ln(S_{325}/S_{610})}{\ln(325/610)} \quad (6.1)$$

where S_{325} and S_{610} are the flux densities at frequencies 325 and 610 MHz, respectively. The error on the spectral index, $\delta\alpha_{\text{GMRT}}$, was calculated using standard propagation of error theory (e.g. Ku, 1966), where

$$\delta\alpha_{\text{GMRT}} = \frac{1}{|\ln(325/610)|} \left[\left(\frac{\delta S_{325}}{S_{325}} \right)^2 + \left(\frac{\delta S_{610}}{S_{610}} \right)^2 \right]^{1/2} \quad (6.2)$$

and δS_{325} and δS_{610} are the errors on the flux densities at 325 and 610 MHz, respectively. The spectral indices between the two GMRT frequencies for each source and their associated errors are listed in Table 6.1.

6.3 DISCUSSION

6.3.1 L1551

L1551 IRS 5 (HH 154; see Section 4.4) is a Class I, deeply embedded multiple protostellar system that drives a pair of closely aligned (within $\approx 12^\circ$) bipolar ionised jets with position angles of 67° and 55° (Rodríguez et al., 2003b). The high-velocity jets are themselves aligned with the larger scale bipolar molecular outflow (Snell et al., 1980), although more recent observations in CO reveal a more complex array of molecular outflow activity (Stojimirović et al., 2006; Wu et al., 2009). The binary (N and S) components are each comprised of a circumstellar dust disk (~ 10 au) and bipolar ionised jet, separated by 45 au (Rodríguez et al., 1998). Lim & Takakuwa (2006) report a third component approximately 13 au southeast of the N component as another circumstellar dust disk, suggesting that IRS 5 is instead a triple protostellar system. The IRS 5 sources are then nested within a larger $\sim 10,000$ au envelope (Fridlund et al., 2002).

The GMRT does not resolve the separate components, but detects the overall integrated emission over the IRS 5 system. At 325 MHz, L1551 IRS 5 is a point source with respect to the synthesised beam (see Figure 6.2 top). At 610 MHz however, the emission appears ex-

tended to the west (see [Figure 6.2 bottom](#)) consistent with the “anomalous redshifted lobe” (ARL) of CO emission ([Moriarty-Schieven & Wannier, 1991](#)). This emission has been seen to be highly collimated (length-to-width ratio of ~ 5) with an extent of 0.85 pc ([Stojimirović et al., 2006](#)). Possible origins of the east–west outflow include (1) a fossil outflow of the current IRS 5 molecular outflow, (2) a molecular outflow driven by a different or completely new source, or (3) the deflection of high-velocity molecular gas out of the main outflow by some dense structure ([Moriarty-Schieven & Wannier, 1991](#); [Pound & Bally, 1991](#); [Stojimirović et al., 2006](#)).

The GMRT spectral index $\alpha_{\text{GMRT}} = 0.20 \pm 0.47$ is in agreement with previous measurements made at gigahertz frequencies (e.g. [Ainsworth et al., 2012](#), see [Chapter 4](#)) and consistent with free–free emission from a collimated jet ([Reynolds, 1986](#)).

6.3.2 T Tau

Historically, T Tau has served as the prototype for an entire class of YSOs ([Joy, 1945](#)), but has proved to be more and more unique over the years. It is a Class II triple system consisting of T Tau N, an optically visible K0 star, and T Tau S, a heavily extincted binary system approximately $0''.6$ south of T Tau N ([Dyck et al., 1982](#); [Koresko, 2000](#)). The southern binary is completely undetectable at visible wavelengths ([Stapelfeldt et al., 1998](#)), but is brighter than T Tau N at $\lambda > 3 \mu\text{m}$ and may dominate the overall energetics ([Ghez et al., 1991](#); [Herbst et al., 1997](#)). The easternmost object of the binary (T Tau Sa) has been revealed to be the “infrared companion” whilst the other object (T Tau Sb) appears to be a relatively typical, but embedded, T Tauri star ([Duchêne et al., 2002](#); [Beck et al., 2004](#)).

The most prominent outflow from this system has a very well defined axis at a PA of 325° , with the northern lobe extending up to 0.78 pc in projection from T Tau and the southern lobe reaching 0.77 pc, resulting in a total projected extent of 1.55 pc ([Reipurth et al., 1997](#)). T Tau Sa is believed to power the large-scale northwest–southeast outflow, whilst T Tau N is responsible for an east–west outflow, and T Tau Sb drives an outflow in the southwest direction ([Gustafsson et al., 2010](#)). There are many shocks and extended features associated with this system of outflows.

At 325 and 610 MHz (see [Figure 6.3](#)), T Tau shows clear extension in the north–south direction. The spectral index between the GMRT data is $\alpha_{\text{GMRT}} = 0.13 \pm 0.16$, consistent with the overall radio spectral index α' (see [Figure 6.5](#)) and indicative of free–free radiation from a collimated jet. The GMRT does not resolve the separate components but detects the overall emission of the T Tau system, which shows clear extension directly to the north. This morphology is consistent with the “A” bubble of emission described by [Herbst et al. \(1997\)](#) and is likely associated with T Tau Sa driving the northwest–southeast outflow.

6.3.3 *DG Tau*

DG Tau is one of the most enigmatic young stars studied today (see [Chapter 5](#)). It is a highly active T Tauri star (Class II), and has a bipolar outflow (e.g. [Lavalley et al., 1997](#)) although the blueshifted side is better studied. It was one of the first T Tauri stars to be associated with an optical jet and exhibits several shocks and knots in its outflow, the most prominent of which was first observed $8''$ away from the star (HH 158, [Mundt & Fried, 1983](#)). The optical blueshifted jet has a PA of 223° close to the source ([Lavalley et al., 1997](#)), however large-scale studies trace the jet out to a total projected distance of approximately 0.5 pc and show that the position angle of the outflow changes to 218° (HH 702, [McGroarty & Ray, 2004](#)). Additionally, knots and clumps in the outflow have proper motions that deviate from the bulk jet motion ([Eislöffel & Mundt, 1998](#)). Radial velocities in the jet have been found to range up to 350 km s^{-1} with average velocities of 200 km s^{-1} ([Dougados et al., 2000](#)). Extended X-ray emission has been detected for the DG Tau jet out to $5''$ coincident with the optical outflow ([Güdel et al., 2008](#)) and, in the radio, DG Tau has been shown to have a compact and elongated morphology in the known outflow direction and to possess a spectral index typical of free-free emission at frequencies greater than 5 GHz ([Cohen et al., 1982](#); [Cohen & Bieging, 1986](#); [Rodríguez et al., 2012](#); [Scaife et al., 2012a](#); [Lynch et al., 2013](#); [Ainsworth et al., 2013](#)).

At 325 and 610 MHz, DG Tau is marginally detected (4 and $3 \sigma_{\text{rms}}$, respectively, see [Figure 6.4](#)) and appears as a point-source. The spectral index between the GMRT data is $\alpha_{\text{GMRT}} = -0.84 \pm 0.48$, vastly different than the overall spectral index $\alpha' = 0.22 \pm 0.04$ (see [Section 6.3.4](#)) which is inconsistent with free-free emission and indicative of non-thermal emission. However, there is a puzzling offset between the radio emission associated with the source at each GMRT frequency (see [Figure 6.7](#) for an overlay). I have calculated the optical stellar position, corrected for proper motion/precession for this epoch ([Zacharias et al., 2013](#)), and the predicted position is denoted by the asterisk in [Figure 6.7](#). At 610 MHz, the emission is consistent with the optical stellar position indicating it is associated with the base of the jet, however the 325 MHz emission is several arcseconds to the east. Emission at the noise level at this location is also seen in the EVLA maps at 5.4 and 8.5 GHz ([Lynch et al., 2013](#)). It is possible that this emission is associated with the DG Tau counterjet, however without a stronger signal and a spectral index it is impossible to confirm at this time. If the emission at 325 MHz is not associated with the base of the jet, than the spectral index α_{GMRT} is unreliable as it is extrapolated between two separate sources of emission, and only the 610 MHz flux density is relevant to the SED. I therefore only use the flux density at 610 MHz to fit the SED in [Section 6.3.4](#) and plot the flux density at 325 MHz for illustration (see [Figure 6.6](#)).

In addition to emission associated with the base of the DG Tau jet and potentially the counterjet, a significant signal is detected to the southwest that is extended in an approximate east–west direction, and I investigate the nature of this emission in [Section 6.3.5](#).

6.3.4 Spectral Energy Distributions

I conducted an extensive literature search for unresolved, integrated flux densities to include in the spectral energy distributions for T Tau and DG Tau and used the previously compiled SED from [Section 4.5.3](#) for L1551 IRS 5 (see [Appendix C](#) for references). The list of archival data used in the spectral energy distributions for T Tau and DG Tau can be found in [Appendix F](#). Only data $\nu < 3$ THz ($\lambda > 100 \mu\text{m}$) were included in the fit, but *IRAS* data $\nu > 3$ THz are included in the plots for illustration. METRO ([Hobson & Baldwin, 2004](#)) was used to fit a combined radio power law, with spectral index α' , and blackbody model to the larger dataset for each source following [Section 4.5.3](#). For the two Class II sources, T Tau and DG Tau, the likelihood distribution pushed the upper limit of the prior range for the dust temperature, $\Pi_{T_d}(5, 45)$. I therefore used the characteristic temperatures found from measurements in the sub-millimetre for these targets from [Andrews & Williams \(2005\)](#) which provide good fits to the SEDs. The results are presented in [Table 6.2](#) and the SEDs with the model fits are shown in [Figure 6.5](#) and [Figure 6.6](#).

For all three targets, the GMRT data show a continuation of the spectral index extrapolated from gigahertz frequencies, and the transitional frequency at which the emission becomes optically thin has not yet been reached. The spectral indices for all three sources are consistent with that from a collimated jet (~ 0.25 , [Reynolds, 1986](#)). The results for L1551 IRS 5 are consistent with [Section 4.5.3](#). It is clear from [Table 6.2](#) that the Class I and Class II SEDs are qualitatively different: the value of β for L1551 IRS 5 indicates that there is still a contribution to the SED from the envelope, in comparison with T Tau and DG Tau which have $\beta < 1$, indicating large dust grains in their circumstellar disks and lack of a circumstellar envelope (see [Section 2.4.2](#)).

Table 6.2.: SED results. Column 1 contains the source name; 2 the spectral index; 3 the opacity index and 4 the dust temperature. ^a Characteristic temperatures from [Andrews & Williams \(2005\)](#).

Source	α'	β	T_d (K)
L1551 IRS 5	0.23 ± 0.02	1.48 ± 0.06	26.95 ± 1.61
T Tau	0.18 ± 0.01	0.79 ± 0.02	62^a
DG Tau	0.22 ± 0.04	0.72 ± 0.02	40^a

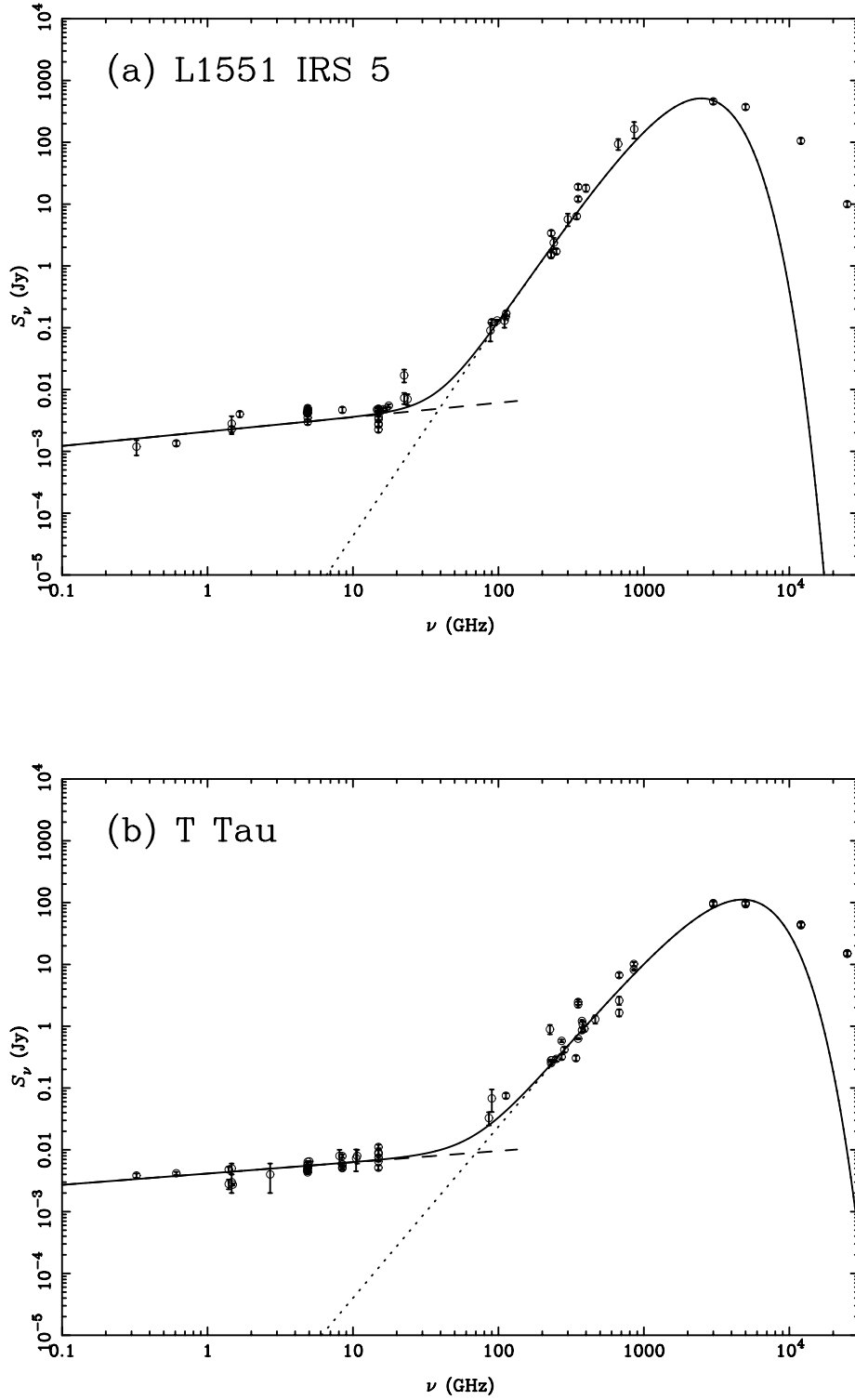


Figure 6.5.: The spectral energy distributions for (a) L1551 IRS 5 and (b) T Tau modelled with a combined radio power-law α' (dashed line) and modified blackbody with opacity index β and dust temperature T_d (dotted line) listed in Table 6.2. The total fit is shown as a solid line.

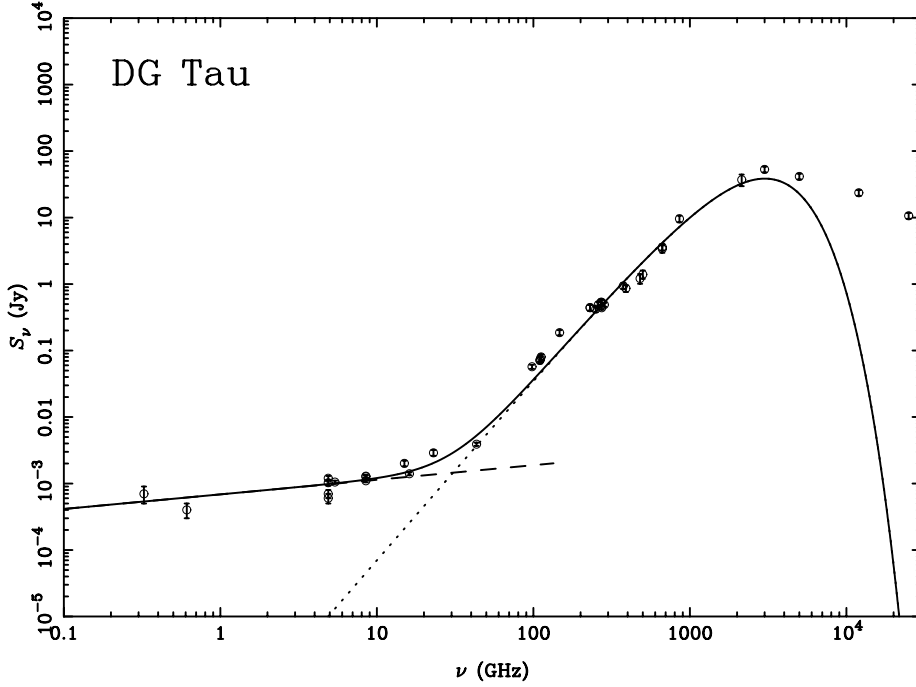


Figure 6.6.: The spectral energy distribution for the DG Tau jet close to the source, modelled with a combined radio power-law a' (dashed line) and modified blackbody with opacity index β and dust temperature T_d (dotted line) listed in Table 6.2. The total fit is shown as a solid line.

6.3.5 The DG Tau Bow Shock

I re-imaged the 610 MHz data convolved with the same CLEAN beam as the 325 MHz data (see Table 6.1 for the dimensions of the synthesised beam) to better detect the significant extended emission $\approx 18''$ (2,500 au) to the southwest of DG Tau and directly compare the two datasets. I recover an rms noise of $\sigma_{\text{rms}} = 93 \mu\text{Jy}$ in the new 610 MHz map. An overlay of the resulting maps is shown in Figure 6.7.

Based on its curved morphology at 610 MHz (further enhanced in the original higher resolution, ROBUST=0 image, see Figure 6.4), I identify this radio emission to be associated with the prominent bow shock reported by Eislöffel & Mundt (1998, driven by their Knot C) when due allowance is made for its tangential motion in the intervening period. These authors detect the associated bright knot $8''.7$ away from the star (epoch 1986.99), traveling across the sky at $(0''.168 \pm 0''.007) \text{ yr}^{-1}$ and $\text{PA} = 216.6 \pm 2.7$. Based on a simple extrapolation in time, the position of the knot is expected to be $\approx 13''$ away from the star at the epoch of the GMRT observations, and this is confirmed by nearly coeval optical observa-

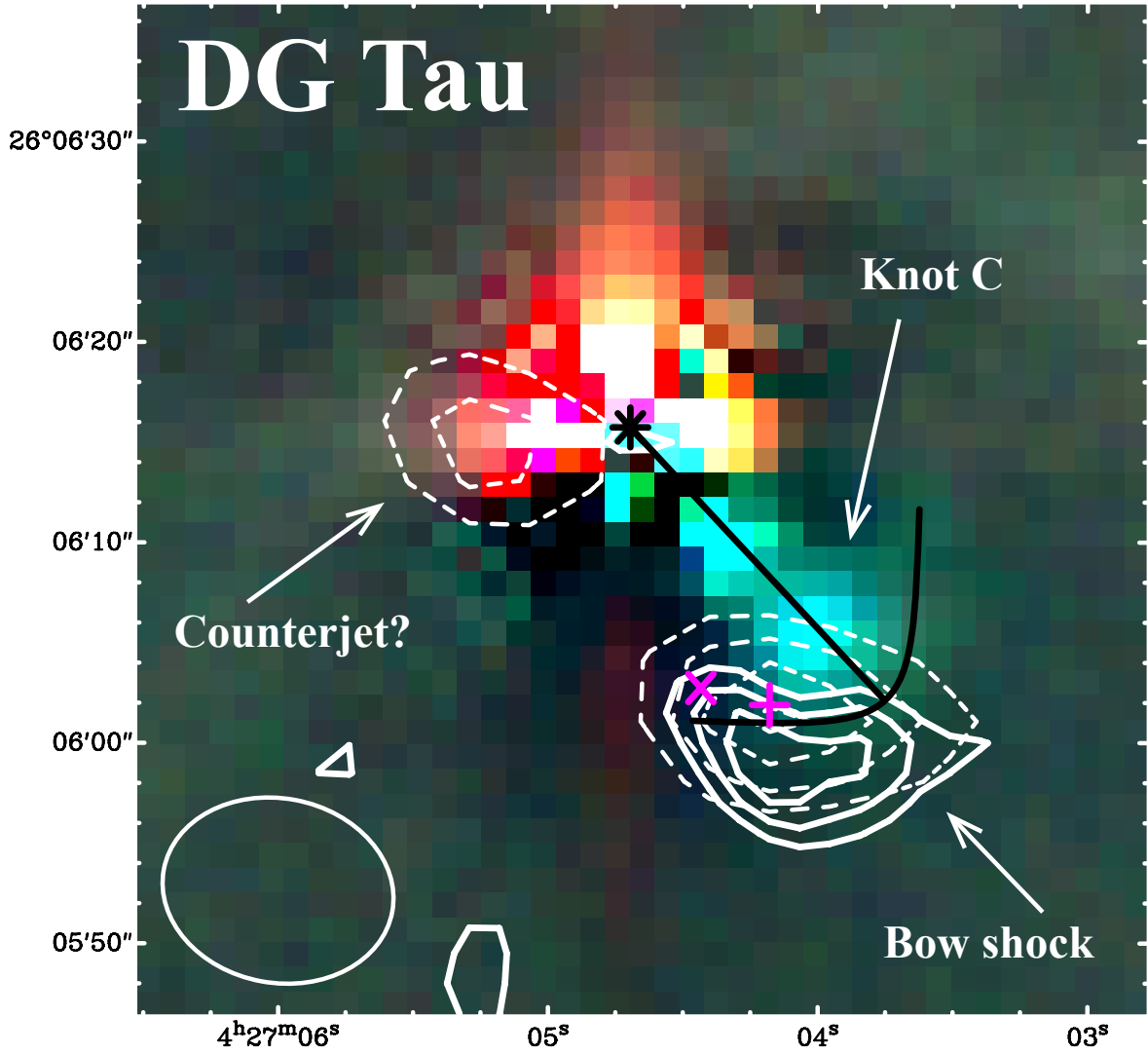


Figure 6.7.: The GMRT observations at 325 MHz (dashed contours) and 610 MHz (solid contours) overlaid on a composite RGB image built from I, $H\alpha$ and [SII] bands from the TLS Alfred Jensch Schmidt Telescope at a similar epoch (2012.92; B. Stecklum, private communication) to illustrate detection of the bow shock driven by Knot C from [Eislöffel & Mundt \(1998\)](#). GMRT contours are $-3, 3, 4, 5, 6 \times \sigma_{\text{rms}}$, where $\sigma_{\text{rms}} = 146 \mu\text{Jy beam}^{-1}$ at 325 MHz and $93 \mu\text{Jy beam}^{-1}$ at 610 MHz, although I note there are no negative contours within the section of the field shown. The synthesised beam is shown as an ellipse in the bottom left corner. All coordinates are J2000.0. The EVLA positions of the bow shock at 5.4 and 8.5 GHz are shown as a plus (+) and a cross (x), respectively (see [Table 6.3](#); [Lynch et al., 2013](#)). The optical stellar position corrected for proper motion ([Zacharias et al., 2013](#)) is shown as an asterisk (*) and the optical jet axis and bow shock are shown as solid black lines. I note there is a 3σ contour at 610 MHz at the optical stellar position tracing the base of the jet that may be difficult to see.

tions taken with the Thüringer Landessternwarte (TLS) Alfred Jensch Schmidt Telescope (epoch 2012.92; Bringfried Stecklum, private communication 2014). The radio emission is detected at the edge of the optical knot (see Figure 6.7), indicating the emission arises close to, if not at, the shock front itself.

There is a slight offset of the peak emission from the optical jet axis (and thus apex of the bow shock). Radio emission at this location is also apparent in nearly coeval (epoch 2012.22) observations from the expanded-VLA (EVLA) at 5.4 and (marginally) 8.5 GHz (Lynch et al., 2013, see also Figure 3 in Rodríguez et al. 2012). The peak of the significant signal detected with the EVLA at 5.4 GHz is in almost perfect agreement with the emission at 325 MHz and within $\sim 3''$ of the peak of the 610 MHz emission. The positional uncertainty of the bow shock in the GMRT data is $\sim 1''$ relative to other sources detected in the same image at both 325 and 610 MHz based on the spatial resolution and signal-to-noise ratios (Condon et al., 1998), and I find the peak locations of the GMRT data consistent within these uncertainties.

I extrapolate the results of Condon (1984, e.g., following similar procedures as in the Appendix of Anglada et al. 1998), and calculate the likelihood of this emission arising from a background extragalactic object based on the separation from DG Tau and the optical jet axis. It is assumed that all the background sources have the same effective spectral index α . Therefore the flux density scales as $S_\nu \propto \nu^\alpha$ and the number of background sources observed at frequency ν with a limiting flux density S_0 will be the same number observed at ν_1 with a flux density above a limit given by $S_0(\nu/\nu_1)^{-\alpha}$. The expected number of background sources in a field of angular diameter θ_F and $\alpha = -0.7$ (Condon, 1984) is given by

$$\langle N \rangle = 1.4 \left\{ 1 - \exp \left[-0.0066 \left(\frac{\theta_F}{\text{arcmin}} \right)^2 \left(\frac{\nu}{5 \text{ GHz}} \right)^2 \right] \right\} \left(\frac{S_0}{\text{mJy}} \right)^{-0.75} \left(\frac{\nu}{5 \text{ GHz}} \right)^{-2.52} \quad (6.3)$$

(Anglada et al., 1998). The probability of finding a background object within $\pm 20^\circ$ in PA from the jet axis and within a distance of $18''$ from the star (an area of about 110 arcsec^2), is therefore 0.0004 (or $\sim 10^{-3}$ if considering a symmetric bipolar jet). It is therefore reasonable to propose that this emission arises from the DG Tau bow shock. A plausible explanation for the offset from the optical jet axis could be due to the jet slamming into an inhomogeneous medium.

A Synchrotron Jet

Due to the asymmetric (and non-Gaussian) nature of the emission at 325 and 610 MHz, flux densities were extracted for the bow shock following the technique described in Green (2007) and the results are listed in Table 6.3. This method calculates flux densities by removing a tilted plane fitted to the local background and integrating the remaining flux. This is done by drawing a polygon around the source and fitting a tilted plane to the pixels

around the edge of the polygon. Where an edge of the polygon crosses a region confused by another source the background is subjective and this edge is omitted from the fitting. Since the extracted flux density is dependent to some degree on the background emission, I repeat this process using five irregular polygons, each varying slightly in shape. The final flux density is the average of that extracted from the five polygons. The errors are calculated as in [Section 6.2](#) where σ_{fit} is now the standard deviation of the fluxes measured in the five polygonal apertures. To remain consistent, I also use this method to extract flux densities for the emission near the base of the DG Tau jet in the $\text{ROBUST} = 0$ maps and these values are listed in [Table 6.1](#).

I then extract flux densities from the EVLA data at 5.4 and 8.5 GHz ([Lynch et al., 2013](#)) following the same technique as described above (image files obtained from Christene Lynch, private communication 2014) and combine these data with the GMRT measurements to construct the spectrum for the DG Tau bow shock (see [Figure 6.8](#)). Flux densities used in the fitting and positions of the peak emission of the bow shock with frequency are listed in [Table 6.3](#).

Using METRO, I fit a power-law spectral index α to the spectrum and find $\alpha = -0.89 \pm 0.07$, distinctly discrepant with free-free emission and indicative of synchrotron radiation. I dismiss gyro-synchrotron radiation as the emission mechanism at this location in the jet as kilogauss magnetic field strengths would be required which are expected to be present only close to the stellar surfaces ([Ray et al., 1997](#)).

The combination of the synchrotron spectrum with the detection of the emission at the edge of the optical knot implies active particle acceleration at the shock. The acceleration of relativistic particles may not be altogether unlikely in shocked regions where the fast thermal jet impacts on the ambient medium ([Carrasco-González et al., 2010a](#)). Electrons and protons can gain energy via the first-order Fermi mechanism, by diffusing upstream across a shock front and gaining additional energy after recrossing downstream relative to the shock ([Drury, 1991](#)).

Although the radio spectra of YSOs are typically dominated by thermal radiation emitted by jet plasma, the dominance of an additional emission mechanism is being revealed at these low frequencies. This investigation of a young star at very low frequencies exposes a potentially new regime for studying the non-thermal processes, and hence the magnetic fields, associated with YSOs. Although the function of the magnetic field in the role of jet launching has been hotly debated (see [Section 2.3](#)), its relevance on large-scales is less studied and the magnetic field strength remains the last piece of the physical puzzle regarding protostellar jets ([Ray, 2009](#)).

The relativistic particle energy present can be estimated from the *minimum energy requirements* for synchrotron radiation (see Section 16.5 of [Longair, 2011](#)). The radio luminosity L_ν at frequency ν can be related to the energy spectrum of the relativistic electrons and the

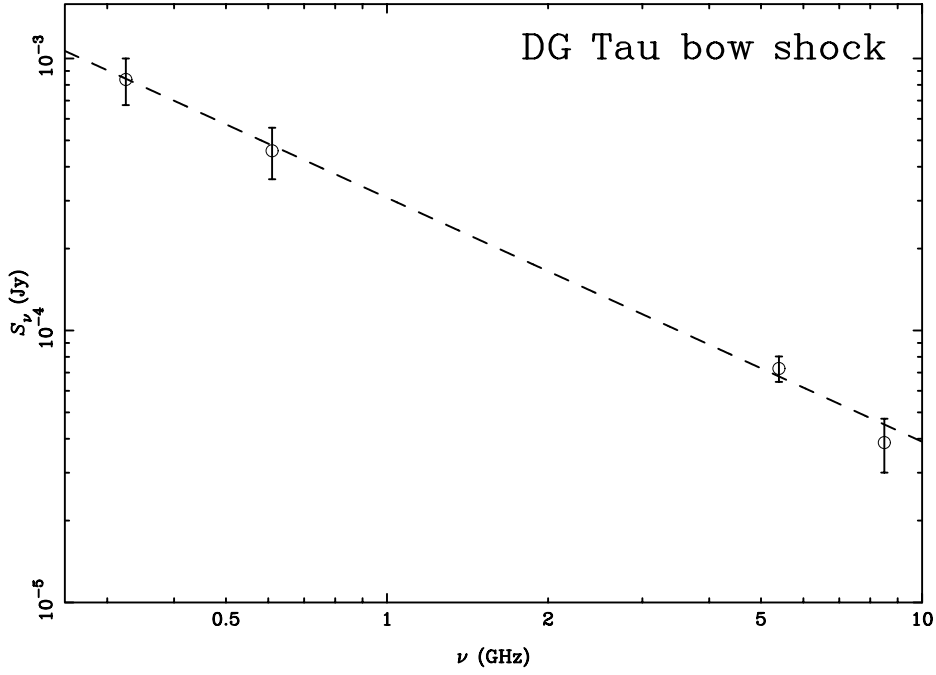


Figure 6.8.: Spectrum of the DG Tau bow shock. The GMRT data at 325 and 610 MHz and EVLA data at 5.4 and 8.5 GHz used are listed in [Table 6.3](#). Dashed line denotes a spectral index $\alpha = -0.89$.

magnetic flux density B in the source. The radio luminosity may be produced either by a large flux of relativistic electrons in a weak magnetic field or vice versa, however there is no way of deciding which combination produces the observed L_ν . Between the extremes of dominant magnetic field and dominant particle energy there is a minimum total energy requirement.

The total energy present in the source responsible for the radio emission is

$$W_{\text{total}} = G(\alpha)\eta L_\nu B^{-3/2} + V \frac{B^2}{2\mu_0} \text{ J} \quad (6.4)$$

where η is the ratio of the energy of the heavy particle (proton) population to that of the electron population, V is the source volume, μ_0 is the vacuum permeability and $G(\alpha)$ is

Table 6.3.: DG Tau bow shock results. Column 1 lists the telescope used; 2 the observing frequency; 3 the integrated flux density and columns 4 and 5 list the Right Ascension and Declination of the peak emission measured with the AIPS task MAXFIT. ^a The EVLA observations at 5.4 and 8.5 GHz are from [Lynch et al. \(2013\)](#).

Telescope	ν (MHz)	S_ν (μ Jy)	$\alpha_{J2000.0}$ (^h ^m ^s)	$\delta_{J2000.0}$ ([°] ['] ^{''})
GMRT	325	837 ± 163	04 27 04.15	+26 06 01.3
GMRT	610	458 ± 98	04 27 04.18	+26 05 59.3
EVLA	5400 ^a	73 ± 8	04 27 04.18	+26 06 01.9
EVLA	8500 ^a	39 ± 9	04 27 04.44	+26 06 02.7

a function of the spectral index and of the minimum and maximum frequencies of the observed radio spectrum. $G(\alpha)$ is defined as

$$G(\alpha) = \frac{1}{a(p)(p-2)} [v_{\min}^{-(p-2)/2} - v_{\max}^{-(p-2)/2}] v^{(p-1)/2} \times \frac{(7.4126 \times 10^{-19})^{-(p-2)}}{2.344 \times 10^{-25}} (1.253 \times 10^{37})^{-(p-1)/2} \quad (6.5)$$

where

$$a(p) = \frac{\sqrt{\pi}}{2} \frac{\Gamma(\frac{p}{4} + \frac{19}{12}) \Gamma(\frac{p}{4} - \frac{1}{12}) \Gamma(\frac{p}{4} + \frac{5}{4})}{(p+1) \Gamma(\frac{p}{4} + \frac{7}{4})} \quad (6.6)$$

and $p = 1 - 2\alpha$. (I note that [Longair \(2011\)](#) uses the notation $L_\nu \propto \nu^{-\alpha}$, however I change all relevant equations here to reflect the $\propto \nu^\alpha$ notation used throughout this thesis.)

The minimum total energy can be found by minimising [Equation 6.4](#) with respect to B ,

$$B_{\min} = \left[\frac{3\mu_0}{2} \frac{G(\alpha)\eta L_\nu}{Vf} \right]^{2/7} T \quad (6.7)$$

where I have included a volume filling factor, f , to describe the assumed fraction of the volume occupied by radio emitting material. This magnetic flux density $B_{\min}$ corresponds approximately to equality of the energies in the relativistic particles and magnetic field, often referred to as *equipartition*. The minimum energy requirement corresponding to equipartition is thus

$$W_{\text{total}}(\min) = \frac{7}{6\mu_0} (Vf)^{3/7} \left[\frac{3\mu_0}{2} G(\alpha)\eta L_\nu \right]^{4/7} J. \quad (6.8)$$

I use the result in this work for the spectral index along with Equation 6.7 and Equation 6.8 to calculate the minimum requirements to generate the observed synchrotron emission. The values of the magnetic field strength and minimum energy which come out of these arguments should be considered as order of magnitude estimates only (Longair, 2011). For the measured flux density at 610 MHz, $\alpha = -0.89$, $V \simeq 6 \times 10^{43} \text{ m}^3$ with $f = 0.5$, and $\eta = 40$ for electrons undergoing Fermi shock acceleration in a non-relativistic jet (Beck & Krause, 2005), I find $B_{\min} \simeq 1 \times 10^{-8} \text{ T}$ ($1 \times 10^{-4} \text{ G}$) and $W_{\text{total}}(\min) \simeq 4 \times 10^{33} \text{ J}$ ($4 \times 10^{40} \text{ erg}$) for the DG Tau bow shock. Such a field strength is similar to values obtained from Zeeman observations in star-forming cores (Crutcher, 1999).

Cosmic Rays from a Low-mass YSO Jet?

Diffusive shock acceleration is thought to be the mechanism that gives rise to cosmic rays, and therefore jets from YSOs could potentially provide a new laboratory to test the theory of Galactic cosmic ray production (Ray, 2010). Shocks with large Mach numbers ($M = v_s/c_s \gg 1$) may give rise to efficient particle acceleration, where v_s is the shock velocity and c_s is the sound speed. For $v_s \approx 110 \text{ km s}^{-1}$ (Eisloffel & Mundt, 1998) and a temperature of $T \sim 10^4 \text{ K}$, the sound speed at the bow shock is $c_s \sim 10 \text{ km s}^{-1}$ and therefore $M \approx 11$, which satisfies the limit of very strong shocks (Longair, 2011).

Cosmic ray electrons accelerated in association with star formation have already been shown to arise from the Galactic Center (Carretti et al., 2013) and parallel studies of gamma rays and radio emission have revealed an excess at GeV energies within the Milky Way (Orlando & Strong, 2013). Assuming $W_{\text{total}}(\min)$ is released over the dynamical timescale of the bow shock ($t_{\text{bow}} \sim 100 \text{ years}$, Eisloffel & Mundt, 1998), the luminosity released in the form of low energy cosmic ray electrons would be $L_e \approx W_{\text{total}}(\min)/(\eta t_{\text{bow}}) \sim 3 \times 10^{29} \text{ erg s}^{-1}$ over this period. Furthermore, if the average outflow phase of a T Tauri star lasts $\tau \sim 1 \text{ Myr}$ and the star formation rate in the Milky Way is $\sim 1 \text{ star per year}$ ($0.68 - 1.45 M_{\odot}$; Robitaille & Whitney, 2010), the number of stars in the Galaxy in this phase at any given time is thus $\sim 10^6$. Therefore, the total Galactic luminosity of cosmic ray electrons generated in YSO jets is $L_e^{\text{tot.}} = 10^6 \times L_e \sim 3 \times 10^{35} \text{ erg s}^{-1}$.

Due to their low energy and the strength of the cloud magnetic field, I calculate the built-up energy density in the cloud to compare with that in the ISM, as it is not clear whether these cosmic ray electrons can escape the molecular cloud region over its lifetime. The Taurus Molecular Cloud has an approximate volume $V_c \sim 3 \times 10^{53} \text{ m}^3$ ($3 \times 10^{59} \text{ cm}^3$; Rebull et al., 2010), therefore the output from a single YSO gives rise to an energy density of $U_e = W_e/V_c = L_e\tau/V_c \approx 3 \times 10^{-17} \text{ erg cm}^{-3}$ ($2 \times 10^{-5} \text{ eV cm}^{-3}$). Assuming an average cloud lifetime of 10 Myr (e.g. Bergin & Tafalla, 2007) and a star formation rate of $\sim 8 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ (forming YSOs of mass $\sim 1 M_{\odot}$; Lada et al., 2010), an energy density of $U_e^{\text{tot.}} = U_e \times 10^7 \text{ yr} \times 8 \times 10^{-5} M_{\odot} \text{ yr}^{-1} / 1 M_{\odot} \sim 2 \times 10^{-2} \text{ eV cm}^{-3}$ can be supported. The

Galactic cosmic ray electron energy density is $\sim 10^{-2} \text{ eV cm}^{-3}$, hence the pressure from cosmic rays accelerated by these YSO systems within the cloud is similar to that from the ISM. This calculation has been done for a region with a known low star formation efficiency and the corresponding energy density for regions of higher efficiency, for example in regions such as the core of the Orion Nebula ($\sim 7 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1}$, [Lada et al., 2010](#)), could be considerably higher. It is therefore plausible that cosmic ray electrons could escape from molecular cloud regions over their lifetimes and contribute to the Galactic cosmic ray population.

For $B_{\min} = 1 \times 10^{-4} \text{ G}$ and the photon energy $E_{\gamma} = h\nu = 2.5 \times 10^{-6} \text{ eV}$ for $\nu = 610 \text{ MHz}$ (where h is Planck's constant), the Lorentz factor γ is

$$\gamma = \left[\left(\frac{E_{\gamma}}{m_e} \right) \left(\frac{B_{\text{crit}}}{B_{\min}} \right) \right]^{1/2} \approx 1400 \quad (6.9)$$

where $m_e = 0.5 \text{ MeV}$ is the rest mass of the electron and $B_{\text{crit}} = (2\pi m_e^2 c^3)/(he) \sim 4.4 \times 10^{13} \text{ G}$ is the electron critical magnetic field at which the cyclotron energy of an electron reaches the electron mass energy. This yields an electron energy of $E_e = \gamma m_e \approx 700 \text{ MeV}$. For this γ , the Larmor radius is

$$r_L \approx \frac{E_e}{ecB_{\min}} \approx 2 \times 10^8 \text{ m} \sim 1 \times 10^{-3} \text{ au}. \quad (6.10)$$

The acceleration time for such cosmic ray electrons is $t_{\text{acc}} = r_L/(c\beta) \approx 115 \text{ days}$ for $\beta = v_s/c \approx 10^{-3}$. Such a short acceleration time implies ongoing acceleration at the shock, although this is a lower limit and factors such as turbulence can considerably increase this timescale.

6.4 SUMMARY

In this chapter I have presented the first investigations of low-mass YSOs at sub-gigahertz frequencies. At 325 and 610 MHz, the GMRT has angular resolutions between those of AMI and e-MERLIN, allowing structures on intermediate scales to be studied. I compile the spectral energy distributions for each source, and find that these new GMRT data show a continuation of the free-free spectrum extrapolated from gigahertz frequencies, and that the frequency at which the emission becomes optically thin has not yet been reached.

The results for DG Tau suggest that non-thermal processes may begin to dominate the radio spectra of extended protostellar jets in this regime. I detect emission with a synchrotron spectral index in the proximity of the DG Tau jet and interpret this emission as arising from cosmic ray electrons at a prominent bow shock associated with this outflow. This result provides tentative evidence for the acceleration of particles to relativistic energies

due to the shock impact of this otherwise very low-power jet against the ambient medium. I calculate the equipartition magnetic field strength ($B_{\min} \approx 1 \times 10^{-4} \text{ G}$) and particle energy ($W_{\text{total}}(\min) \approx 4 \times 10^{40} \text{ erg}$) necessary to account for the synchrotron emission from the DG Tau bow shock. Although follow-up observations are required to obtain the proper motion of the radio emission to verify its origin in the jet and detect linearly polarised emission to measure the direction of the magnetic field, these results suggest the possibility of low energy cosmic rays being generated by young Sun-like stars.

CONCLUSIONS AND FUTURE PROSPECTS

The goal of this thesis was to explore young stars over a wide range of radio frequencies and angular resolutions to study the role of their jets on all scales and how they evolve with time. This was achieved by observing YSOs from evolutionary Classes 0–II on large scales at 16 GHz with AMI, on sub-arcsecond scales at 5 GHz with e-MERLIN, and on intermediate-scales in a new, very low frequency regime with the GMRT. Observations of the thermal component can be used to discriminate between various MHD jet launching scenarios (see [Section 2.3](#)) as these models predict different radio emission profiles close to the source, whilst measurements of non-thermal emission can be used to determine the strength and direction of the magnetic field. In the following sections I summarise the main results of this thesis and make some brief concluding remarks before looking towards the future.

7.1 CONCLUSIONS

Large-scale Investigations of YSOs at 16 GHz with AMI

In [Chapter 4](#) I presented 16 GHz deep radio continuum observations taken with AMI of a sample of low-mass YSOs known to drive powerful outflows. With an angular resolution of approximately $30''$, AMI explored these protostellar systems on large scales (e.g. ~ 4000 au for the nearest star forming regions) where the outflow has interacted with the surrounding envelope and/or molecular cloud. Previous studies of the total, integrated radio emission at 16 GHz from YSOs (e.g. [Scaife et al., 2011a](#)) revealed correlations of the radio luminosity with other global properties of these systems, including bolometric luminosity, envelope mass and outflow force, which were further improved by this work. 16 GHz emission is therefore a useful proxy for source, envelope and outflow properties.

16 GHz is an important frequency as it delineates the boundary of two distinct components described by the spectral energy distributions for YSOs: the partially ionised jet which is traced by emission at radio wavelengths and the circumstellar material, such as the en-

velope and disk, that is traced by thermal dust emission at sub-millimetre wavelengths. The region between ~ 15 and 30 GHz has contributions to the radio flux density of these young stars from both the outflow and the long wavelength tail of the thermal dust emission. It is critical to disentangle these two sources of emission at this overlap in order to accurately determine the underlying physics of each.

A major achievement from my work with the AMI data was the construction of the SEDs for all 15 protostellar sources in the sample. I conducted an extensive literature search to compile the integrated flux densities reported for these sources longward of $100\ \mu\text{m}$ and organised them in a library for easy reference (see [Appendix C](#)). I combined these new AMI data with the archival information, and the SEDs for each source were examined and fit with maximum likelihood models to calculate the radio spectral index, opacity index, dust temperature, and the contribution of thermal dust emission at 16 GHz. The contribution of the thermal dust emission was subtracted from the measured flux density at 16 GHz to obtain values of only the radio luminosity associated with the outflow, which was then used to redraw the correlations from [Scaife et al. \(2011a\)](#) with other system properties.

The main results of this study are as follows.

- From the AMI data alone and from the fitting applied to the SEDs, 80% of the objects in this sample provide support for free-free radiation as the dominant physical mechanism for producing the radio emission.
- Correlations of the radio luminosity with bolometric luminosity (L_{bol}), envelope mass (M_{env}), and outflow momentum force ($F_{\text{out}} = \dot{M}v_*$) were examined. It was found that these data are consistent with the correlation with bolometric luminosity seen in lower luminosity samples ($L_{\text{bol}} < 1\ L_{\odot}$, [Scaife et al., 2011a](#)), and strengthen the correlation with envelope mass.
- I quantified the errors in determining the radio luminosity, and the uncertainty on the opacity index, β , was found to dominate the overall error. This emphasises the importance of multi-frequency observations between the radio and sub-millimetre, especially at the boundary between these two regimes. More accurate modelling is required to constrain the opacity index as it is a diagnostic of grain growth: excess emission and a shallow β indicate a significant population of large dust grains. The typical value for the ISM is $\beta = 1.7$, but values closer to $\beta \approx 1$ are observed in disks, indicating the beginnings of grain growth and possibly the onset of planet formation.
- Variability in these young objects was also examined using their SEDs, from which evidence for possible radio flare events in the histories of some of the objects were revealed.

Sub-arcsecond Investigations of YSOs at 5 GHz with e-MERLIN

The protostellar sources studied in the previous section were selected to match the target sample for the e-MERLIN Legacy Program on the “Morphology and Time Evolution of Thermal Jets Associated with Low-mass Young Stars” (P.I. L. Rodríguez), of which the data acquisition, reduction, and analysis were to form the basis of this thesis. However, during the course of this research, e-MERLIN had not yet been fully upgraded. I therefore became involved in the commissioning, which included the reduction and analysis of data intermediate to the original MERLIN and the fully upgraded e-MERLIN.

In [Chapter 5](#) I presented observations at 5 GHz of the classical T Tauri star DG Tau taken during the commissioning phase of e-MERLIN with only the five 25 m dishes, resulting in an angular resolution of 100 mas. At 5 GHz, the radio emission from YSOs is expected to arise predominantly from free-free radiation, however the improved sensitivity of the fully upgraded e-MERLIN ($\sim 1 \mu\text{Jy}$) and high angular resolution may allow for the detection of synchrotron radiation generated by electrons spiralling along magnetic field lines. Any observed polarisation can be used to determine the direction and magnitude of the outflow’s magnetic field, which are crucial for discriminating between different MHD jet launching models (see [Section 2.3](#)). Also of vital importance to test morphological predictions of jet launch models are the dimensions of the base of the jet, for which the high spatial resolution of the fully upgraded e-MERLIN is essential. With an angular resolution of 100 mas, these commissioning data probe the jet on scales of $\sim 14 \text{ au}$.

The main results from this investigation are as follows.

- These e-MERLIN commissioning data have provided the highest resolution images of DG Tau (and also the nearby Class I protostar DG Tau B) at centimetre wavelengths to date.
- The emission from both YSOs is in the known direction of the outflow indicating that it traces the free-free radiation associated with the jet, although additional measurements at high resolution are necessary to confirm the spectral index.
- With these data I measured the initial opening angle of the DG Tau jet which implied that the jet starts initially as a poorly collimated wind and becomes collimated on scales of 50 au, in line with MHD disk-wind theory.
- Using the measured jet opening angle I calculated the mass-loss rate in the ionised component of the jet and found it to be $\sim 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$, consistent values derived use optical/near-IR emission line ratio diagnostics. Incorporating this into the non-ionised component yields a mass ejection to mass accretion ratio of 0.05 – 0.2. These results are in accord with predictions of MHD jet-launching models.

This work gives a preview on how e-MERLIN will contribute to the study of low-mass YSOs and their outflows, as observations of the inner 20 au are essential to test different jet-launching scenarios. I have already probed these objects with a new level of angular resolution and sensitivity with e-MERLIN during the commissioning phase, and they will be further improved with the final array.

Intermediate-scale Investigations of YSOs at 325 and 610 MHz with the GMRT

In [Chapter 6](#) I presented observations of three protostellar targets at 325 and 610 MHz taken with the GMRT to detect radio emission from YSOs at very low frequencies and which are the first investigations of these systems at such low frequencies. These observations also provide an idea of what potentially could be observed in the future using LOFAR. The angular resolution of the GMRT is approximately $10''$ at 325 MHz and $5''$ at 610 MHz, allowing a scale intermediate between AMI and e-MERLIN to be explored. Observations at these low frequencies of specific Class 0-II targets, selected based on previous studies at GHz frequencies, allow unique spectral constraints to be placed and the mechanism responsible for the radio emission to be characterised. The goal of this study was to constrain the frequency of the transition from optically thick to optically thin behaviour in the free-free spectrum and determine the physical conditions of the ionised gas.

The main results from this investigation are as follows.

- The measurements at 325 and 610 MHz for these YSOs imply a continuation of the thermal jet spectrum seen at GHz frequencies to this new low frequency regime, and the frequency at which the emission transitions from optically thick to thin has not yet been reached. Therefore, further investigations with instruments such as the Low-Frequency Array (LOFAR) are needed to extend this study to even lower frequencies to identify this transition and place constraints on the mass of the ionised gas surrounding the YSO.
- An extensive literature search was conducted to construct the spectral energy distributions for T Tau and DG Tau. The flux densities and references are organised in [Appendix F](#).
- The most interesting result from this work is the detection of emission with a synchrotron spectral index in the proximity of the optical DG Tau bow shock. I interpret this emission as a prominent radio bow shock associated with this outflow. This result provides tentative evidence for the acceleration of particles to relativistic energies due to the shock impact of this otherwise very low-power jet against the ambient medium. I calculated the equipartition magnetic field strength $B_{\min} \approx 1 \times 10^{-4} \text{ G}$ and particle energy $E_{\min} \approx 4 \times 10^{40} \text{ erg}$, which are the minimum requirements to account for the

synchrotron emission of the DG Tau bow shock. These results suggest the possibility of low energy (~ 1 GeV) cosmic rays being generated by young Sun-like stars and permeating the Galaxy. This is further supported by recent *Herschel* observations which reveal the necessity of energetic particles to produce the chemistry observed in the envelope of the young Sun (Ceccarelli et al., 2014).

Observations in the radio can address a number of the open questions remaining with regard to protostellar outflows that cannot be solved at other wavelengths. In particular, my investigations have revealed that non-thermal emission may begin to dominate the spectra of protostellar jets at very low radio frequencies, and thus may be a tool for obtaining information on the magnetic field. This information is crucial for studies of structure, formation and evolution of these collimated outflows. Multi-frequency, multi-scale investigations of YSOs are vital to obtain a complete physical demography of how stars like our Sun form. Data at well-sampled frequencies are crucial to precisely model and differentiate between the competing emission mechanisms. This is well-illustrated with the AMI observations, where the flux densities have contributions from both the jet and the circumstellar material, and with the GMRT data, where I have revealed the dominance of an additional emission mechanism at low frequencies. Measurements at intermediate frequencies are thus required to constrain the properties of the ionised plasma. In addition, radio data over a range of angular scales reveals outflow characteristics and structure. The high spatial resolution of e-MERLIN allows the regions closest to the protostar to be explored to identify the location of jet-launch. Spatial resolution comparable with that of the GMRT exposes large scale structure in the outflow, such as bow shocks, whilst instruments such as AMI detect the overall interaction of the outflow with the ambient medium. All of these ingredients are vital to obtain a comprehensive view of low-mass star formation.

7.2 FUTURE PROSPECTS

Radio astronomy is undergoing a revolution, through the construction of new facilities (e.g. LOFAR, the Atacama Large Millimeter Array/ALMA, MeerKAT, and the Australian Square Kilometre Array Pathfinder/ASKAP) or with major upgrades to existing facilities (e.g. JVLA, e-MERLIN and the GMRT, see Section 3.4). The microwave links that previously connected individual antennae have been replaced by optical fibre, allowing much broader bandwidths to be observed and much higher sensitivities to be achieved. These are the “Golden Years” of radio astronomy as many of these instruments are pathfinder projects for the Square Kilometre Array (SKA), a global science and engineering project

to build the world’s largest radio interferometer. The scale of the SKA represents major advances in both engineering and in research and development. The advances in angular resolution, sensitivity, field-of-view and frequency ranges in this new generation of radio telescopes will revolutionise the way we conduct radio astronomy, and challenges will have to be overcome to store, calibrate and analyse data volumes as they become larger and larger.

In this thesis I have shown that it is possible to extend the study of jets from young stars, which are typically weak radio emitters, to lower frequencies and higher resolutions, making them relevant targets for instruments such as LOFAR and the SKA. The new generation of radio telescopes will have sufficient sensitivity to routinely image protostellar jets and high enough spatial resolution to resolve the central jet engine. This is important as the precise location of jet launch is still elusive, and observations of the inner ~ 10 au are crucial for discriminating between different jet launching scenarios (see [Section 2.3](#)). With an angular resolution of $\approx 0''.3$, observations with LOFAR long baselines have the potential to spatially resolve the jet not only along the flow, but also across to reveal structure in two dimensions. Although the magnetic field is expected to play a crucial role in the jet launching and collimation process, observational support for properties such as the strength and direction of the magnetic field on all scales is still lacking. With the advances in sensitivity, polarisation measurements will give reliable estimates of the magnetic field distribution in the outflows, enabling investigations of the role it plays in the launching and collimation of the jets and on extended scales.

The e-MERLIN Legacy Program on the “Morphology and Time Evolution of Thermal Jets Associated with Low-mass Young Stars” is ongoing. When the telescope is fully upgraded and Legacy data is routinely observed (expected late 2014), the resolution and sensitivity will be further improved in comparison to that presented in [Chapter 5](#). An angular resolution of 50 mas can be achieved with the inclusion of the Cambridge antenna, and the instantaneous bandwidth will increase from 512 MHz to 2 GHz. The analysis of such high spatial resolution images for the sample presented in [Chapter 4](#) will provide unique information on the structure of the radio emission which will allow specific morphological predictions of jet models to be tested. Additionally, this data can be compared with matching-beam 43 GHz observations ($0''.05$) made with the JVL A that are expected to trace the dust from the disk. This will allow for the direct comparison between the free-free emission from the jet and the dust emission from the disk/envelope for the first time at such high angular resolution, which will improve our understanding of the jet-disk relation and therefore of the physics that governs low-mass star formation.

Part III

APPENDICES

AMI COMBINED CHANNEL MAPS

This appendix presents the maps of each field taken with AMI discussed in [Chapter 4](#). AMI data is shown uncorrected for the primary beam response. The positions of known Class 0 and Class I objects are indicated as crosses (+) and stars (*), respectively. The positions for those found in Perseus (L1448 and HH 7 – 11) are from [Hatchell et al. \(2007b\)](#), HH 1 – 2 from [Fischer et al. \(2010\)](#), and Serpens from [Duarte-Cabral et al. \(2010\)](#). Crosses (×) represent known sources of unknown evolutionary class. We plot the half power point of the primary beam as a solid circle (≈ 6 arcmin at 16 GHz) and the synthesised beam as the filled ellipse in the bottom left corner (see [Table 4.1](#)). Contours at 5, 10, 15, 20 σ_{rms} etc, where σ_{rms} values for each source are listed in [Table 4.1](#).

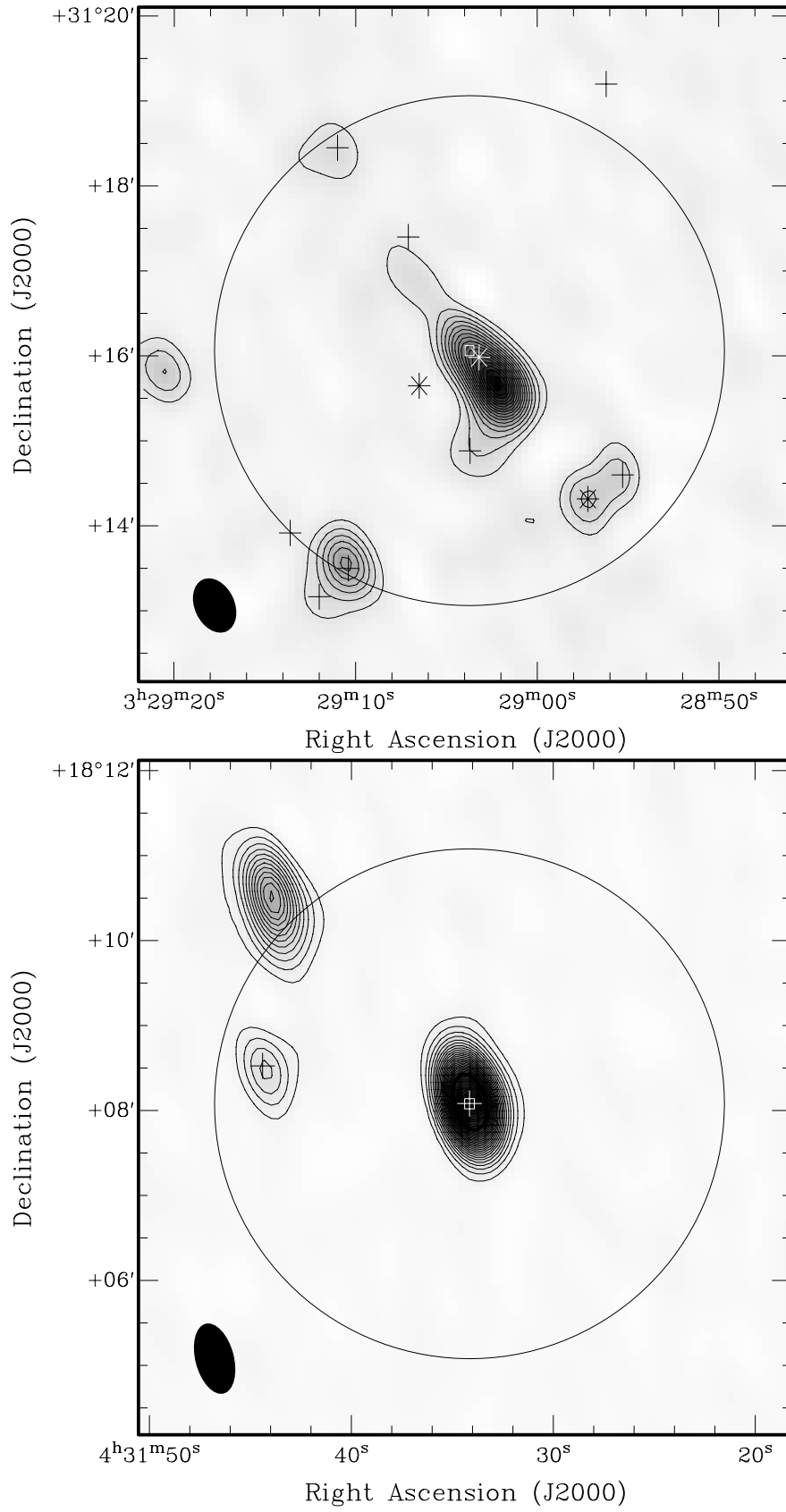


Figure A.1.: The AMI 16 GHz combined-channel map for (*top*) HH 7 – 11 and (*bottom*) L1551 IRS 5.

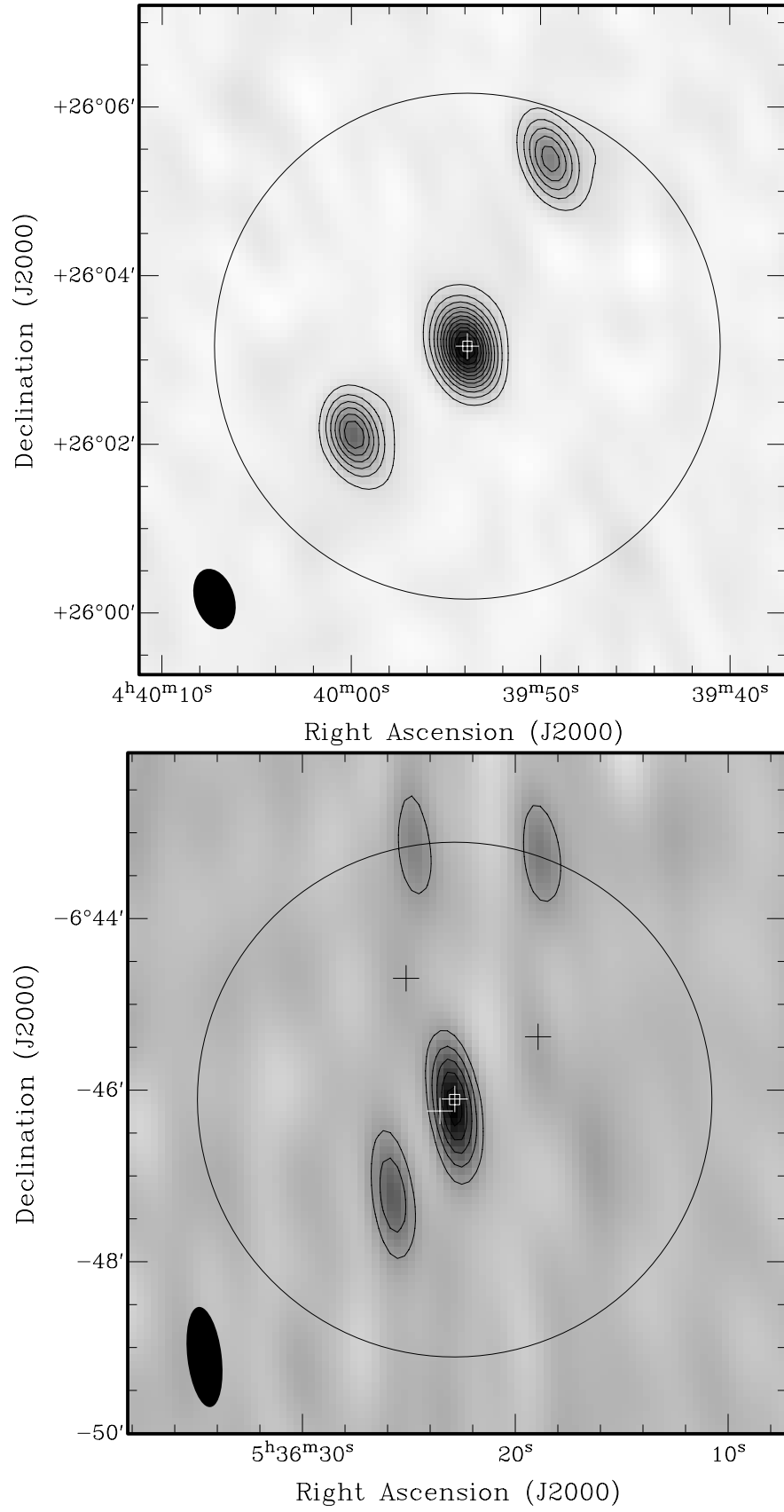


Figure A.2.: The AMI 16 GHz combined-channel map for (top) L1527 and (bottom) HH 1 – 2.

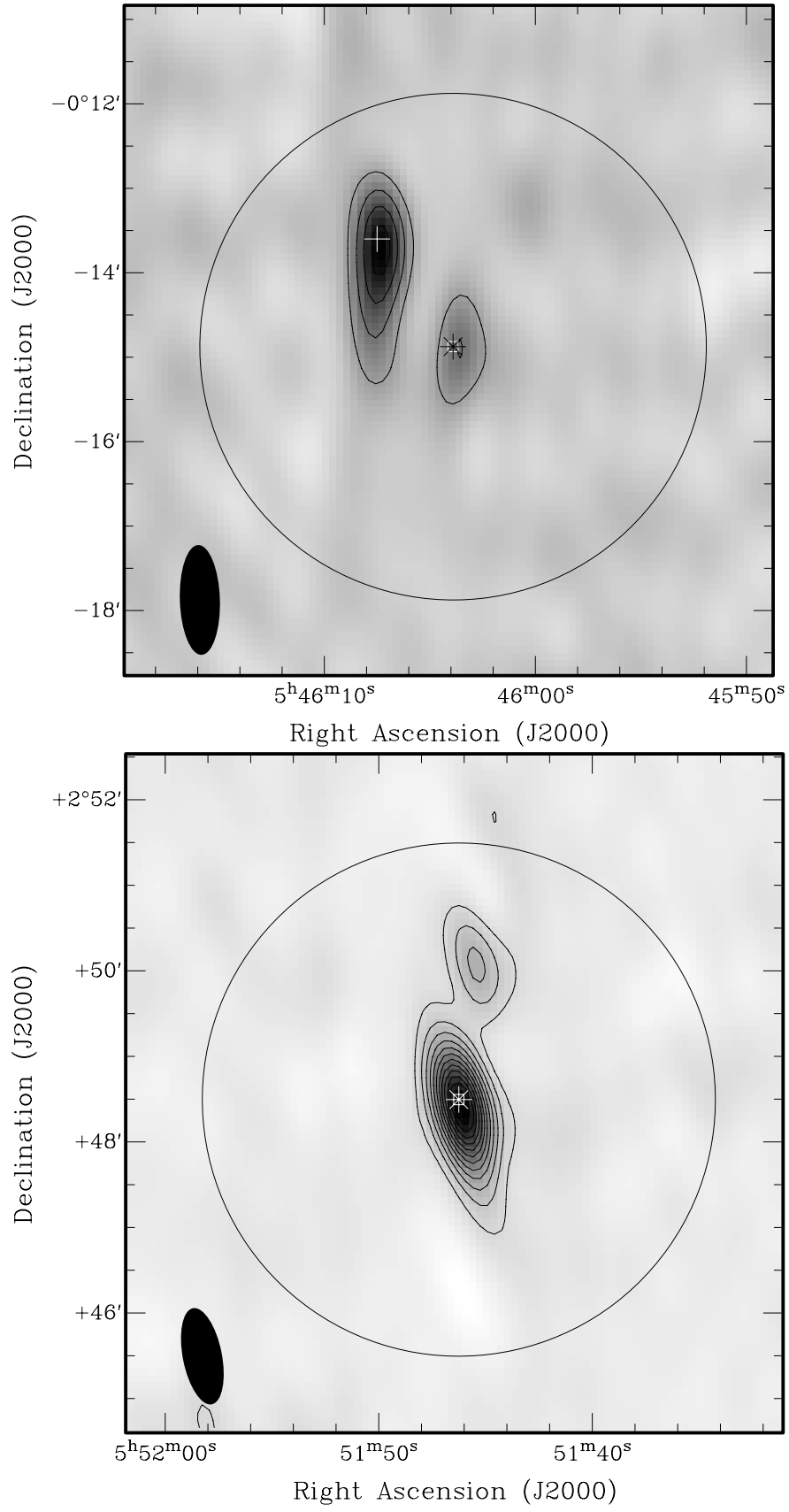


Figure A.3.: The AMI 16 GHz combined-channel map for (top) HH 26 IR and (bottom) HH 111.

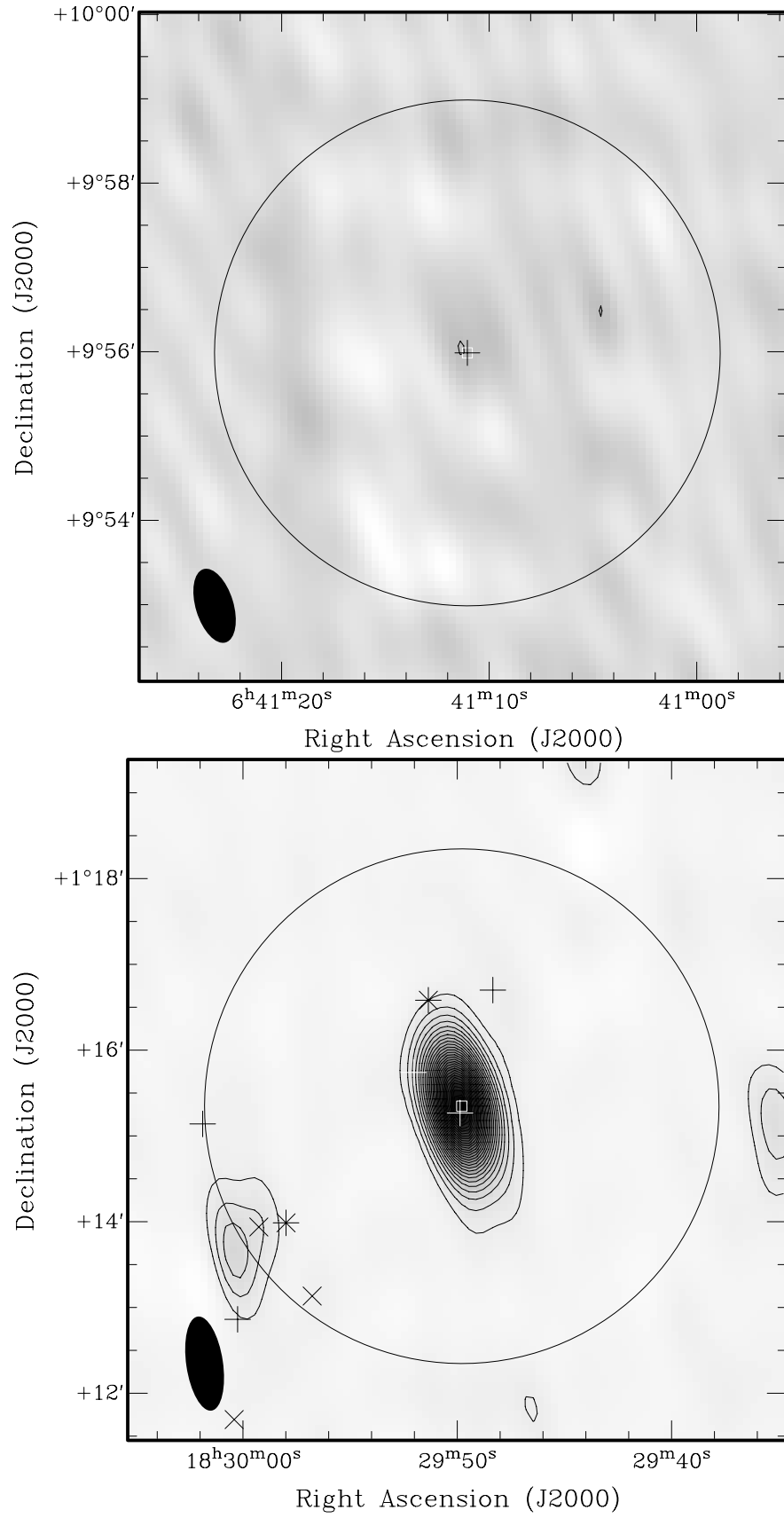


Figure A.4.: The AMI 16 GHz combined-channel map for (*top*) NGC 2264 G and (*bottom*) Serpens SMM 1.

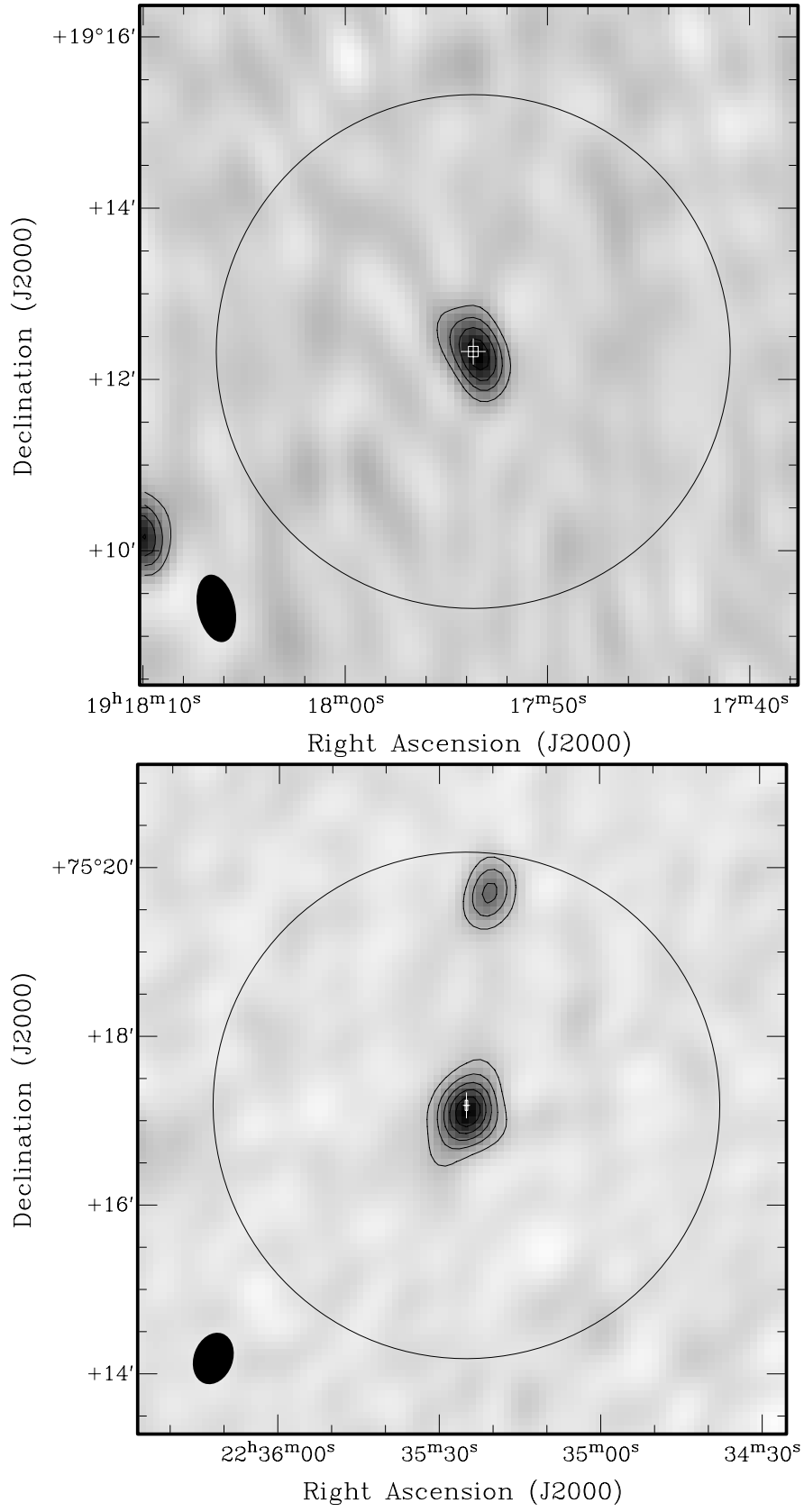


Figure A.5.: The AMI 16 GHz combined-channel map for (*top*) L723 and (*bottom*) L1251 A.

AMI SAMPLE SPECTRAL ENERGY DISTRIBUTIONS

This appendix presents the SEDs for each of the target sources discussed in [Chapter 4](#). The observed radio spectra over the AMI frequency channels 3 – 8 are combined with flux densities from the literature. Maximum likelihood results from Scenario (ii) are overlaid (see [Table 4.8](#)), where the dashed line in each SED represents the power-law with index α' that traces the jet, the dotted line represents the modified blackbody model of the envelope/disk (with opacity index β and dust temperature T_d) and the solid line is the total model fit. The list of archival data used in the spectral energy distributions can be found in [Appendix C](#). Only data $\nu < 3$ THz ($\lambda > 100 \mu\text{m}$) were included in the fit, but *IRAS* data $\nu > 3$ THz are included in the plots for illustration.

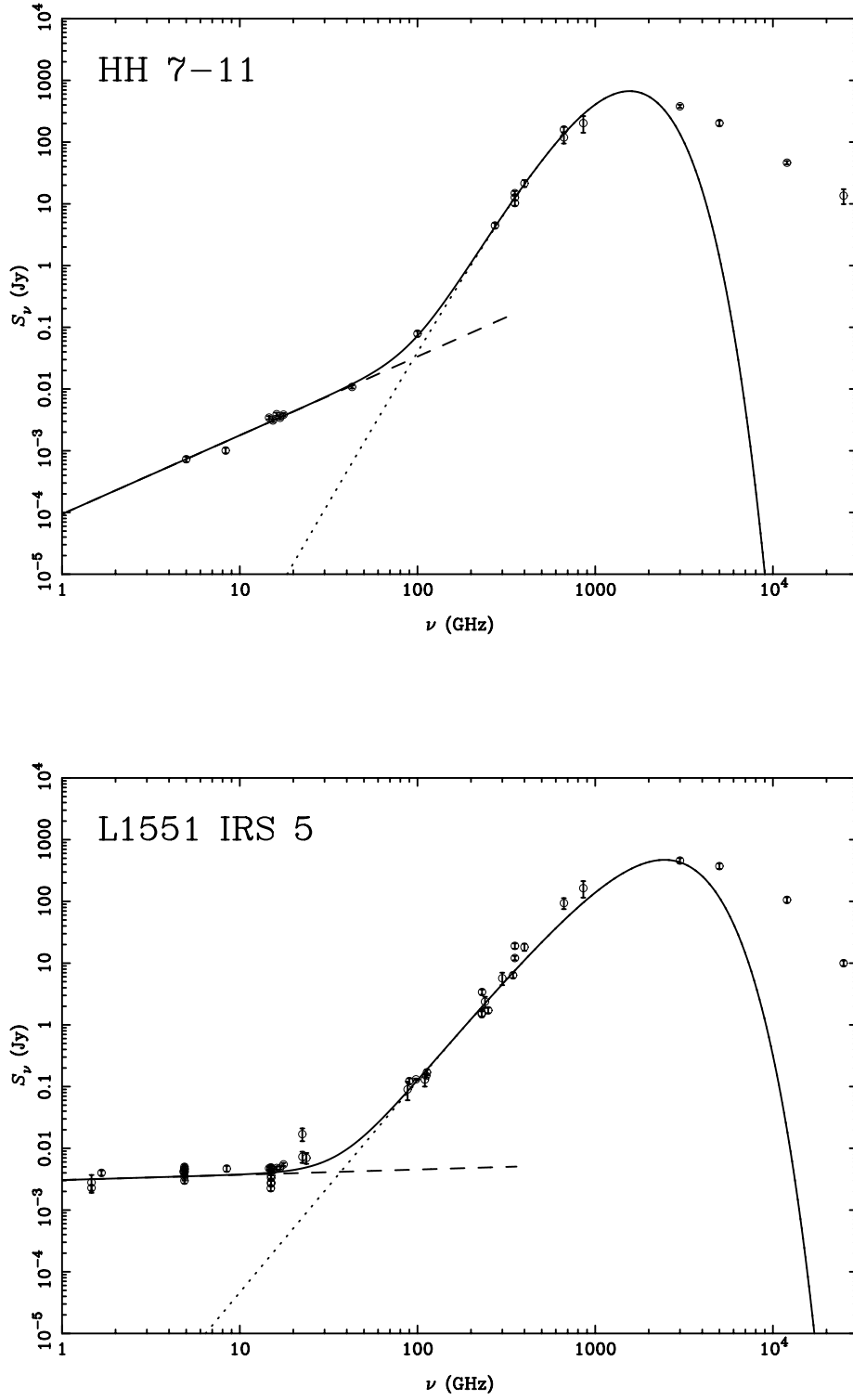


Figure B.1.: The spectral energy distributions for (*top*) HH 7 – 11 and (*bottom*) L1551 IRS 5.

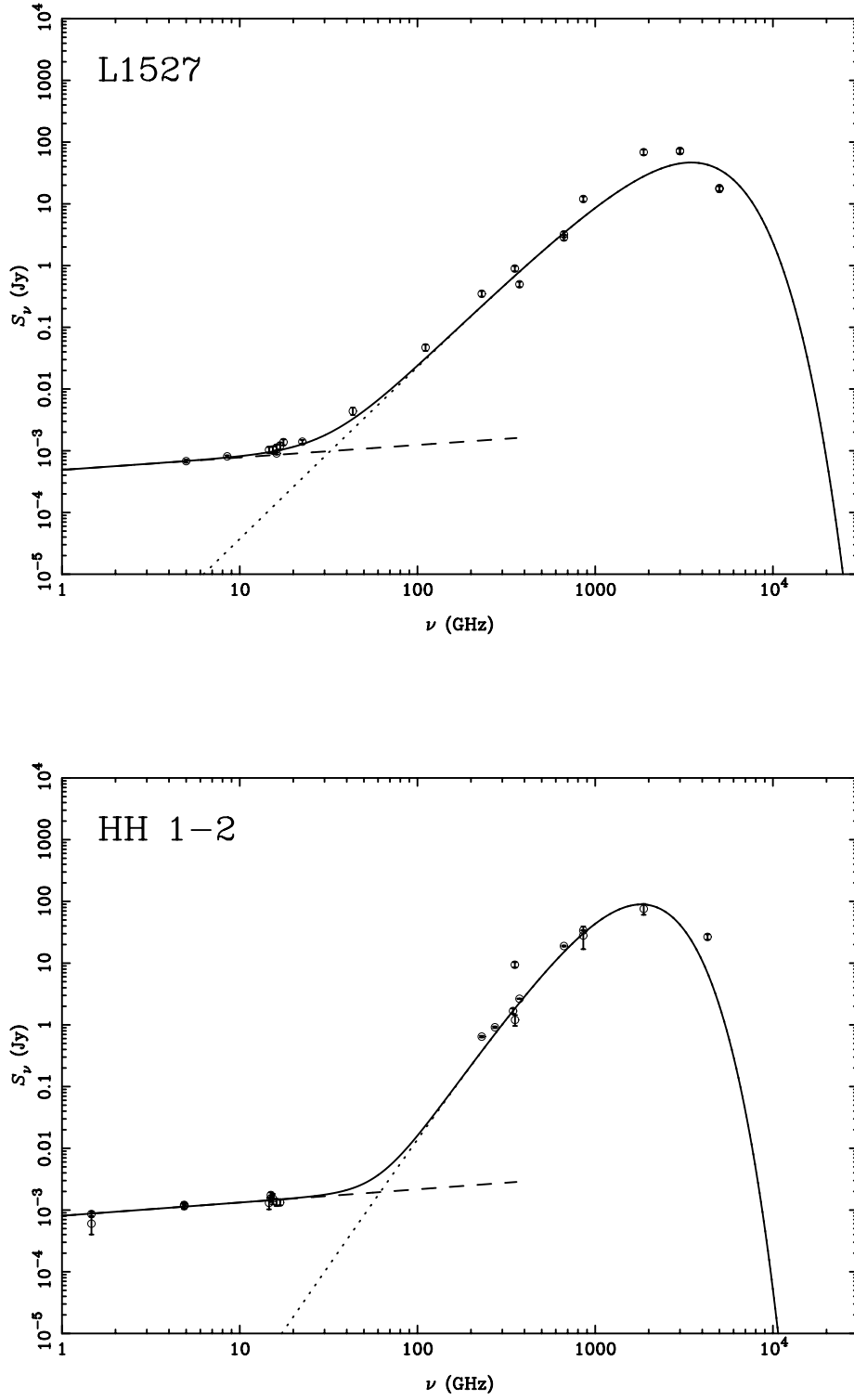


Figure B.2.: The spectral energy distributions for (*top*) L1527 and (*bottom*) HH 1 – 2.

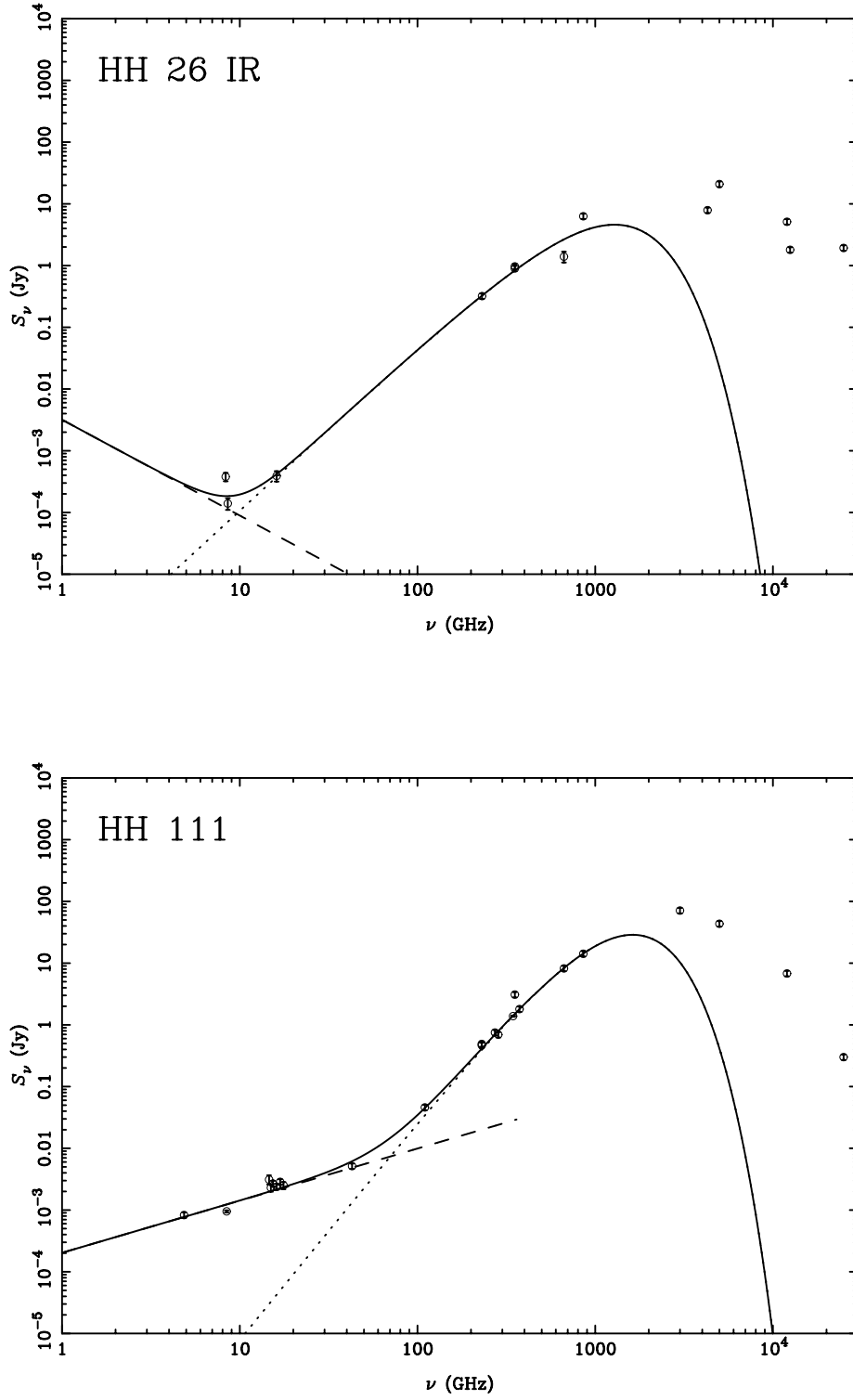


Figure B.3.: The spectral energy distributions for (*top*) HH 26 IR and (*bottom*) HH 111.

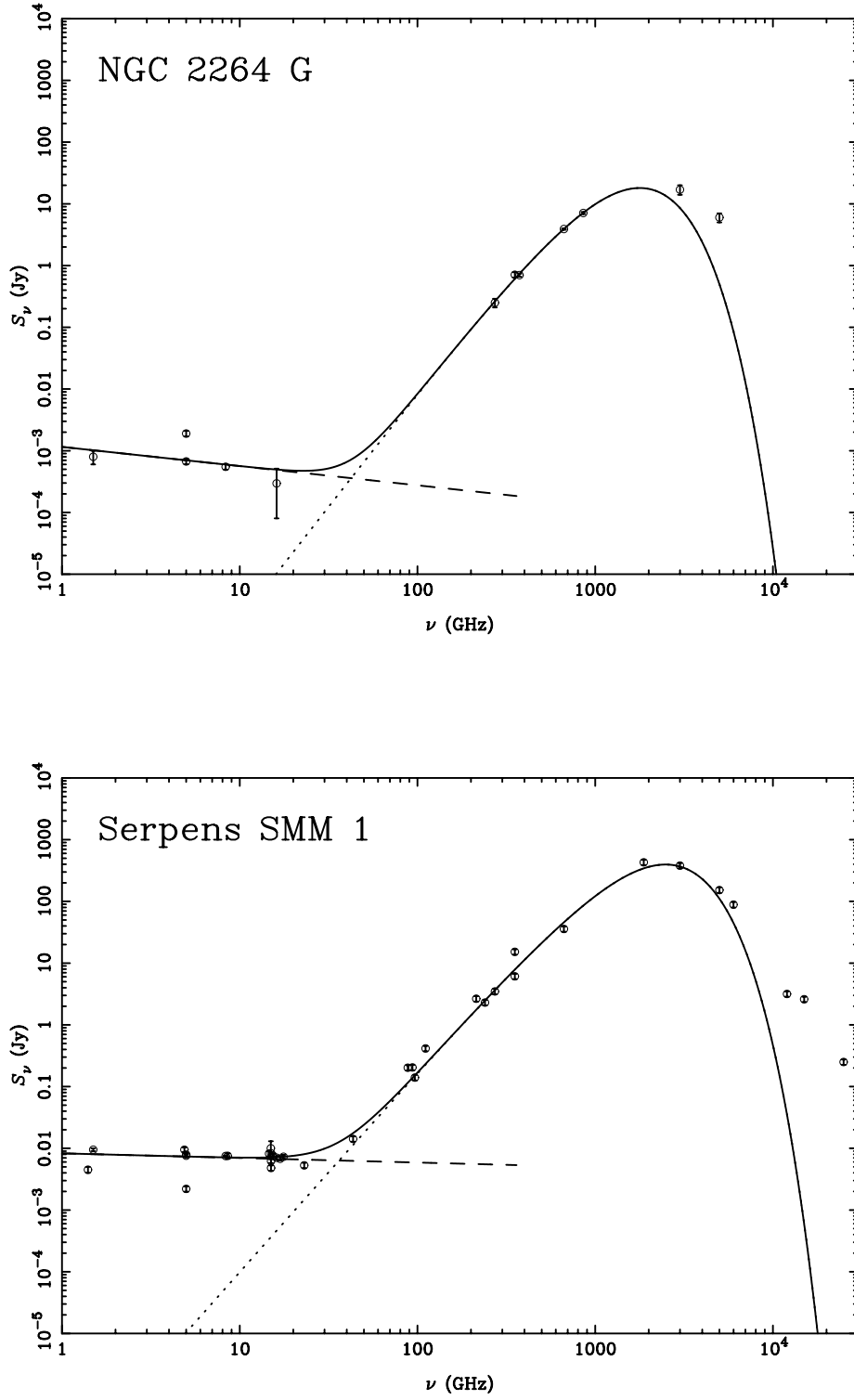


Figure B.4.: The spectral energy distributions for (*top*) NGC 2264 G and (*bottom*) Serpens SMM 1.

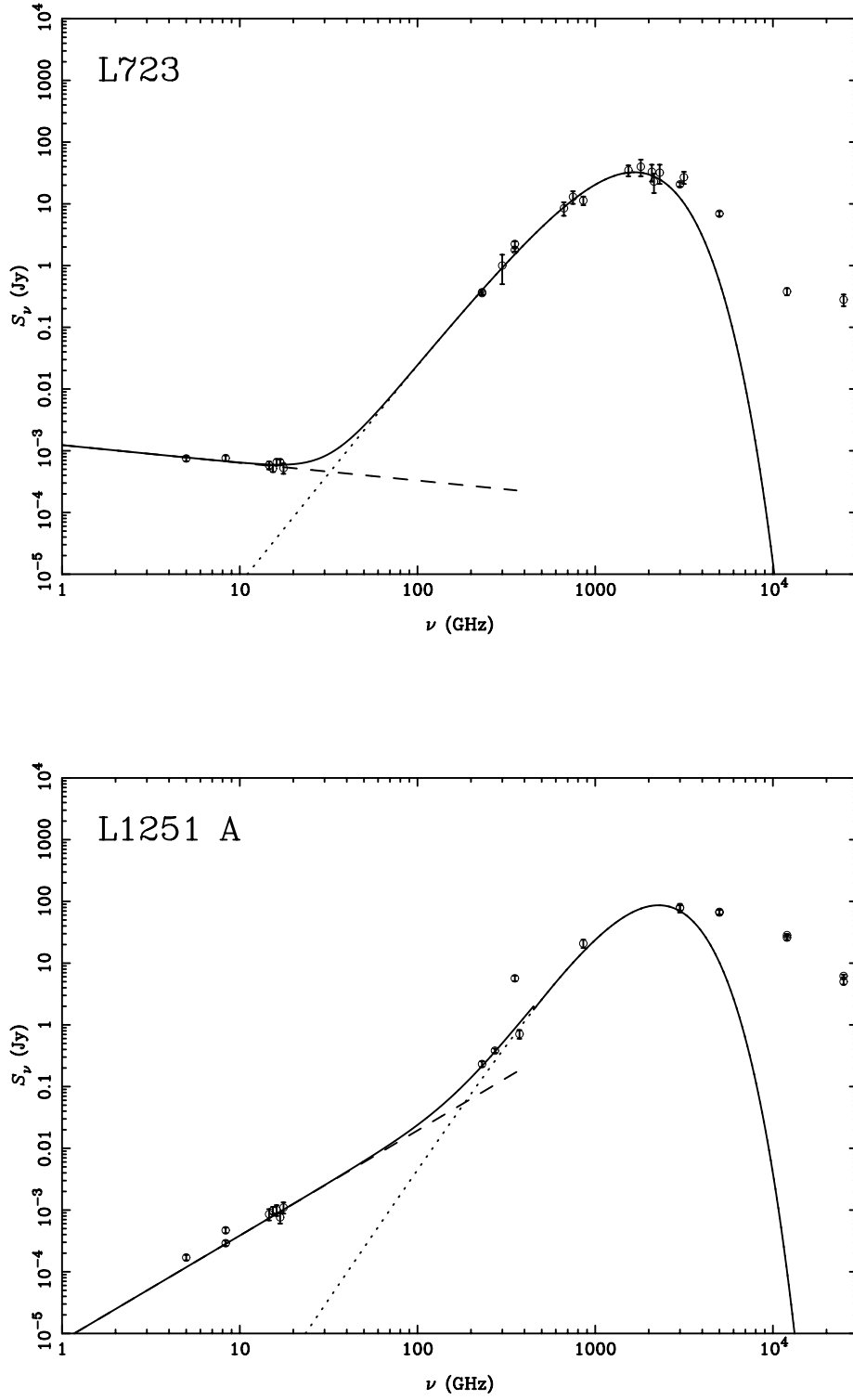


Figure B.5.: The spectral energy distributions for (*top*) L723 and (*bottom*) L1251 A.

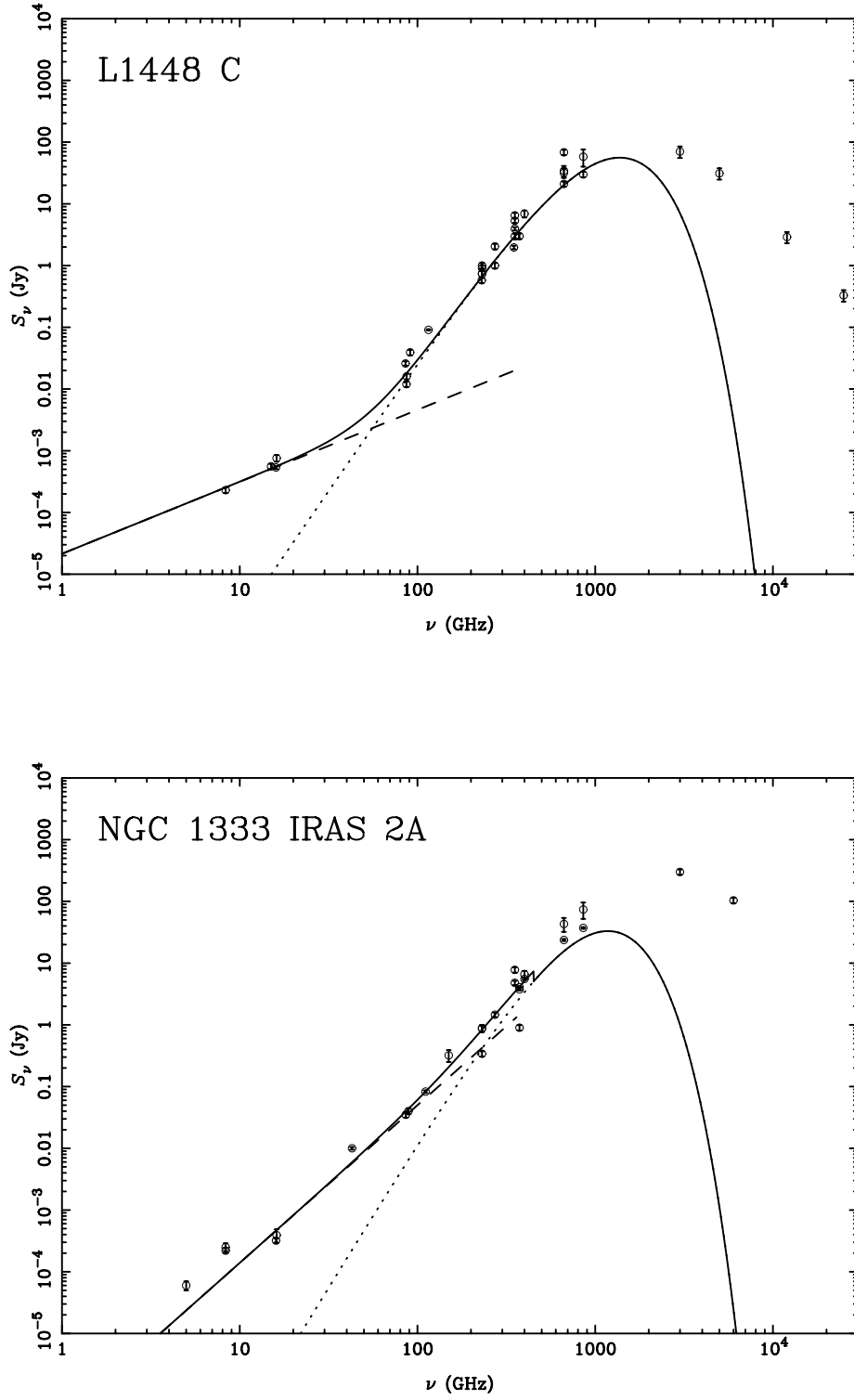


Figure B.6.: The spectral energy distributions for (*top*) L1448 C and (*bottom*) NGC 1333 IRAS 2A.

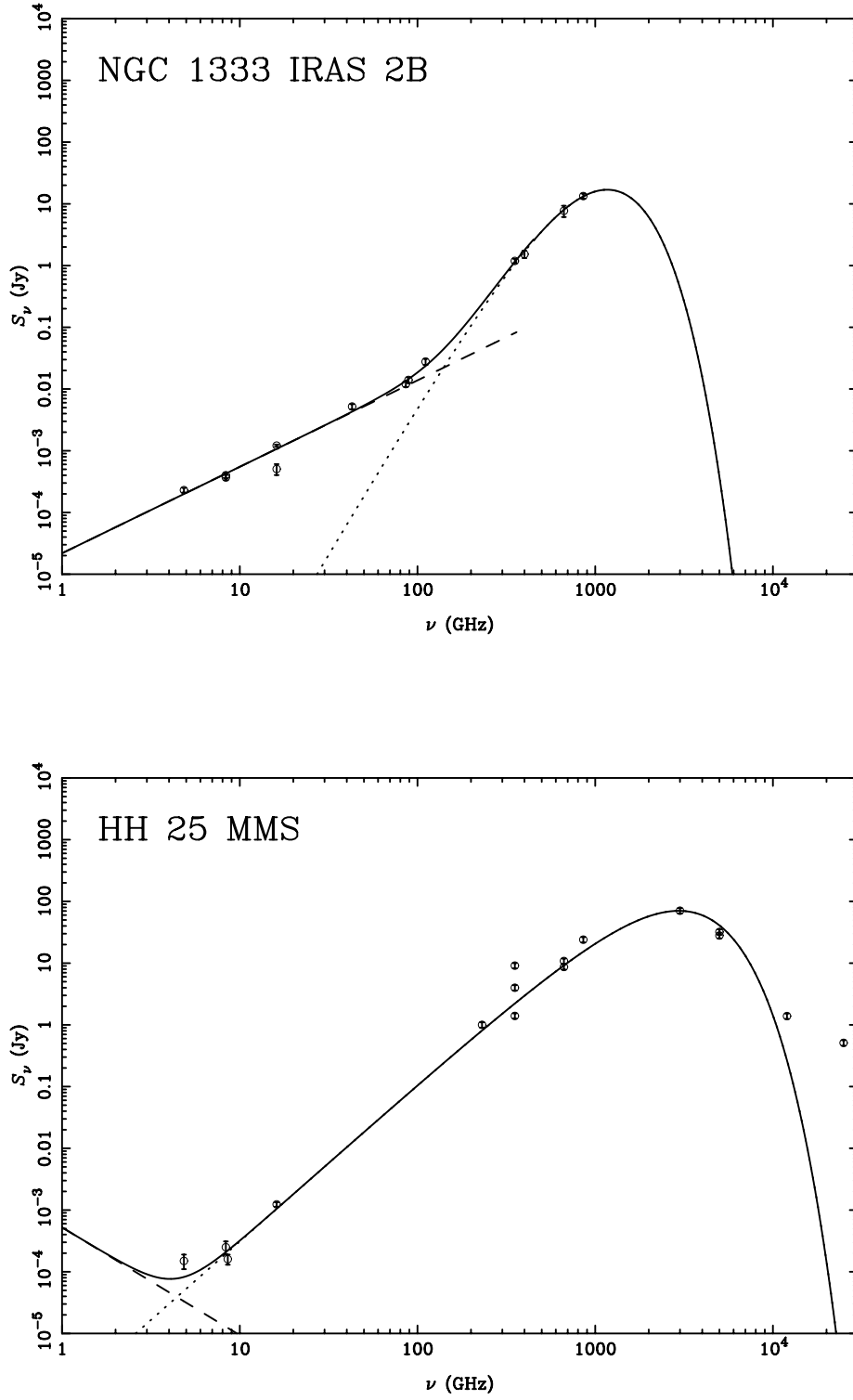


Figure B.7.: The spectral energy distributions for (*top*) NGC 1333 *IRAS* 2B and (*bottom*) HH 25 MMS.

AMI SAMPLE SPECTRAL ENERGY DISTRIBUTION REFERENCE TABLE

An extensive literature search was conducted for unresolved, integrated flux densities to include in the spectral energy distributions discussed in [Chapter 4](#). It should be noted that [Wendker \(1995\)](#) was a useful reference. High resolution data that were highly discrepant due to flux loss or data with high uncertainties (e.g. $450\ \mu\text{m}$ data from [di Francesco et al., 2008](#)) were not included. Where uncertainties were not provided, an error of 10% was used in the model fittings and this is indicated by a [†].

Table C.1.: Reference list for the spectral energy distribution data.

Source	ν (GHz)	S_ν (Jy)	Reference
L1448 IRS 3	5	$1.15 \times 10^{-3\dagger}$	Curiel et al. (1990)
	8	$1.6 \times 10^{-3\dagger}$	Reipurth et al. (2002)
	14.62	$(2.40 \pm 0.25) \times 10^{-3}$	this work
	15.37	$(2.34 \pm 0.26) \times 10^{-3}$	this work
	16	$(2.06 \pm 0.12) \times 10^{-3}$	Scaife et al. (2011b)
	16.12	$(2.41 \pm 0.37) \times 10^{-3}$	this work
	16.87	$(2.26 \pm 0.24) \times 10^{-3}$	this work
	17.62	$(2.62 \pm 0.29) \times 10^{-3}$	this work
	91	0.1 ± 0.01	Shirley et al. (2011)
	231	2.6 ± 0.14	Barsony et al. (1998)
	231	$3^\dagger$	Motte & André (2001)
	273	4.7 ± 0.05	Enoch et al. (2006)
	273	2.3 ± 0.20	Barsony et al. (1998)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	349	7.12 ± 0.33	Shirley et al. (2011)
	353	10.18^+	di Francesco et al. (2008)
	353	16.86^+	Hatchell et al. (2007b)
	353	8.37 ± 0.91	Chandler & Richer (2000)
	353	14.7 ± 0.62	Shirley et al. (2000)
	375	7.8 ± 0.64	Barsony et al. (1998)
	400	10.9 ± 1.15	Chandler & Richer (2000)
	666	56.1 ± 12.28	Chandler & Richer (2000)
	666	100.3 ± 12.40	Shirley et al. (2000)
	857	91.5 ± 22.78	Chandler & Richer (2000)
	857	45 ± 3	Barsony et al. (1998)
	3×10^3	112 ± 20.15	Barsony et al. (1998)
	5×10^3	32 ± 6.12	Barsony et al. (1998)
	1.2×10^4	5.75 ± 1.2	Barsony et al. (1998)
	2.5×10^4	0.69 ± 0.15	Barsony et al. (1998)
HH 7 – 11	5	$7.3 \times 10^{-4+}$	Rodríguez et al. (1999)
	8	$1.01 \times 10^{-3+}$	Rodríguez et al. (1999)
	14.62	$(3.43 \pm 0.20) \times 10^{-3}$	this work
	15.37	$(3.10 \pm 0.18) \times 10^{-3}$	this work
	16.12	$(3.91 \pm 0.22) \times 10^{-3}$	this work
	16.87	$(3.43 \pm 0.19) \times 10^{-3}$	this work
	17.62	$(3.83 \pm 0.24) \times 10^{-3}$	this work
	43	$(1.08 \pm 0.06) \times 10^{-2}$	Anglada et al. (2004)
	100	$(7.89 \pm 0.79) \times 10^{-2}$	Chen et al. (2009)
	273	4.46^+	Enoch et al. (2006)
	353	10.3^+	di Francesco et al. (2008)
	353	12.7^+	Hatchell et al. (2007b)
	353	14.9 ± 1.2	Chandler & Richer (2000)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	400	21.5 ± 2.8	Chandler & Richer (2000)
	666	119 ± 24	Chandler & Richer (2000)
	666	159.9^+	Hatchell et al. (2007b)
	857	203 ± 61	Chandler & Richer (2000)
	3×10^3	381 ± 23	IRAS
	5×10^3	204 ± 20	IRAS
	1.2×10^4	46.5 ± 2.8	IRAS
	2.5×10^4	13.6 ± 3.7	IRAS
L1551 IRS 5	1.5	$2.28 \times 10^{-3+}$	Bieging & Cohen (1985)
	1.5	$(2.8 \pm 0.9) \times 10^{-3}$	Snell et al. (1985)
	1.7	$4 \times 10^{-3+}$	Rodríguez et al. (1989a)
	5	$4.2 \times 10^{-3+}$	Duncan et al. (1987)
	5	$(3.5 \pm 0.5) \times 10^{-3}$	Cohen et al. (1982)
	5	$3 \times 10^{-3+}$	Bieging et al. (1984)
	5	$4.69 \times 10^{-3+}$	Bieging & Cohen (1985)
	5	$(4.3 \pm 0.5) \times 10^{-3}$	Snell et al. (1985)
	5	$(5 \pm 0.5) \times 10^{-3}$	Evans et al. (1987)
	5	$(4.1 \pm 0.4) \times 10^{-3}$	Keene & Masson (1990)
	8	$(4.7 \pm 0.5) \times 10^{-3}$	Keene & Masson (1990)
	14.62	$(4.74 \pm 0.25) \times 10^{-3}$	this work
	15	$2.25 \times 10^{-3+}$	Rodríguez et al. (1986)
	15	$4.59 \times 10^{-3+}$	Bieging & Cohen (1985)
	15	$(4.9 \pm 0.5) \times 10^{-3}$	Keene & Masson (1990)
	15	$(3.6 \pm 0.2) \times 10^{-3}$	Rodríguez et al. (2003a)
	15	$(2.8 \pm 0.2) \times 10^{-3}$	Rodríguez et al. (2003a)
	15	$(3.3 \pm 0.2) \times 10^{-3}$	Rodríguez et al. (2003a)
	15	$(2.7 \pm 0.2) \times 10^{-3}$	Rodríguez et al. (2003a)
	15.37	$(3.10 \pm 0.18) \times 10^{-3}$	this work

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	16.12	$(3.91 \pm 0.22) \times 10^{-3}$	this work
	16.87	$(3.43 \pm 0.19) \times 10^{-3}$	this work
	17.62	$(3.83 \pm 0.24) \times 10^{-3}$	this work
	22.5	$(1.7 \pm 0.4) \times 10^{-2}$	Torrelles et al. (1985)
	22.5	$(7.3 \pm 1.5) \times 10^{-3}$	Keene & Masson (1990)
	23.7	$(7 \pm 1.4) \times 10^{-3}$	Gomez et al. (1993)
	88	0.09 ± 0.03	Keene & Masson (1990)
	90	0.12^+	Altenhoff et al. (1994)
	98	0.13 ± 0.004	Ohashi et al. (1991)
	110	0.13 ± 0.03	Keene & Masson (1990)
	112	0.15^+	Wilking et al. (1989)
	113	0.17^+	Keene & Masson (1986)
	230	1.5^+	Cabrit & Andre (1991)
	230	1.57 ± 0.02	Reipurth et al. (1993)
	231	3.4^+	Motte & André (2001)
	240	2.37 ± 0.48	Keene & Masson (1990)
	250	1.72^+	Altenhoff et al. (1994)
	300	5.7 ± 1.3	Keene & Masson (1990)
	345	6.36 ± 0.06	Reipurth et al. (1993)
	353	19.01^+	di Francesco et al. (2008)
	353	12.1 ± 1	Chandler & Richer (2000)
	400	18.2 ± 2.4	Chandler & Richer (2000)
	666	94 ± 19	Chandler & Richer (2000)
	857	164 ± 49	Chandler & Richer (2000)
	3×10^3	458^+	Reipurth et al. (1993)
	5×10^3	373^+	Reipurth et al. (1993)
	1.2×10^4	106^+	Reipurth et al. (1993)
	2.5×10^4	10^+	Reipurth et al. (1993)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
L1527	5	$(6.8 \pm 0.4) \times 10^{-4}$	Melis et al. (2011)
	8.5	$(8.10 \pm 0.3) \times 10^{-4}$	Melis et al. (2011)
	14.62	$(1.04 \pm 0.11) \times 10^{-3}$	this work
	15.37	$(1.04 \pm 0.14) \times 10^{-3}$	this work
	16	$(0.9 \pm 0.03) \times 10^{-3}$	Scaife et al. (2012a)
	16.12	$(1.12 \pm 0.13) \times 10^{-3}$	this work
	16.87	$(1.20 \pm 0.16) \times 10^{-3}$	this work
	17.62	$(1.38 \pm 0.15) \times 10^{-3}$	this work
	22.5	$(1.4 \pm 0.1) \times 10^{-3}$	Melis et al. (2011)
	43.3	$(4.4 \pm 0.6) \times 10^{-3}$	Melis et al. (2011)
	111	$(4.7 \pm 0.56) \times 10^{-2}$	Ohashi et al. (1997)
	230	$0.35^\dagger$	Gramajo et al. (2010)
	353	0.90 ± 0.01	Gramajo et al. (2010)
	375	$0.50^\dagger$	Gramajo et al. (2010)
	666	2.85 ± 0.22	Gramajo et al. (2010)
	666	$3.21^\dagger$	Gramajo et al. (2010)
	857	$12^\dagger$	Gramajo et al. (2010)
	1.87×10^3	$68.8^\dagger$	Gramajo et al. (2010)
	3×10^3	$71.3^\dagger$	Gramajo et al. (2010)
	3×10^3	$72^\dagger$	Gramajo et al. (2010)
	5×10^3	$17.4^\dagger$	Gramajo et al. (2010)
	5×10^3	$18^\dagger$	Gramajo et al. (2010)
HH 1 – 2 MMS 1	1.5	$(6 \pm 2) \times 10^{-4}$	Pravdo et al. (1985)
	1.5	$8.6 \times 10^{-4\dagger}$	Rodríguez et al. (1990)
	5	$(1.19 \pm 1.6) \times 10^{-3}$	Morgan et al. (1990)
	5	$(1.2 \pm 0.04) \times 10^{-3}$	Pravdo et al. (1985)
	5	$1.17 \times 10^{-3\dagger}$	Rodríguez et al. (1990)
	14.62	$(1.30 \pm 0.28) \times 10^{-3}$	this work

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	15	$(1.54 \pm 0.18) \times 10^{-3}$	Pravdo et al. (1985)
	15	$1.75 \times 10^{-3\dagger}$	Rodríguez et al. (1990)
	15.37	$(1.53 \pm 0.30) \times 10^{-3}$	this work
	16.12	$(1.34 \pm 0.18) \times 10^{-3}$	this work
	16.87	$(1.33 \pm 0.14) \times 10^{-3}$	this work
	230	0.65 ± 0.02	Reipurth et al. (1993)
	273	0.92 ± 0.03	Dent et al. (1998)
	345	1.67 ± 0.02	Reipurth et al. (1993)
	353	$9.44^\dagger$	di Francesco et al. (2008)
	354	1.2 ± 0.24	Fischer et al. (2010)
	375	2.65 ± 0.03	Dent et al. (1998)
	666	18.9 ± 0.35	Dent et al. (1998)
	857	33.95 ± 0.29	Dent et al. (1998)
	857	28 ± 11.2	Fischer et al. (2010)
	1.88×10^3	75.7 ± 15.14	Fischer et al. (2010)
	4.29×10^3	26.6 ± 2.66	Fischer et al. (2010)
HH 26 IR	8	$(3.8 \pm 0.6) \times 10^{-4}$	Anglada et al. (1998)
	8	$(1.4 \pm 0.3) \times 10^{-4}$	Gibb (1999)
	16.12	$(3.92 \pm 0.76) \times 10^{-4}$	this work
	231	$0.32^\dagger$	Lis et al. (1999)
	353	$0.97^\dagger$	di Francesco et al. (2008)
	353	0.9 ± 0.09	Nutter & Ward-Thompson (2007)
	666	1.4 ± 0.28	Nutter & Ward-Thompson (2007)
	857	$6.3^\dagger$	Lis et al. (1999)
	4.29×10^3	$7.9^\dagger$	Antoniucci et al. (2008)
	5×10^3	$20.87^\dagger$	Antoniucci et al. (2008)
	1.2×10^4	$5.13^\dagger$	Antoniucci et al. (2008)
	1.25×10^3	$1.8^\dagger$	Antoniucci et al. (2008)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	2.5×10^4	$1.93^\dagger$	Antoniucci et al. (2008)
HH 111	5	$(8.3 \pm 0.9) \times 10^{-4}$	Rodríguez et al. (2008b)
	8	$(9.5 \pm 0.4) \times 10^{-4}$	Rodríguez & Reipurth (1994)
	14.62	$(3.11 \pm 0.53) \times 10^{-3}$	this work
	15	$(2.3 \pm 0.32) \times 10^{-3}$	Rodríguez & Reipurth (1994)
	15.37	$(2.68 \pm 0.28) \times 10^{-3}$	this work
	16.12	$(2.39 \pm 0.26) \times 10^{-3}$	this work
	16.87	$(2.86 \pm 0.30) \times 10^{-3}$	this work
	17.62	$(2.51 \pm 0.34) \times 10^{-3}$	this work
	43	$(5.15 \pm 0.52) \times 10^{-3}$	Rodríguez et al. (2008b)
	110	$(4.6 \pm 0.46) \times 10^{-2}$	Stapelfeldt & Scoville (1993)
	230	0.49 ± 0.02	Reipurth et al. (1993)
	230	0.47 ± 0.05	Wilking et al. (1989)
	273	0.75 ± 0.01	Dent et al. (1998)
	285	$0.69^\dagger$	Stapelfeldt & Scoville (1993)
	345	1.39 ± 0.03	Reipurth et al. (1993)
	353	$3.09^\dagger$	di Francesco et al. (2008)
	375	1.8 ± 0.02	Dent et al. (1998)
	666	8.22 ± 0.26	Dent et al. (1998)
	857	14.2 ± 0.9	Dent et al. (1998)
	3×10^3	$71.1^\dagger$	Reipurth et al. (1993)
	5×10^3	$43.5^\dagger$	Reipurth et al. (1993)
	1.2×10^4	$6.8^\dagger$	Reipurth et al. (1993)
	2.5×10^4	$0.3^\dagger$	Reipurth et al. (1993)
NGC 2264 G	1.5	$(8 \pm 2) \times 10^{-4}$	Rodríguez & Curiel (1989)
	5	$(1.9 \pm 0.2) \times 10^{-3}$	Rodríguez & Curiel (1989)
	5	$6.7 \times 10^{-4\dagger}$	Gómez et al. (1994)
	8	$5.5 \times 10^{-4\dagger}$	Gómez et al. (1994)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	16.12	$(2.96 \pm 2.16) \times 10^{-4}$	this work
	273	0.25 ± 0.04	Ward-Thompson et al. (1995)
	353	0.71^+	di Francesco et al. (2008)
	375	0.7 ± 0.04	Ward-Thompson et al. (1995)
	666	3.9 ± 0.1	Ward-Thompson et al. (1995)
	857	7.1 ± 0.28	Ward-Thompson et al. (1995)
	3×10^3	17 ± 3	Ward-Thompson et al. (1995)
	5×10^3	6 ± 1	Ward-Thompson et al. (1995)
Serpens SMM 1	1.5	$(4.5 \pm 0.5) \times 10^{-3}$	Condon et al. (1998)
	1.5	$(9.5 \pm 0.49) \times 10^{-3}$	Curiel et al. (1993)
	5	$(9.5 \pm 0.8) \times 10^{-3}$	Snell & Bally (1986)
	5	$(7.9 \pm 0.48) \times 10^{-3}$	Rodríguez et al. (1989b)
	5	$(7.6 \pm 0.3) \times 10^{-3}$	Curiel et al. (1993)
	5	$2.2 \times 10^{-3+}$	McMullin et al. (1994)
	8	$(7.5 \pm 0.17) \times 10^{-3}$	Curiel et al. (1993)
	8	$7.54 \times 10^{-3+}$	Eiroa et al. (2005)
	14.62	$(8.21 \pm 0.77) \times 10^{-3}$	this work
	15	$(1 \pm 0.3) \times 10^{-2}$	Snell & Bally (1986)
	15	$(8.3 \pm 0.3) \times 10^{-3}$	Curiel et al. (1993)
	15	$(6.2 \pm 0.044) \times 10^{-3}$	Rodríguez et al. (1989b)
	15	$4.8 \times 10^{-3+}$	McMullin et al. (1994)
	15.37	$(7.66 \pm 0.55) \times 10^{-3}$	this work
	16	$(4.74 \pm 0.24) \times 10^{-3}$	Scaife et al. (2012b)
	16.12	$(7.04 \pm 0.43) \times 10^{-3}$	this work
	16.87	$(6.77 \pm 0.44) \times 10^{-3}$	this work
	17.62	$(7.30 \pm 0.54) \times 10^{-3}$	this work
	23	$5.3 \times 10^{-3+}$	McMullin et al. (1994)
	43	$(1.42 \pm 0.04) \times 10^{-2}$	Choi (2009)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	88	$0.2^\dagger$	Hogerheijde et al. (1999)
	94	$0.2^\dagger$	Hogerheijde et al. (1999)
	97	$0.14^\dagger$	McMullin et al. (1994)
	111	$0.41^\dagger$	Hogerheijde et al. (1999)
	214	$2.65^\dagger$	Hogerheijde et al. (1999)
	240	$2.3^\dagger$	McMullin et al. (1994)
	273	3.47 ± 0.1	Casali et al. (1993)
	353	$15.23^\dagger$	di Francesco et al. (2008)
	353	$6.1^\dagger$	Davis et al. (1999)
	666	$35.7^\dagger$	Davis et al. (1999)
	1.88×10^3	$430^\dagger$	McMullin et al. (1994)
	3×10^3	$380^\dagger$	McMullin et al. (1994)
	5×10^3	$152.92^\dagger$	McMullin et al. (1994)
	6×10^3	$88.6^\dagger$	McMullin et al. (1994)
	1.2×10^4	$3.17^\dagger$	McMullin et al. (1994)
	1.5×10^4	$2.6^\dagger$	McMullin et al. (1994)
	2.5×10^4	$0.25^\dagger$	McMullin et al. (1994)
L723	5	$7.5 \times 10^{-4\dagger}$	Anglada et al. (1996)
	8	$7.6 \times 10^{-4\dagger}$	Anglada et al. (1996)
	14.62	$(5.82 \pm 0.86) \times 10^{-4}$	this work
	15.37	$(5.16 \pm 0.64) \times 10^{-4}$	this work
	16.12	$(6.53 \pm 0.78) \times 10^{-4}$	this work
	16.87	$(6.55 \pm 0.69) \times 10^{-4}$	this work
	17.62	$(5.22 \pm 1.00) \times 10^{-4}$	this work
	230	$0.37^\dagger$	Motte & André (2001)
	230	0.36 ± 0.02	Reipurth et al. (1993)
	300	1 ± 0.5	Reipurth et al. (1993)
	353	1.79 ± 0.11	Shirley et al. (2000)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	353	2.24^+	di Francesco et al. (2008)
	666	8.5 ± 2.1	Shirley et al. (2000)
	750	13 ± 3	Reipurth et al. (1993)
	857	11.3 ± 1.8	Wu et al. (2007)
	1.54×10^3	35 ± 7	Reipurth et al. (1993)
	1.81×10^3	40 ± 12	Reipurth et al. (1993)
	2.08×10^3	33 ± 10	Reipurth et al. (1993)
	2.14×10^3	23 ± 8	Reipurth et al. (1993)
	2.31×10^3	32 ± 11	Reipurth et al. (1993)
	3×10^3	20.7 ± 1.7	Shirley et al. (2000)
	3.16×10^3	27 ± 6	Shirley et al. (2000)
	5×10^3	6.93 ± 0.62	Shirley et al. (2000)
	1.2×10^4	0.38 ± 0.05	Shirley et al. (2000)
	2.5×10^4	0.28 ± 0.06	Shirley et al. (2000)
L1251 A	5	$(1.7 \pm 0.03) \times 10^{-4}$	Beltrán et al. (2001)
	8	$2.9 \times 10^{-4+}$	Reipurth et al. (2004)
	8	$(4.7 \pm 0.03) \times 10^{-4}$	Beltrán et al. (2001)
	14.62	$(8.57 \pm 1.77) \times 10^{-4}$	this work
	15.37	$(9.85 \pm 1.36) \times 10^{-4}$	this work
	16.12	$(1.00 \pm 0.20) \times 10^{-3}$	this work
	16.87	$(7.61 \pm 1.58) \times 10^{-4}$	this work
	17.62	$(1.10 \pm 0.23) \times 10^{-3}$	this work
	230	0.23 ± 0.02	Rosvick & Davidge (1995)
	273	0.38 ± 0.03	Rosvick & Davidge (1995)
	353	5.68^+	di Francesco et al. (2008)
	375	0.71 ± 0.11	Rosvick & Davidge (1995)
	857	20.8 ± 3.2	Wu et al. (2007)
	3×10^3	78.5 ± 12.6	Rosvick & Davidge (1995)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	3×10^3	79^+	Sato & Fukui (1989)
	5×10^3	67.7 ± 6.1	Rosvick & Davidge (1995)
	5×10^3	66^+	Sato & Fukui (1989)
	1.2×10^4	28.3 ± 1.4	Rosvick & Davidge (1995)
	1.2×10^4	26^+	Sato & Fukui (1989)
	2.5×10^4	6.2 ± 0.3	Rosvick & Davidge (1995)
	2.5×10^4	5^+	Sato & Fukui (1989)
L1448 C	8	$2.3 \times 10^{-4\ddagger}$	Reipurth et al. (2002)
	15	$(5.6 \pm 0.5) \times 10^{-4}$	Curiel et al. (1990)
	16	$(5.37 \pm 0.33) \times 10^{-4}$	Scaife et al. (2011b)
	16.12	$(7.58 \pm 0.94) \times 10^{-4}$	this work
	86	$(2.6 \pm 0.2) \times 10^{-2}$	Shirley et al. (2000)
	87	$1.2 \times 10^{-2\ddagger}$	Bachiller et al. (1991)
	87	$1.6 \times 10^{-2\ddagger}$	Guilloteau et al. (1992)
	91	$(3.92 \pm 0.39) \times 10^{-2}$	Shirley et al. (2011)
	115	$(9.1 \pm 0.2) \times 10^{-2}$	Shirley et al. (2000)
	230	1 ± 0.1	Barsony et al. (1998)
	230	0.74 ± 0.11	Shirley et al. (2000)
	230	0.91^+	Motte & André (2001)
	230	0.58^+	Bachiller et al. (1991)
	273	2.04^+	Enoch et al. (2006)
	273	1 ± 0.1	Barsony et al. (1998)
	349	1.97 ± 0.13	Shirley et al. (2011)
	353	2.98^+	di Francesco et al. (2008)
	353	6.51^+	Hatchell et al. (2007b)
	353	3.95 ± 0.24	Shirley et al. (2000)
	353	5.34 ± 0.43	Chandler & Richer (2000)
	375	3 ± 0.3	Barsony et al. (1998)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	400	6.91 ± 0.91	Chandler & Richer (2000)
	666	68.4^+	Hatchell et al. (2007b)
	666	21 ± 2	Barsony et al. (1998)
	666	31.8 ± 5.5	Shirley et al. (2000)
	666	34.2 ± 6.9	Chandler & Richer (2000)
	857	58 ± 18	Chandler & Richer (2000)
	857	30 ± 3	Barsony et al. (1998)
	3×10^3	70.3 ± 14.8	Barsony et al. (1998)
	5×10^3	31.2 ± 6.5	Barsony et al. (1998)
	1.2×10^4	2.9 ± 0.6	Barsony et al. (1998)
	2.5×10^4	0.33 ± 0.07	Barsony et al. (1998)
NGC 1333 IRAS 2A	5	$(6 \pm 1) \times 10^{-5}$	Rodríguez et al. (1999)
	8	$2.2 \times 10^{-4+}$	Reipurth et al. (2002)
	8	$(2.5 \pm 0.4) \times 10^{-4}$	Rodríguez et al. (1999)
	16	$(3.2 \pm 0.25) \times 10^{-4}$	Scaife et al. (2011b)
	16.12	$(3.92 \pm 0.96) \times 10^{-4}$	this work
	43	$(1 \pm 0.5) \times 10^{-2}$	Anglada et al. (2004)
	86	$3.5 \times 10^{-2+}$	Jørgensen et al. (2004)
	89	$4 \times 10^{-2+}$	Jørgensen et al. (2004)
	111	$(8.28 \pm 0.4) \times 10^{-2}$	Looney et al. (2000)
	150	0.32 ± 0.07	Sandell et al. (1994)
	230	0.88^+	Motte & André (2001)
	230	0.88 ± 0.12	Sandell et al. (1994)
	273	1.46 ± 0.12	Sandell et al. (1994)
	353	7.78^+	Kirk et al. (2007)
	353	4.79 ± 0.39	Chandler & Richer (2000)
	375	4.08 ± 0.05	Sandell et al. (1994)
	375	3.75 ± 0.15	Sandell et al. (1994)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	400	5.54 ± 0.21	Sandell et al. (1994)
	400	6.61 ± 0.86	Chandler & Richer (2000)
	666	43 ± 11	Chandler & Richer (2000)
	666	23.7 ± 0.9	Sandell et al. (1994)
	857	37.2 ± 1.2	Sandell et al. (1994)
	857	74 ± 22	Chandler & Richer (2000)
	3×10^3	$300^\dagger$	Jennings et al. (1987)
	6×10^3	$104^\dagger$	Jennings et al. (1987)
NGC 1333 <i>IRAS</i> 2B	5	$(2.3 \pm 0.1) \times 10^{-4}$	Rodríguez et al. (1999)
	8	$(4 \pm 0.2) \times 10^{-4}$	Rodríguez et al. (1999)
	8	$(3.7 \pm 0.37) \times 10^{-4}$	Reipurth et al. (2002)
	16	$(1.21 \pm 0.05) \times 10^{-3}$	Scaife et al. (2011b)
	16.12	$(5.05 \pm 1.01) \times 10^{-4}$	this work
	43	$(5.2 \pm 0.3) \times 10^{-3}$	Anglada et al. (2004)
	86	$1.2 \times 10^{-2\dagger}$	Jørgensen et al. (2004)
	89	$1.4 \times 10^{-2\dagger}$	Jørgensen et al. (2004)
	111	$(2.77 \pm 0.32) \times 10^{-2}$	Looney et al. (2000)
	353	1.19 ± 0.1	Chandler & Richer (2000)
	400	1.53 ± 0.21	Chandler & Richer (2000)
	666	7.7 ± 1.6	Chandler & Richer (2000)
	857	13.4 ± 1.3	Chandler & Richer (2000)
L1551 NE	8	$6.6 \times 10^{-4\dagger}$	Reipurth et al. (2002)
	16.12	$(7.43 \pm 0.92) \times 10^{-4}$	this work
	230	$1.5^\dagger$	Motte & André (2001)
	230	0.85 ± 0.01	Andrews & Williams (2005)
	230	0.85 ± 0.08	Moriarty-Schieven et al. (2000)
	238	0.8 ± 0.12	Barsony & Chandler (1993)
	272	1.07 ± 0.11	Barsony & Chandler (1993)

Table continued on next page...

Table C.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	353	2.78^+	Moriarty-Schieven et al. (2006)
	353	10.5^+	di Francesco et al. (2008)
	379	2.22 ± 0.37	Barsony & Chandler (1993)
	666	8.33^+	Moriarty-Schieven et al. (2006)
	677	16.2 ± 4.6	Barsony & Chandler (1993)
	857	22.83 ± 0.72	Andrews & Williams (2005)
	3×10^3	130^+	Emerson et al. (1984)
	5×10^3	80^+	Emerson et al. (1984)
	1.2×10^4	16^+	Emerson et al. (1984)
	2.5×10^4	1.2^+	Emerson et al. (1984)
HH 25 MMS	5	$(1.5 \pm 0.4) \times 10^{-4}$	Bontemps et al. (1995)
	8	$(2.5 \pm 0.6) \times 10^{-4}$	Bontemps et al. (1995)
	8	$(1.6 \pm 0.3) \times 10^{-4}$	Gibb (1999)
	16.12	$(1.23 \pm 0.10) \times 10^{-3}$	this work
	231	1^+	Lis et al. (1999)
	353	9.11^+	di Francesco et al. (2008)
	353	4^+	Nutter & Ward-Thompson (2007)
	666	10.8^+	Nutter & Ward-Thompson (2007)
	666	8.7^+	Phillips et al. (2001)
	353	1.4^+	Phillips et al. (2001)
	857	24^+	Lis et al. (1999)
	3×10^3	70.66^+	IRAS
	5×10^3	28.04^+	IRAS
	5×10^3	32^+	IRAS
	1.2×10^4	1.39^+	Gezari et al. (1999)
	2.5×10^4	0.51^+	Gezari et al. (1999)

GMRT DATA REDUCTION PIPELINE

This appendix presents the tasks followed in AIPS to reduce and image the GMRT data presented in [Chapter 6](#). Standard AIPS tasks were used to calibrate the data, and wide-field imaging using facets following [Garn et al. \(2007\)](#) was conducted due to the large primary beam of the GMRT. This pipeline can be used to reduce standard, single-pointing continuum data taken at 325 or 610 MHz with the GMRT.

Table D.1.: GMRT Data Reduction Pipeline for AIPS

Work with CH256 (256 channel) dataset	
AIM: to find a good subset of channels for calibration	
INDXR	
UVFLG	(apply .FLAG file)
SPFLG	(ANTENNAS 1, 3, 5, 7, 9, 11, 13, 0, BASELINE 2, 4, 6, 8, 10, 12, 14, 0 identify $\sim 5 - 11$ good channels in wider dataset to make CH0 with, also take note of particularly bad channels & check interference on short baselines to make flagging the entire the entire dataset in the next CH256 section easier)
TVFLG	
UVFLG	(flag any known bad antennae, keep track of FG table numbers)
BPASS	(bandpass calibration on CH256 so as to calibrate the selected channels for CH0)
BPLOT	(check bandpass calibration, note channels where amp dips, if more flagging needs to be done, redo TVFLG, BPASS, BPLOT)
UVFLG	(flag any additional bad antennae and redo bandpass calibration, keep track of FG table numbers)

Work with CH0 (11 channels) dataset

AIM: to calibrate a subset of good channels that will then be applied to larger dataset

SPLAT	(ICHANSEL 95 105 1 1, OUTCLASS 'CH0')
TVFLG	(CH0, if more flagging is needed, flag then start over at CH256 BPASS before further calibration, ENTER STOKES FLAG 1111)
SETJY	(calculate flux of flux calibrator)
CALIB	(SOLINT 2, flux cal, note errors)
CALIB	(SOLINT 0, phase cal, note errors)
GETJY	(get flux of phase calibrator, note errors)
CLCAL	($\times 2$ to apply solution (SN 1 & 2) tables to both calibrators (CL 2) and then to just the phase calibrator (CL 3), keep track of CL table numbers)
SNPLT	(INEXT 'CL', INVERS 2 & 3 to check calibration)
TVFLG	(with DOCALIB 1, GAINUSE 3, check phases, use AMP v DIFF)
IMAGR	(flux cal)
IMAGR	(phase cal)
IMAGR	($\times 3$ target sources)
TACOP	(to copy phase-only CL table from CH0 (CL 3) to CH256 (becomes CL 2) dataset)

Back to CH256 dataset

AIM: to apply calibration to wider dataset

TVFLG	(to inspect bad channels identified in SPFLG and flag all bad data in full dataset, DON'T FORGET TO CHECK BOTH POLARISATIONS)
EXTDES	(to delete old/first BP table)
BPASS	(to make bandpass calibration good for all channels)
BPLOT	(check bandpass calibration, note channels where amp dips, if more flagging needs to be done, redo TVFLG, BPASS, BPLOT)

Work with CH24 (24 channel) dataset

AIM: to achieve good SNR and remove artifacts

NOTE: keep track of total flux cleaned and noise values every time IMAGR is run

NOTE: use TVBLINK to compare first image facet between self-calibrations

SPLAT	(average 256 channels to 24 channels to make CH24 for each source, drop a few end channels)
SPLIT	(need single source file for self-calibration & imaging)
WIPER	(and/or CLIP, to flag remaining bad data in target source, flag each day separately)
DBCON	(to combine datasets from different days)
IMAGR	(reimage with FLAGVER -1 v 0 to compare before & after flagging)
IMAGR	(make large low resolution maps to determine how many facets is needed for SETFC)
SETFC	(make BOXFILE for facetting)
IMAGR	(image facets for target source field, CH24S0: no self-calibration yet)
FLATN	(combine CH24S0 facets)
CALIB	(SOLINT 10, SOLMODE 'P' to flag & self-calibrates phases, writes out new uv dataset CH24S1)
SNPLT	(to print out SN plots & check self-calibration, check consistency between RR & LL)
IMAGR	(reimage facets for target source field, CH24S1: first round of self-calibration, IMEAN for rms)
FLATN	(combine CH24S1 facets)
CALIB	(SOLINT 3, SOLMODE 'P' for second round of self-calibration of phases, writes out new uv dataset CH24S2)
SNPLT	(to print out SN plots & check self-calibration, check consistency between RR & LL)
IMAGR	(reimage facets for target source field, CH24S2: second round of self-calibration, IMEAN for rms)

FLATN	(combine CH24S2 facets)
CALIB	(SOLINT 1, SOLMODE 'P' for third round of self-calibration of phases, writes out new uv dataset CH24S3)
SNPLT	(to print out SN plots & check self-calibration, check consistency between RR & LL)
IMAGR	(reimage facets for target source field, CH24S3: third round of self-calibration, IMEAN for rms)
FLATN	(combine CH24S3 facets)
UVSUB	(make UVSUB dataset with removed effects of clean components aka only noise left)
WIPER	(to remove remaining bad data from UVSUB dataset)
UVSUB	(FACTOR -1 to make UVADD dataset)
CALIB	(SOLINT 10, SOLMODE 'A&P' for fourth round of self-calibration, this time for phases AND amplitude, writes out new uv dataset CH24S4)
SNPLT	(to print out SN plots & check self-calibration, check consistency between RR & LL)
IMAGR	(with UVADD, UVBOX 5, NCHAV 24 to make combined channel map, reimage facets for target source field, CH24S4: fourth round of self-calibration, IMEAN for rms $\rightarrow$ FINAL FACETS)
FLATN	(combine CH24S4 facets $\rightarrow$ FINAL FLATN)
JMFIT	(to calculate flux of target source, also check other sources in field)
IMAGR	(with UVADD, UVBOX 5, NCHAV 1 to make CH24S4 single channel maps for spectrum)
JMFIT	(to calculate fluxes of target source from each channel, also check other sources in field, output to file SPECTRUM.TXT $\rightarrow$ grep Integral SPECTRUM.TXT)

Notes: Tests on CH24 dataset to maximise SNR

AIM: to achieve best possible SNR

NOTE: keep track of noise values for each test

TESTA: IMAGR (with ROBUST 5)
 TESTB: IMAGR (with ROBUST 0, UVRANGE 1, 0)
 TESTC: IMAGR (with ROBUST 0, UVRANGE 0, UVBOX 5)
 TESTD: UVSUB (make UVSUB dataset with removed effects of clean components aka only noise left)

WIPER & CLIP (to remove remaining bad data from UVSUB dataset)

UVSUB (FACTOR -1 to make UVADD dataset)

→ TESTC + TESTD = CH24S4 + UVSUB (UVADD) + UVBOX 5 worked best for TTAU

Notes: Final maps

AIM: to obtain fluxes & spectrum

IMAGR (with CH24S4, UVADD, UVBOX 5, NCHAV 24 to make combined channel map)

JMFIT (to calculate flux of target source, also check other sources in field)

IMAGR (with CH24S4, UVADD, UVBOX 5, NCHAV 1 to make single channel maps for spectrum)

JMFIT (to calculate fluxes of target source from each channel, also check other sources in field, output to file SPECTRUM.TXT → grep Integral SPECTRUM.TXT)

GMRT FIELD MAPS

Due to the large primary beam of the GMRT, I followed [Garn et al. \(2007\)](#) and conducted wide-field imaging using facets (see [Chapter 6](#) and [Appendix D](#)). The task `SETFC` was used to create a list of facet positions for use in `IMAGR`. Each field was divided into 61 smaller facets for the 325 MHz data and into 31 facets for the 610 MHz data, and arranged in a hexagonal grid. In each case the area covered is large compared with the GMRT primary beam, allowing bright sources well outside of the observed region to be cleaned from the images. The faceting technique avoids the introduction of phase errors due to the non-planar nature of the sky ([Garn et al., 2007](#)). Each field went through several iterations of self-calibration and re-imaging, improving the noise levels up to 30% and significantly reducing the residual side lobes around bright sources. The resulting facets were then stitched together and corrected for the primary beam using `FLATN`. To illustrate the quality of the data, the central facet from the L1551 IRS 5 region is shown in [Figure 6.1](#) and the full, `FLATN` images for each source at each frequency are presented in this appendix.

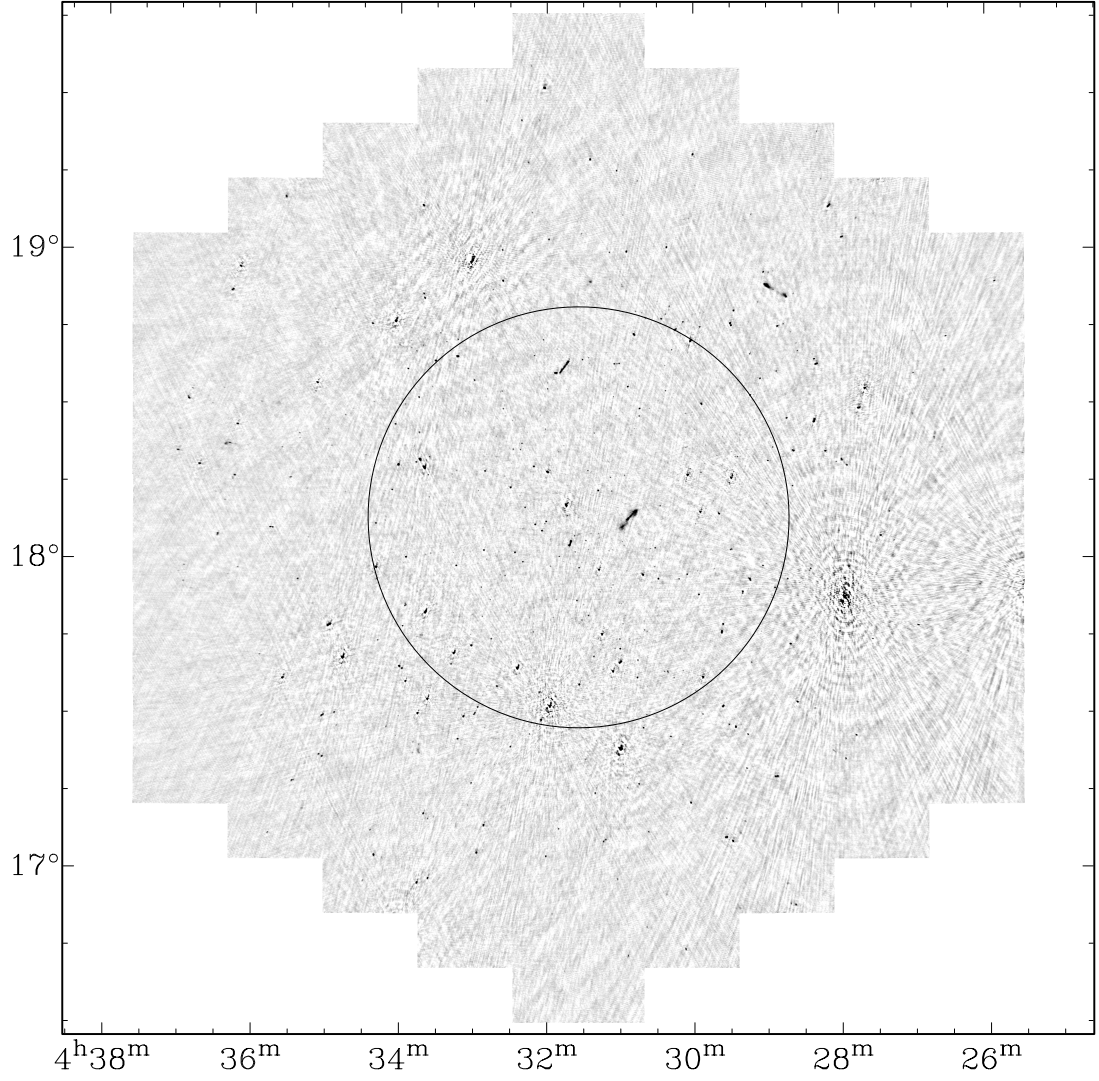


Figure E.1.: The FLATN image comprised of 61 facets for the L1551 IRS 5 field at 325 MHz. The GMRT primary beam is denoted by the circle with a width at half power of approximately $81'$. The grey-scale ranges between -0.2 and 2 mJy beam^{-1} and the resolution is $11''.4 \times 9''.5$, P.A. $-88^\circ.5$.

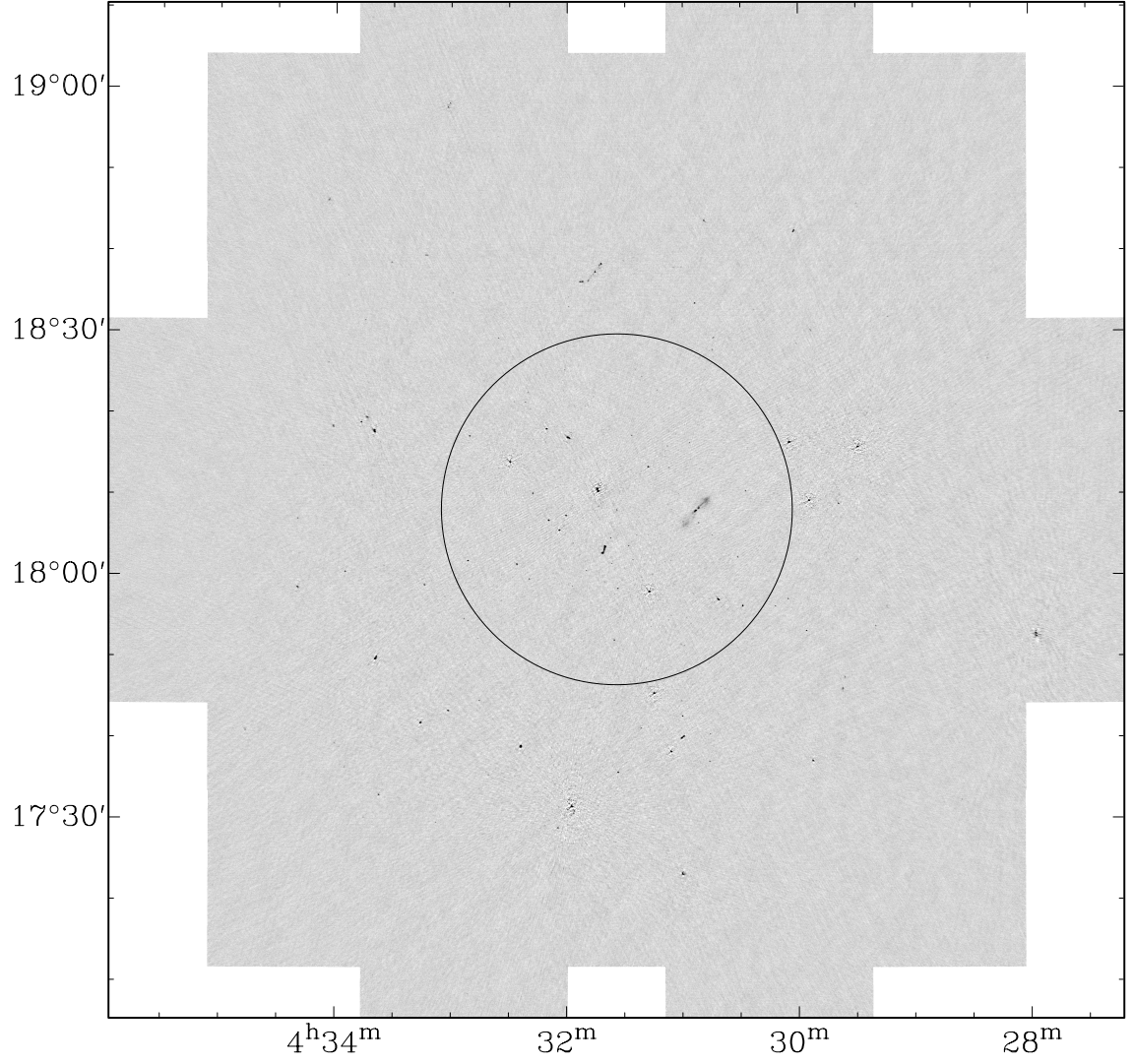


Figure E.2.: The FLATN image comprised of 31 facets for the L1551 IRS 5 field at 610 MHz. The GMRT primary beam at is denoted by the circle with a width at half power of approximately 43'. The grey-scale ranges between -0.2 and 1 mJy beam^{-1} and the resolution is $6''.2 \times 4''.9$, P.A. $76^\circ.5$.

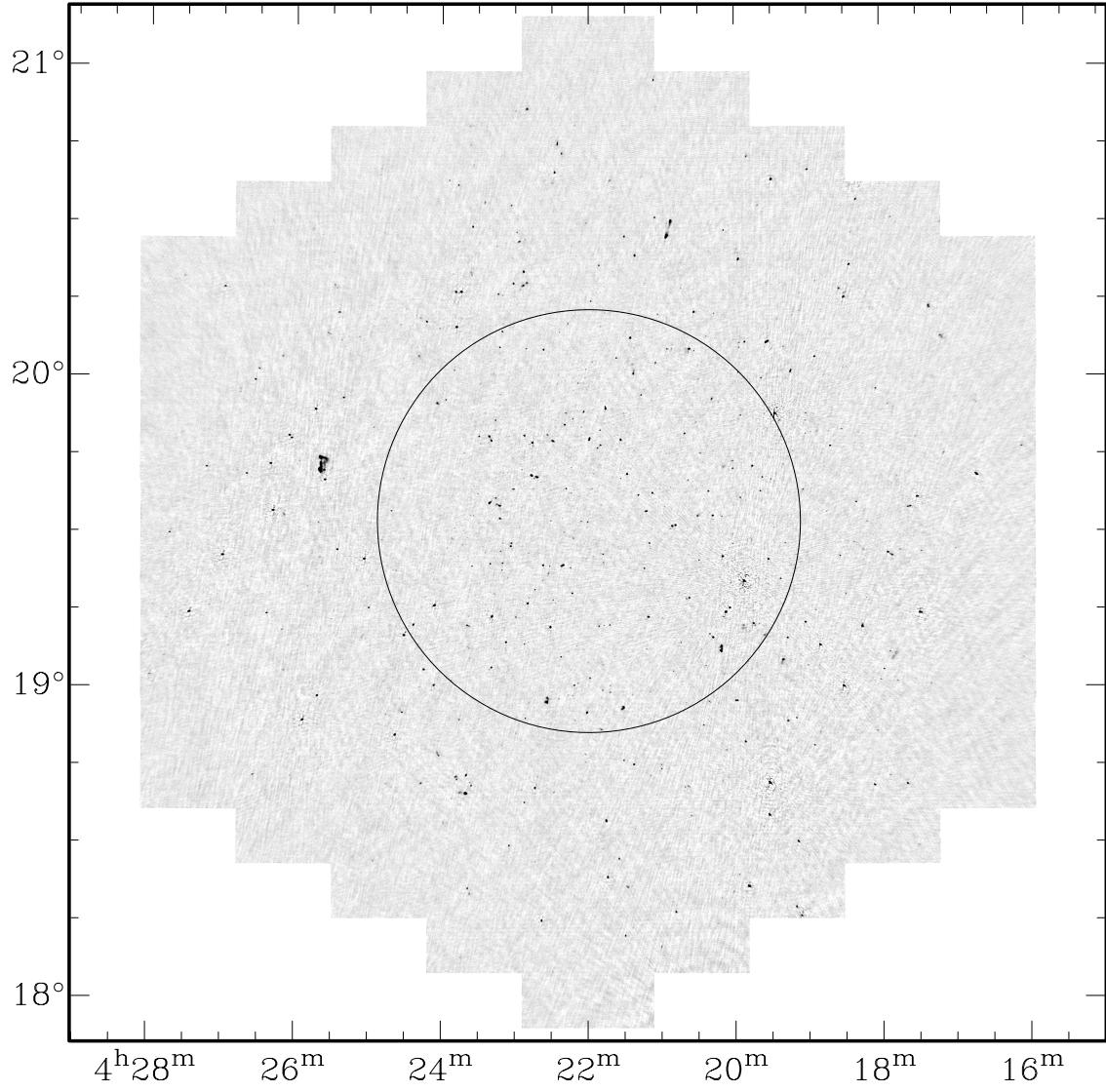


Figure E.3.: The FLATN image comprised of 61 facets for the T Tau field at 325 MHz. The GMRT primary beam is denoted by the circle with a width at half power of approximately $81'$. The grey-scale ranges between -0.2 and 2 mJy beam^{-1} and the resolution is $10''.8 \times 9''.5$, P.A. $-81^\circ.6$.

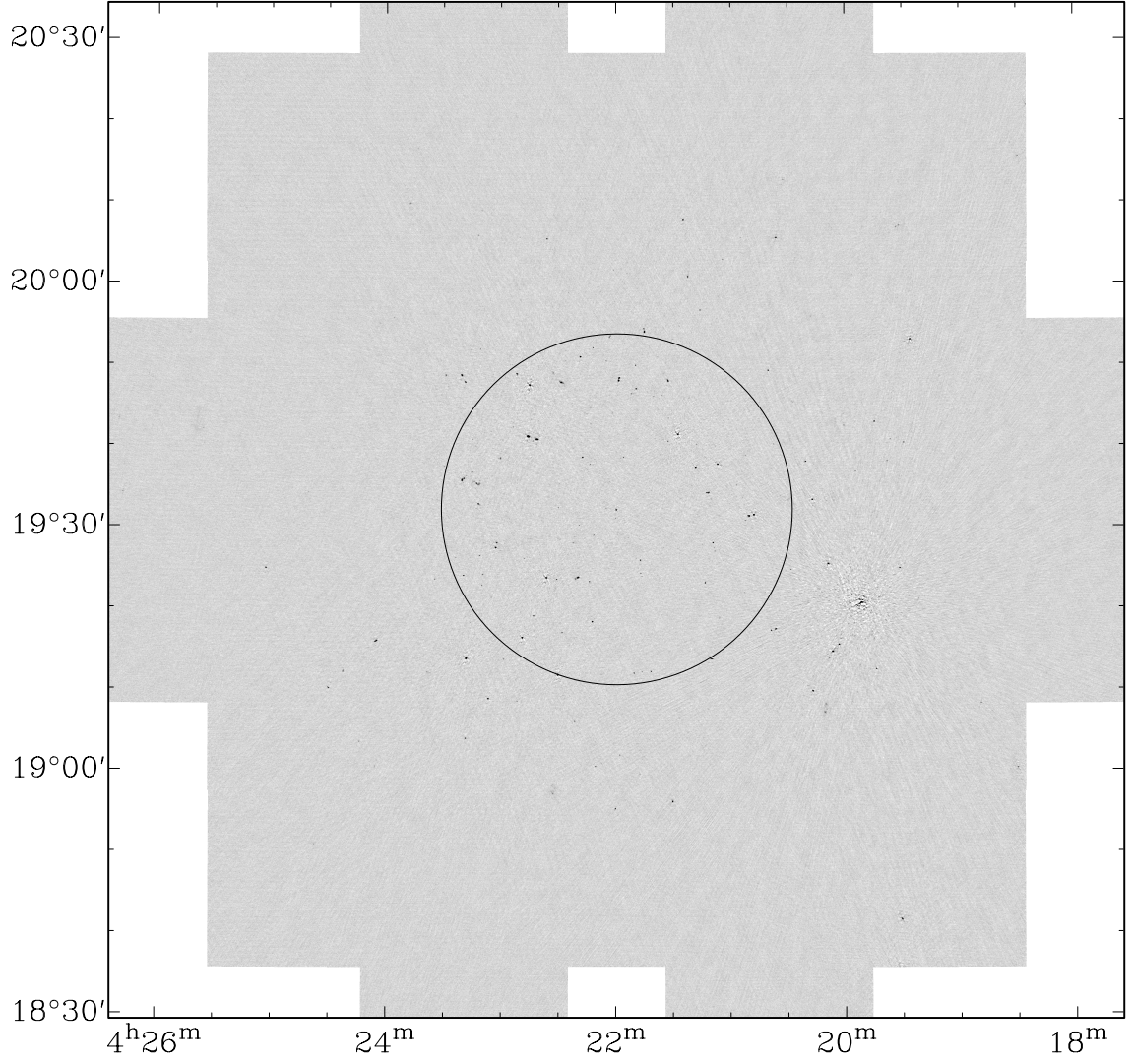


Figure E.4.: The FLATN image comprised of 31 facets for the T Tau field at 610 MHz. The GMRT primary beam is denoted by the circle with a width at half power of approximately 43'. The grey-scale ranges between -0.2 and 1 mJy beam^{-1} and the resolution is $6''.0 \times 5''.0$, P.A. $83^\circ.8$.

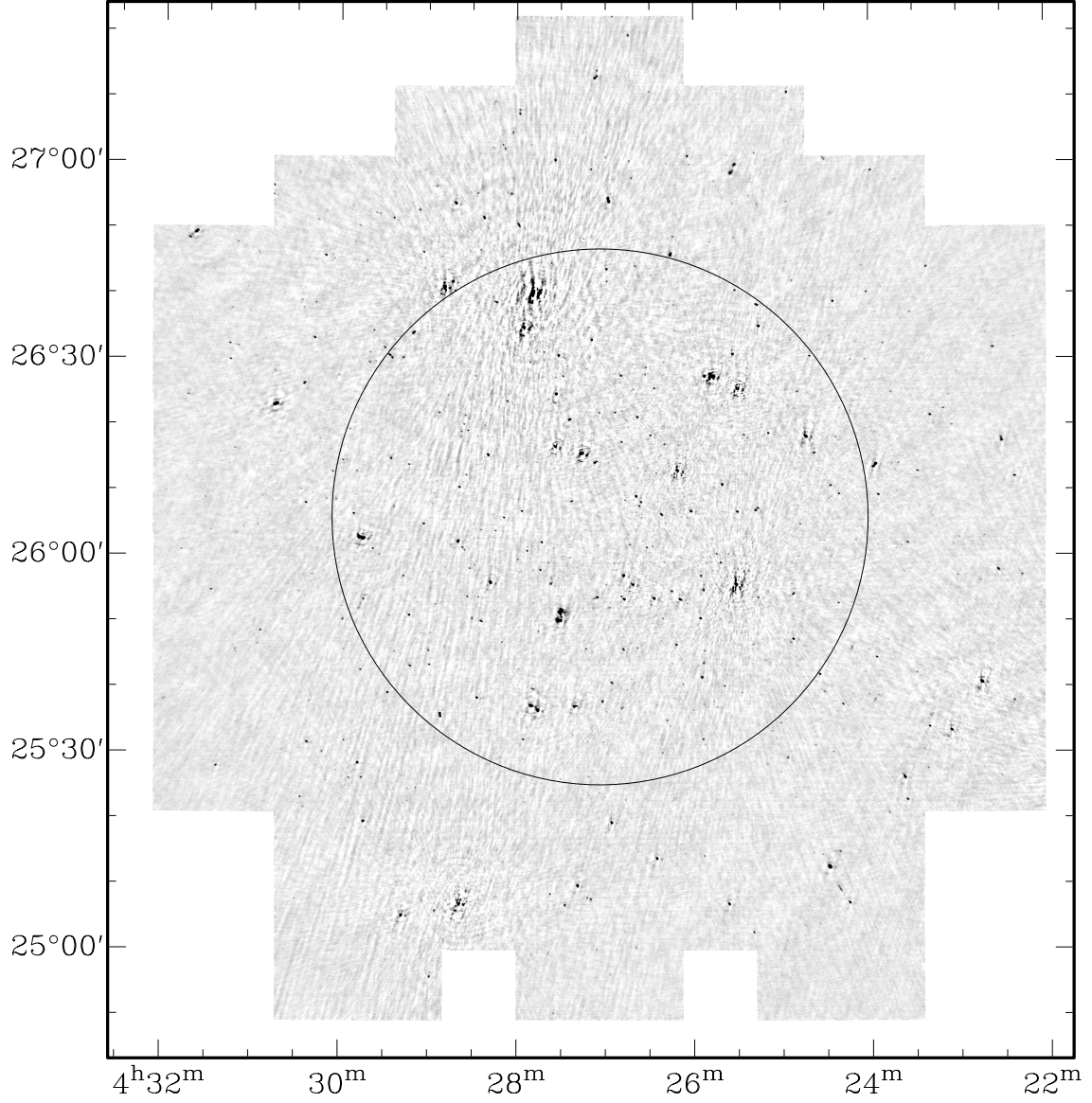


Figure E.5.: The FLATN image comprised of 61 facets for the DG Tau field at 325 MHz. The GMRT primary beam is denoted by the circle with a width at half power of approximately $81'$. The grey-scale ranges between -0.2 and 2 mJy beam^{-1} and the resolution is $11''.6 \times 9''.2$, P.A. $79^\circ.6$

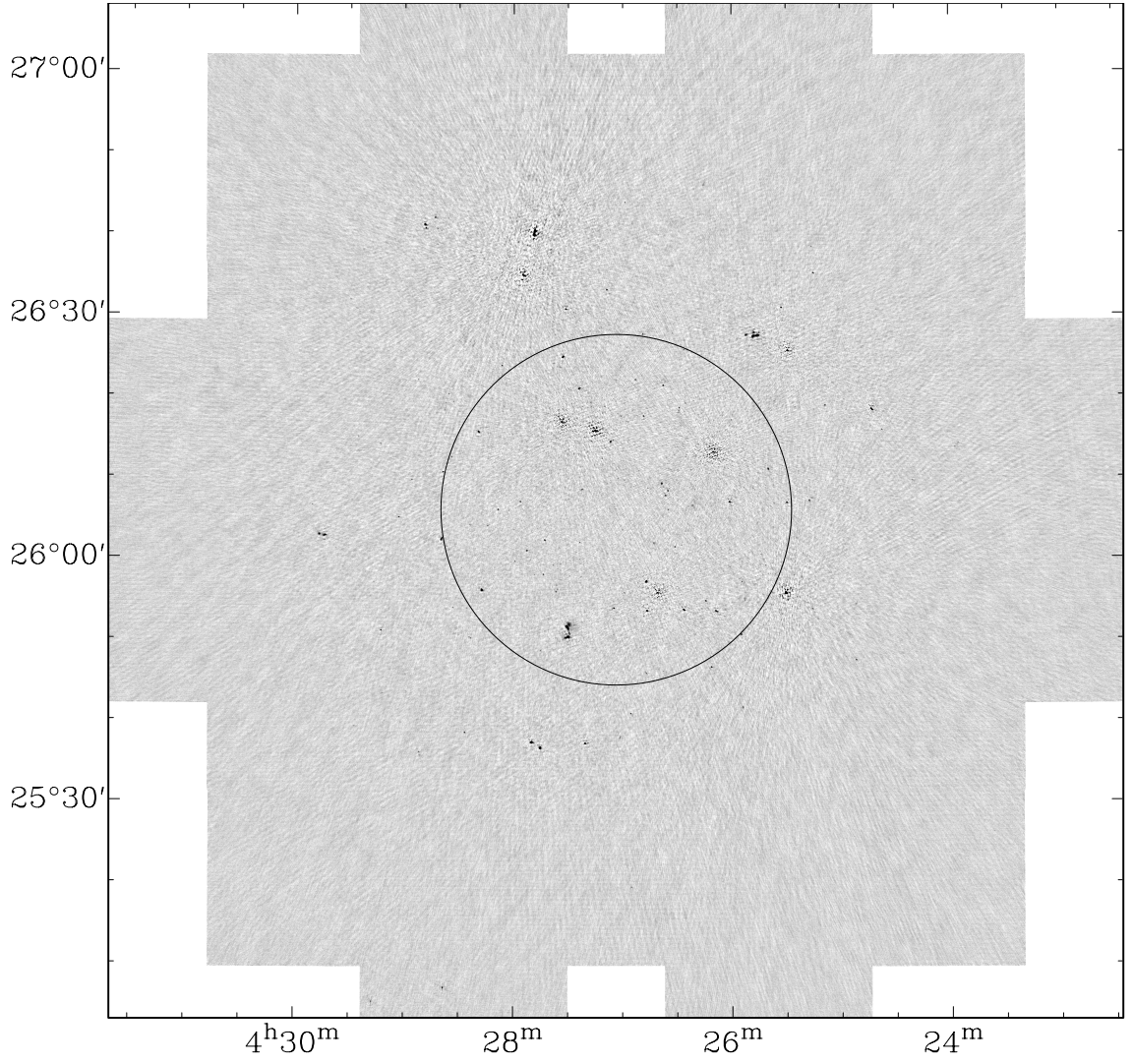


Figure E.6.: The FLATN image comprised of 31 facets for the DG Tau field at 610 MHz. The GMRT primary beam is denoted by the circle with a width at half power of approximately $43'$. The grey-scale ranges between -0.2 and 1 mJy beam^{-1} and the resolution is $6''.5 \times 5''.2$, P.A. $74^\circ.0$

GMRT SAMPLE SPECTRAL ENERGY DISTRIBUTION REFERENCE
TABLE

An extensive literature search was conducted for unresolved, integrated flux densities to include in the spectral energy distributions discussed in [Chapter 6](#). It should be noted that [Wendker \(1995\)](#) was a useful reference. High resolution data that were highly discrepant due to flux loss or data with high uncertainties (e.g. $450\ \mu\text{m}$ data from [di Francesco et al., 2008](#)) were not included. Where uncertainties were not provided, an error of 10% was used in the model fittings and this is indicated by a [†].

Table F.1.: Reference list for the spectral energy distribution data.

Source	ν (GHz)	S_ν (Jy)	Reference
T Tau	0.325	$(3.83 \pm 0.31) \times 10^{-3}$	this work
	0.61	$(4.16 \pm 0.23) \times 10^{-3}$	this work
	1.4	$4.80 \times 10^{-3\dagger}$	
	1.4	$(2.80 \pm 0.50) \times 10^{-3}$	Schwartz et al. (1986)
	1.465	$(5.00 \pm 1.00) \times 10^{-3}$	Rodríguez & Canto (1983)
	1.465	$(3.00 \pm 1.00) \times 10^{-3}$	Schwartz et al. (1984)
	1.49	$(2.74 \pm 0.11) \times 10^{-3}$	Cohen & Bieging (1986)
	2.695	$(4.00 \pm 2.00) \times 10^{-3}$	Spencer & Schwartz (1974)
	4.86	$(4.94 \pm 0.34) \times 10^{-3}$	Skinner & Brown (1994)
	4.86	$(4.62 \pm 0.26) \times 10^{-3}$	Skinner & Brown (1994)
	4.86	$(4.53 \pm 0.29) \times 10^{-3}$	Skinner & Brown (1994)
	4.885	$(5.80 \pm 0.60) \times 10^{-3}$	Cohen et al. (1982)
	4.885	$(5.00 \pm 0.60) \times 10^{-3}$	Rodríguez & Canto (1983)

Table continued on next page...

Table F.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	4.885	$(4.30 \pm 0.20) \times 10^{-3}$	Schwartz et al. (1984)
	4.885	$(5.20 \pm 0.50) \times 10^{-3}$	Bieging et al. (1984)
	4.885	$(5.70 \pm 0.50) \times 10^{-3}$	Schwartz et al. (1986)
	4.885	$6.40 \times 10^{-3\dagger}$	Evans et al. (1987)
	5	$(6.50 \pm 0.07) \times 10^{-3}$	Cohen et al. (1982)
	8.085	$(8.00 \pm 2.00) \times 10^{-3}$	Spencer & Schwartz (1974)
	8.44	$(5.19 \pm 0.30) \times 10^{-3}$	Skinner & Brown (1994)
	8.44	$(5.05 \pm 0.31) \times 10^{-3}$	Skinner & Brown (1994)
	8.44	$(5.79 \pm 0.34) \times 10^{-3}$	Skinner & Brown (1994)
	8.44	$(7.93 \pm 0.51) \times 10^{-3}$	Skinner & Brown (1994)
	8.44	$(5.81 \pm 0.41) \times 10^{-3}$	Skinner & Brown (1994)
	10.5	$(7.30 \pm 2.80) \times 10^{-3}$	Maran et al. (1979)
	10.69	$(8.00 \pm 2.00) \times 10^{-3}$	Altenhoff et al. (1976)
	14.94	$(6.50 \pm 0.07) \times 10^{-3}$	Cohen & Bieging (1986)
	14.949	$(5.14 \pm 0.43) \times 10^{-3}$	Skinner & Brown (1994)
	14.965	$(9.00 \pm 1.00) \times 10^{-3}$	Schwartz et al. (1984)
	14.965	$(7.50 \pm 0.70) \times 10^{-3}$	Bieging et al. (1984)
	14.965	$(1.11 \pm 0.10) \times 10^{-2}$	Schwartz et al. (1986)
	15	$(8.60 \pm 2.00) \times 10^{-3}$	Bertout & Thum (1982)
	86	$(3.27 \pm 0.78) \times 10^{-2}$	Altenhoff et al. (1986)
	90	$(6.80 \pm 2.70) \times 10^{-2}$	Schwartz & Spencer (1977)
	112.6	$(7.50 \pm 0.75) \times 10^{-2}$	Weintraub et al. (1989b)
	226	$(8.94 \pm 1.53) \times 10^{-1}$	Altenhoff et al. (1986)
	230	$(2.80 \pm 0.09) \times 10^{-1}$	Beckwith et al. (1990)
	230	$(2.53 \pm 0.18) \times 10^{-1}$	Reipurth et al. (1993)
	231	$(2.80 \pm 0.09) \times 10^{-1}$	Andrews & Williams (2005)
	250	$(2.96 \pm 0.25) \times 10^{-1}$	Altenhoff et al. (1994)
	272	$(3.20 \pm 0.30) \times 10^{-1}$	Adams et al. (1990)

Table continued on next page...

Table F.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	272	$(5.79 \pm 0.27) \times 10^{-1}$	Weintraub et al. (1989a)
	284	$(4.17 \pm 0.41) \times 10^{-1}$	Beckwith & Sargent (1991)
	341	$3.04 \times 10^{-1+}$	Harris et al. (2012)
	353	2.25^+	Sadavoy et al. (2010)
	353	2.47^+	di Francesco et al. (2008)
	353	$(6.28 \pm 0.17) \times 10^{-1}$	Andrews & Williams (2005)
	375	1.22 ± 0.04	Weintraub et al. (1989a)
	375	$(8.60 \pm 0.80) \times 10^{-1}$	Jewitt (1994)
	380	1.07 ± 0.11	Adams et al. (1990)
	390	$(9.10 \pm 0.09) \times 10^{-1}$	Beckwith & Sargent (1991)
	463	1.30 ± 0.20	Adams et al. (1990)
	676	2.60 ± 0.40	Adams et al. (1990)
	676	1.66 ± 0.22	Andrews & Williams (2005)
	676	6.71 ± 0.61	Weintraub et al. (1989a)
	854	10.2 ± 0.70	Weintraub et al. (1989a)
	854	8.15 ± 0.25	Andrews & Williams (2005)
	3×10^3	98.1^+	IRAS
	5×10^3	98.7^+	IRAS
	12×10^3	44.2^+	IRAS
	25×10^3	14.9^+	IRAS
DG Tau	0.325	$(7.00 \pm 2.00) \times 10^{-4}$	this work
	0.61	$(4.00 \pm 1.00) \times 10^{-4}$	this work
	4.89	$(7.00 \pm 1.00) \times 10^{-4}$	Cohen et al. (1982)
	4.89	$(1.20 \pm 0.10) \times 10^{-3}$	Bieging et al. (1984)
	4.89	$(1.03 \pm 0.07) \times 10^{-3}$	Cohen & Bieging (1986)
	4.89	$(6.00 \pm 1.00) \times 10^{-4}$	Evans et al. (1987)
	5.4	$(1.05 \pm 0.05) \times 10^{-3}$	Lynch et al. (2013)
	8.5	$(1.27 \pm 0.05) \times 10^{-3}$	Rodríguez et al. (2012)

Table continued on next page...

Table F.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	8.5	$(1.29 \pm 0.07) \times 10^{-3}$	Lynch et al. (2013)
	8.5	$(1.10 \pm 0.06) \times 10^{-3}$	Lynch et al. (2013)
	15	$2.01 \times 10^{-3\dagger}$	Cohen & Bieging (1986)
	16.12	$(1.40 \pm 0.07) \times 10^{-3}$	Scaife et al. (2012a)
	23	$2.90 \times 10^{-3\dagger}$	Bertout & Thum (1982)
	43.3	$(3.90 \pm 0.22) \times 10^{-3}$	Lynch et al. (2013)
	98	$(5.70 \pm 0.40) \times 10^{-2}$	Ohashi et al. (1991)
	110	$7.10 \times 10^{-2\dagger}$	Sargent & Beckwith (1989)
	110	$7.20 \times 10^{-2\dagger}$	Kitamura et al. (1996a)
	111	$7.50 \times 10^{-2\dagger}$	Sargent & Beckwith (1994)
	112	$8.00 \times 10^{-2\dagger}$	Woody et al. (1989)
	147	$(1.86 \pm 0.17) \times 10^{-1}$	Kitamura et al. (1996b)
	230	$4.43 \times 10^{-1\dagger}$	Beckwith et al. (1990)
	230	$4.40 \times 10^{-1\dagger}$	Adams et al. (1990)
	250	$(4.20 \pm 0.42) \times 10^{-1}$	Altenhoff et al. (1994)
	260	$4.89 \times 10^{-1\dagger}$	Beckwith & Sargent (1991)
	270	$5.32 \times 10^{-1\dagger}$	Weintraub et al. (1989a)
	273	$(4.40 \pm 0.30) \times 10^{-1}$	Adams et al. (1990)
	273	$(5.32 \pm 0.48) \times 10^{-1}$	Weintraub et al. (1989a)
	284	$(4.89 \pm 0.33) \times 10^{-1}$	Beckwith & Sargent (1991)
	375	$(9.40 \pm 1.00) \times 10^{-1}$	Adams et al. (1990)
	390	$(8.60 \pm 1.00) \times 10^{-1}$	Beckwith & Sargent (1991)
	480	1.21 ± 0.2	Beckwith & Sargent (1991)
	500	1.4 ± 0.2	Adams et al. (1990)
	666	3.39 ± 0.44	Weintraub et al. (1989a)
	666	3.6 ± 0.4	Adams et al. (1990)
	857	9.6 ± 1.1	Adams et al. (1990)
	2.1×10^3	37.03 ± 7.3	Yamamura et al. (2010)

Table continued on next page...

Table F.1 – Continued from previous page.

Source	ν (GHz)	S_ν (Jy)	Reference
	3×10^3	$53.13^\dagger$	<i>IRAS</i>
	5×10^3	$41.59^\dagger$	<i>IRAS</i>
	12×10^3	$23.59^\dagger$	<i>IRAS</i>
	25×10^3	$10.64^\dagger$	<i>IRAS</i>

Part IV

REFERENCES

REFERENCES

- Adams, F. C., Emerson, J. P., & Fuller, G. A., 1990. Submillimeter photometry and disk masses of T Tauri disk systems, *Astrophysical Journal*, **357**, 606–620. (Cited on pages [162](#), [163](#), and [164](#).)
- Agra-Amboage, V., Dougados, C., Cabrit, S., & Reunanen, J., 2011. Sub-arcsecond [Fe ii] spectro-imaging of the DG Tauri jet. Periodic bubbles and a dusty disk wind?, *Astronomy and Astrophysics*, **532**, A59. (Cited on pages [77](#), [82](#), [85](#), and [86](#).)
- Ainsworth, R. E., Scaife, A. M. M., Ray, T. P., Buckle, J. V., Davies, M., Franzen, T. M. O., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A. N., Olamaie, M., Perrott, Y. C., Pooley, G. G., Richer, J. S., Rodríguez-Gonzálvez, C., Saunders, R. D. E., Schammel, M. P., Scott, P. F., Shimwell, T., Titterton, D., & Waldram, E., 2012. AMI radio continuum observations of young stellar objects with known outflows, *Monthly Notices of the Royal Astronomical Society*, **423**, 1089–1108. (Cited on page [98](#).)
- Ainsworth, R. E., Ray, T. P., Scaife, A. M. M., Greaves, J. S., & Beswick, R. J., 2013. Subarc-second high-sensitivity measurements of the DG Tau jet with e-MERLIN, *Mon. Not. R. Astron. Soc. Letters*, **436**, L64–L68. (Cited on page [99](#).)
- Altenhoff, W., Mezger, P. G., Wendker, H., & Westerhout, F., 1960. , *Veröffentlichungen Universitäts-Sternwarte*, **59**, 48. (Cited on page [28](#).)
- Altenhoff, W. J., Braes, L. L. E., Olon, F. M., & Wendker, H. J., 1976. A search for radio emission from stars, *Astronomy and Astrophysics*, **46**, 11–17. (Cited on page [162](#).)
- Altenhoff, W. J., Huchtmeier, W. K., Schmidt, J., Schraml, J. B., & Stumpff, P., 1986. Radio continuum observations of comet Halley, *Astronomy and Astrophysics*, **164**, 227–230. (Cited on page [162](#).)
- Altenhoff, W. J., Thum, C., & Wendker, H. J., 1994. Radio emission from stars: A survey at 250 GHz, *Astronomy and Astrophysics*, **281**, 161–183. (Cited on pages [136](#), [162](#), and [164](#).)
- Ananthakrishnan, S., 2005. The Giant Metrewave Radio Telescope (GMRT): Salient features and recent results, *International Cosmic Ray Conference*, **10**, 125. (Cited on pages [37](#) and [90](#).)
- André, P., Ward-Thompson, D., & Barsony, M., 1993. Submillimeter continuum observations of Rho Ophiuchi A - The candidate protostar VLA 1623 and prestellar clumps, *Astrophysical Journal*, **406**, 122–141. (Cited on pages [7](#) and [8](#).)

- André, P., Ward-Thompson, D., & Barsony, M., 2000. From Prestellar Cores to Protostars: the Initial Conditions of Star Formation, *Protostars and Planets IV*, p. 59. (Cited on pages 15 and 45.)
- Andrews, S. M. & Williams, J. P., 2005. Circumstellar Dust Disks in Taurus-Auriga: The Submillimeter Perspective, *Astrophysical Journal*, **631**, 1134–1160. (Cited on pages 100, 145, 146, 162, and 163.)
- Anglada, G., 1995. Centimeter Continuum Emission from Outflow Sources, in *Revista Mexicana de Astronomía y Astrofísica Conference Series*, vol. 1 of **Revista Mexicana de Astronomía y Astrofísica**, vol. 27, p. 67. (Cited on pages 45, 67, and 89.)
- Anglada, G., Estalella, R., Rodríguez, L. F., Torrelles, J. M., Lopez, R., & Canto, J., 1991. A double radio source at the center of the outflow in L723, *Astrophysical Journal*, **376**, 615–617. (Cited on page 55.)
- Anglada, G., Rodríguez, L. F., & Torrelles, J. M., 1996. A Thermal Radio Jet Associated with the Quadrupolar Molecular Outflow in L723, *Astrophysical Journal, Letters*, **473**, L123. (Cited on pages 56, 66, and 141.)
- Anglada, G., Villuendas, E., Estalella, R., Beltrán, M. T., Rodríguez, L. F., Torrelles, J. M., & Curiel, S., 1998. Spectral Indices of Centimeter Continuum Sources in Star-forming Regions: Implications on the Nature of the Outflow Exciting Sources, *Astronomical Journal*, **116**, 2953–2964. (Cited on pages 104 and 138.)
- Anglada, G., Rodríguez, L. F., Osorio, M., Torrelles, J. M., Estalella, R., Beltrán, M. T., & Ho, P. T. P., 2004. A Single Circumstellar Disk in the SVS 13 Close Binary System, *Astrophysical Journal, Letters*, **605**, L137–L140. (Cited on pages 134, 144, and 145.)
- Antoniucci, S., Nisini, B., Giannini, T., & Lorenzetti, D., 2008. Accretion and ejection properties of embedded protostars: the case of HH26, HH34, and HH46 IRS, *Astronomy and Astrophysics*, **479**, 503–514. (Cited on pages 15, 138, and 139.)
- Arce, H. G., Shepherd, D., Gueth, F., Lee, C.-F., Bachiller, R., Rosen, A., & Beuther, H., 2007. Molecular Outflows in Low- and High-Mass Star-forming Regions, *Protostars and Planets V*, pp. 245–260. (Cited on pages 14 and 15.)
- Bacciotti, F., Mundt, R., Ray, T. P., Eislöffel, J., Solf, J., & Camezind, M., 2000. Hubble Space Telescope STIS Spectroscopy of the Optical Outflow from DG Tauri: Structure and Kinematics on Subarcsecond Scales, *Astrophysical Journal, Letters*, **537**, L49–L52. (Cited on pages 14 and 82.)

- Bacciotti, F., Ray, T. P., Mundt, R., Eisloffel, J., & Solf, J., 2002. Hubble Space Telescope/STIS Spectroscopy of the Optical Outflow from DG Tauri: Indications for Rotation in the Initial Jet Channel, *Astrophysical Journal*, **576**, 222–231. (Cited on pages [14](#), [18](#), [82](#), and [85](#).)
- Bachiller, R., 1996. Bipolar Molecular Outflows from Young Stars and Protostars, *Annual Review of Astronomy and Astrophysics*, **34**, 111–154. (Cited on page [7](#).)
- Bachiller, R., Martin-Pintado, J., Tafalla, M., Cernicharo, J., & Lazareff, B., 1990. High-velocity molecular bullets in a fast bipolar outflow near L1448/IRS3, *Astronomy and Astrophysics*, **231**, 174–186. (Cited on page [49](#).)
- Bachiller, R., Andre, P., & Cabrit, S., 1991. Detection of the exciting source of the spectacular molecular outflow L1448 at $\lambda\lambda$ 1–3 MM, *Astronomy and Astrophysics*, **241**, L43–L46. (Cited on page [143](#).)
- Bachiller, R., Guilloteau, S., Dutrey, A., Planesas, P., & Martin-Pintado, J., 1995. The jet-driven molecular outflow in L 1448. CO and continuum synthesis images., *Astronomy and Astrophysics*, **299**, 857. (Cited on page [49](#).)
- Bally, J. & Devine, D., 1994. A parsec-scale ‘superjet’ and quasi-periodic structure in the HH 34 outflow?, *Astrophysical Journal, Letters*, **428**, L65–L68. (Cited on page [11](#).)
- Bally, J., Devine, D., Alten, V., & Sutherland, R. S., 1997. New Herbig-Haro Flows in L1448 and L1455, *Astrophysical Journal*, **478**, 603. (Cited on page [49](#).)
- Bally, J., Heathcote, S., Reipurth, B., Morse, J., Hartigan, P., & Schwartz, R., 2002. Hubble Space Telescope Observations of Proper Motions in Herbig-Haro Objects 1 and 2, *Astronomical Journal*, **123**, 2627–2657. (Cited on page [20](#).)
- Bally, J., Reipurth, B., & Davis, C. J., 2007. Observations of Jets and Outflows from Young Stars, *Protostars and Planets V*, pp. 215–230. (Cited on pages [4](#), [5](#), [11](#), [13](#), and [14](#).)
- Barsony, M. & Chandler, C. J., 1993. The circumstellar density distribution of L1551NE, *Astrophysical Journal, Letters*, **406**, L71–L74. (Cited on pages [145](#) and [146](#).)
- Barsony, M., Ward-Thompson, D., André, P., & O’Linger, J., 1998. Protostars in Perseus: Outflow-induced Fragmentation, *Astrophysical Journal*, **509**, 733–748. (Cited on pages [133](#), [134](#), [143](#), and [144](#).)
- Beck, R. & Krause, M., 2005. Revised equipartition and minimum energy formula for magnetic field strength estimates from radio synchrotron observations, *Astronomische Nachrichten*, **326**, 414–427. (Cited on page [108](#).)

- Beck, T. L., Schaefer, G. H., Simon, M., Prato, L., Stoesz, J. A., & Howell, R. R., 2004. A High Spatial Resolution Infrared View of the T Tauri Multiple System, *Astrophysical Journal*, **614**, 235–251. (Cited on page 98.)
- Beckwith, S. V. W. & Sargent, A. I., 1991. Particle emissivity in circumstellar disks, *Astrophysical Journal*, **381**, 250–258. (Cited on pages 163 and 164.)
- Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R., 1990. A survey for circumstellar disks around young stellar objects, *Astronomical Journal*, **99**, 924–945. (Cited on pages 162 and 164.)
- Beltrán, M. T., Estalella, R., Anglada, G., Rodríguez, L. F., & Torrelles, J. M., 2001. Radio Spectral Indices of the Powering Sources of Outflows, *Astronomical Journal*, **121**, 1556–1568. (Cited on pages 56 and 142.)
- Bergin, E. A. & Tafalla, M., 2007. Cold Dark Clouds: The Initial Conditions for Star Formation, *Annual Review of Astronomy and Astrophysics*, **45**, 339–396. (Cited on page 108.)
- Bertout, C. & Thum, C., 1982. Radio observations of pre-main-sequence stars - Results and interpretation, *Astronomy and Astrophysics*, **107**, 368–375. (Cited on pages 162 and 164.)
- Bieging, J. H. & Cohen, M., 1985. Multifrequency radio images of L1551 IRS 5, *Astrophysical Journal, Letters*, **289**, L5–L8. (Cited on page 135.)
- Bieging, J. H., Cohen, M., & Schwartz, P. R., 1984. VLA observations of T Tauri stars. II - A luminosity-limited survey of Taurus-Auriga, *Astrophysical Journal*, **282**, 699–708. (Cited on pages 77, 135, 162, and 163.)
- Blandford, R. D. & Payne, D. G., 1982. Hydromagnetic flows from accretion discs and the production of radio jets, *Mon. Not. R. Astron. Soc.*, **199**, 883–903. (Cited on pages 3 and 16.)
- Böhm, K.-H., 1956. A Spectrophotometric Analysis of the Brightest Herbig-Haro Object., *Astrophysical Journal*, **123**, 379. (Cited on page 10.)
- Bontemps, S., Andre, P., & Ward-Thompson, D., 1995. Deep VLA search for the youngest protostars: A Class 0 source in the HH24-26 region, *Astronomy and Astrophysics*, **297**, 98–102. (Cited on page 146.)
- Bontemps, S., André, P., Terebey, S., & Cabrit, S., 1996. Evolution of outflow activity around low-mass embedded young stellar objects, *Astronomy and Astrophysics*, **311**, 858–872. (Cited on pages 8, 9, 15, 45, 70, and 73.)
- Cabrit, S., 2002. Constraints on accretion-ejection structures in young stars, in *EAS Publications Series*, vol. 3 of **EAS Publications Series**, pp. 147–182. (Cited on page 83.)

- Cabrit, S., 2007. The accretion-ejection connexion in T Tauri stars: jet models vs. observations, in *IAU Symposium*, vol. 243 of **IAU Symposium**, pp. 203–214. (Cited on pages [9](#), [14](#), [16](#), [85](#), and [86](#).)
- Cabrit, S. & Andre, P., 1991. An observational connection between circumstellar disk mass and molecular outflows, *Astrophysical Journal, Letters*, **379**, L25–L28. (Cited on page [136](#).)
- Cabrit, S., Edwards, S., Strom, S. E., & Strom, K. M., 1990. Forbidden-line emission and infrared excesses in T Tauri stars - Evidence for accretion-driven mass loss?, *Astrophysical Journal*, **354**, 687–700. (Cited on pages [15](#) and [86](#).)
- Caratti o Garatti, A., Giannini, T., Nisini, B., & Lorenzetti, D., 2006. H₂ active jets in the near IR as a probe of protostellar evolution, *Astronomy and Astrophysics*, **449**, 1077–1088. (Cited on page [54](#).)
- Carrasco-González, C., Anglada, G., Rodríguez, L. F., Torrelles, J. M., Osorio, M., & Girart, J. M., 2008. A Multiple System of Radio Sources at the Core of the L723 Multipolar Outflow, *Astrophysical Journal*, **676**, 1073–1081. (Cited on pages [56](#) and [66](#).)
- Carrasco-González, C., Rodríguez, L. F., Anglada, G., Martí, J., Torrelles, J. M., & Osorio, M., 2010a. A Magnetized Jet from a Massive Protostar, *Science*, **330**, 1209–. (Cited on pages [4](#), [21](#), and [105](#).)
- Carrasco-González, C., Rodríguez, L. F., Torrelles, J. M., Anglada, G., & González-Martín, O., 2010b. A Bright Radio HH Object with Large Proper Motions in the Massive Star-forming Region W75N, *Astronomical Journal*, **139**, 2433–2439. (Cited on page [53](#).)
- Carretti, E., Crocker, R. M., Staveley-Smith, L., Haverkorn, M., Purcell, C., Gaensler, B. M., Bernardi, G., Kesteven, M. J., & Poppi, S., 2013. Giant magnetized outflows from the centre of the Milky Way, *Nature*, **493**, 66–69. (Cited on page [108](#).)
- Casali, M. M., Eiroa, C., & Duncan, W. D., 1993. A Second Phase of Star Formation in the Serpens Core, *Astronomy and Astrophysics*, **275**, 195. (Cited on page [141](#).)
- Ceccarelli, C., Dominik, C., López-Sepulcre, A., Kama, M., Padovani, M., Caux, E., & Caselli, P., 2014. Herschel Finds Evidence for Stellar Wind Particles in a Protostellar Envelope: Is This What Happened to the Young Sun?, *Astrophysical Journal, Letters*, **790**, L1. (Cited on page [115](#).)
- Chandler, C. J. & Richer, J. S., 2000. The Structure of Protostellar Envelopes Derived from Submillimeter Continuum Images, *Astrophysical Journal*, **530**, 851–866. (Cited on pages [134](#), [135](#), [136](#), [143](#), [144](#), and [145](#).)

- Chen, H., Myers, P. C., Ladd, E. F., & Wood, D. O. S., 1995. Bolometric temperature and young stars in the Taurus and Ophiuchus complexes, *Astrophysical Journal*, **445**, 377–392. (Cited on pages 8 and 9.)
- Chen, X., Launhardt, R., & Henning, T., 2009. IRAM-PdBI Observations of Binary Protostars. I. The Hierarchical System SVS 13 in NGC 1333, *Astrophysical Journal*, **691**, 1729–1737. (Cited on page 134.)
- Choi, M., 2009. Multiplicity of the Protostar Serpens SMM 1 Revealed by Millimeter Imaging, *Astrophysical Journal*, **705**, 1730–1734. (Cited on page 140.)
- Coffey, D., Bacciotti, F., Woitas, J., Ray, T. P., & Eislöffel, J., 2004. Rotation of Jets from Young Stars: New Clues from the Hubble Space Telescope Imaging Spectrograph, *Astrophysical Journal*, **604**, 758–765. (Cited on pages 14 and 82.)
- Coffey, D., Bacciotti, F., Ray, T. P., Eislöffel, J., & Woitas, J., 2007. Further Indications of Jet Rotation in New Ultraviolet and Optical Hubble Space Telescope STIS Spectra, *Astrophysical Journal*, **663**, 350–364. (Cited on page 82.)
- Coffey, D., Bacciotti, F., & Podio, L., 2008. T Tauri Jet Physics Resolved Near the Launching Region with the Hubble Space Telescope, *Astrophysical Journal*, **689**, 1112–1126. (Cited on pages 85 and 86.)
- Cohen, M. & Bieging, J. H., 1986. Radio variability and structure of T Tauri stars, *Astronomical Journal*, **92**, 1396–1402. (Cited on pages 99, 161, 162, 163, and 164.)
- Cohen, M., Bieging, J. H., & Schwartz, P. R., 1982. VLA observations of mass loss from T Tauri stars, *Astrophysical Journal*, **253**, 707–715. (Cited on pages 19, 77, 99, 135, 161, 162, and 163.)
- Condon, J. J., 1984. Cosmological evolution of radio sources, *Astrophysical Journal*, **287**, 461–474. (Cited on page 104.)
- Condon, J. J. & Ransom, S. M., 2010. Essential radio astronomy. <http://www.cv.nrao.edu/course/ast534/ERA.shtml>. (Cited on pages 25, 29, 30, 31, 32, 33, and 35.)
- Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J., 1998. The NRAO VLA Sky Survey, *Astronomical Journal*, **115**, 1693–1716. (Cited on pages 92, 104, and 140.)
- Crutcher, R. M., 1999. Magnetic Fields in Molecular Clouds: Observations Confront Theory, *Astrophys. J.*, **520**, 706–713. (Cited on page 108.)

- Curiel, S., Canto, J., & Rodríguez, L. F., 1987. A model for the thermal radio continuum emission produced by a shock wave and its application to the Herbig-Haro objects 1 and 2, *Revista Mexicana de Astronomía y Astrofísica*, **14**, 595–602. (Cited on pages 20 and 72.)
- Curiel, S., Rodríguez, L. F., Bohigas, J., Roth, M., Canto, J., & Torrelles, J. M., 1989. Extended radio continuum emission associated with V645 CYG and MWC1080, *Astrophysical Letters and Communications*, **27**, 299–309. (Cited on pages 20, 72, and 73.)
- Curiel, S., Raymond, J. C., Moran, J. M., Rodríguez, L. F., & Canto, J., 1990. The exciting source of the bipolar outflow in L1448, *Astrophysical Journal, Letters*, **365**, L85–L88. (Cited on pages 49, 133, and 143.)
- Curiel, S., Rodríguez, L. F., Moran, J. M., & Canto, J., 1993. The triple radio continuum source in Serpens - The birth of a Herbig-Haro system?, *Astrophysical Journal*, **415**, 191–203. (Cited on pages 19, 21, 55, 65, 74, and 140.)
- Curiel, S., Torrelles, J. M., Rodríguez, L. F., Gómez, J. F., & Anglada, G., 1999. A Study of the Kinematics and Temperature of the High-Density Molecular Gas Surrounding L1448C, *Astrophysical Journal*, **527**, 310–320. (Cited on page 49.)
- Davies, M. L., Franzen, T. M. O., Waldram, E. M., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A., Olamaie, M., Pooley, G. G., Riley, J. M., Rodriguez-Gonzalvez, C., Saunders, R. D. E., Scaife, A. M. M., Schammel, M. P., Scott, P. F., Shimwell, T. W., Titterton, D. J., & Zwart, J. T. L., 2011. 10C Survey of Radio Sources at 15.7 GHz: II - First Results, *Monthly Notices of the Royal Astronomical Society*, **415**(3), 2708–2722. (Cited on pages 57 and 58.)
- Davis, C. J. & Smith, M. D., 1995. Distinction of parallel outflows in L1448 through H₂ excitation, *Astrophysical Journal, Letters*, **443**, L41–L43. (Cited on page 49.)
- Davis, C. J., Ray, T. P., Eisloffel, J., & Corcoran, D., 1997. Near-IR imaging of the molecular outflows in HH24-26, L1634(HH240-241), L1660(HH72) and RNO15FIR., *Astronomy and Astrophysics*, **324**, 263–275. (Cited on pages 53 and 54.)
- Davis, C. J., Matthews, H. E., Ray, T. P., Dent, W. R. F., & Richer, J. S., 1999. A burst of outflows from the Serpens cloud core: wide-field submillimetre continuum, CO J=2-1 and optical observations, *Monthly Notices of the Royal Astronomical Society*, **309**, 141–152. (Cited on page 141.)
- de Zotti, G., Ricci, R., Mesa, D., Silva, L., Mazzotta, P., Toffolatti, L., & González-Nuevo, J., 2005. Predictions for high-frequency radio surveys of extragalactic sources, *Astronomy and Astrophysics*, **431**, 893–903. (Cited on page 57.)

- Dent, W. R. F., Matthews, H. E., & Ward-Thompson, D., 1998. The submillimetre colour of young stellar objects, *Monthly Notices of the Royal Astronomical Society*, **301**, 1049–1063. (Cited on pages [63](#), [138](#), and [139](#).)
- Devine, D., Reipurth, B., & Bally, J., 1999. L1551 NE or L1551 IRS 5: Which Source Drives HH 28/29?, *Astronomical Journal*, **118**, 972–982. (Cited on page [52](#).)
- di Francesco, J., Johnstone, D., Kirk, H., MacKenzie, T., & Ledwosinska, E., 2008. The SCUBA Legacy Catalogues: Submillimeter-Continuum Objects Detected by SCUBA, *Astrophysical Journal, Supplement*, **175**, 277–295. (Cited on pages [45](#), [58](#), [70](#), [133](#), [134](#), [136](#), [138](#), [139](#), [140](#), [141](#), [142](#), [143](#), [146](#), [161](#), and [163](#).)
- Dougados, C., Cabrit, S., Lavalley, C., & Ménard, F., 2000. T Tauri stars microjets resolved by adaptive optics, *Astronomy and Astrophysics*, **357**, L61–L64. (Cited on pages [17](#), [82](#), [83](#), [85](#), and [99](#).)
- Dougados, C., Cabrit, S., Ferreira, J., Pesenti, N., Garcia, P., & O’Brien, D., 2004. The Origin of Jets from Young Stars: MHD Disk Wind Models Confronted to Observations, *Astrophysics and Space Science*, **292**, 643–650. (Cited on page [84](#).)
- Drury, L. O., 1991. Time-dependent diffusive acceleration of test particles at shocks, *Mon. Not. R. Astron. Soc.*, **251**, 340–350. (Cited on page [105](#).)
- Duarte-Cabral, A., Fuller, G. A., Peretto, N., Hatchell, J., Ladd, E. F., Buckle, J., Richer, J., & Graves, S. F., 2010. The physical and dynamical structure of Serpens. Two very different sub-(proto)clusters, *Astronomy and Astrophysics*, **519**, A27. (Cited on page [119](#).)
- Duchêne, G., Ghez, A. M., & McCabe, C., 2002. Resolved Near-Infrared Spectroscopy of the Mysterious Pre-Main-Sequence Binary System T Tauri S, *Astrophysical Journal*, **568**, 771–778. (Cited on page [98](#).)
- Duncan, R. A., Forster, J. R., Gardner, F. F., & Whiteoak, J. B., 1987. VLA observations of the 4.8-GHz H₂CO transition in L1551, *Monthly Notices of the Royal Astronomical Society*, **224**, 721–731. (Cited on page [135](#).)
- Dunham, M. M. & Vorobyov, E. I., 2012. Resolving the Luminosity Problem in Low-mass Star Formation, *Astrophysical Journal*, **747**, 52. (Cited on page [14](#).)
- Dunham, M. M., Crapsi, A., Evans, II, N. J., Bourke, T. L., Huard, T. L., Myers, P. C., & Kauffmann, J., 2008. Identifying the Low-Luminosity Population of Embedded Protostars in the c2d Observations of Clouds and Cores, *Astrophysical Journal, Supplement*, **179**, 249–282. (Cited on pages [42](#), [45](#), and [67](#).)

- Dyck, H. M., Simon, T., & Zuckerman, B., 1982. Discovery of an infrared companion to T Tauri, *Astrophysical Journal, Letters*, **255**, L103–L106. (Cited on page 98.)
- Eiroa, C., Torrelles, J. M., Curiel, S., & Djupvik, A. A., 2005. Very Large Array 3.5 cm Continuum Sources in the Serpens Cloud Core, *Astronomical Journal*, **130**, 643–651. (Cited on page 140.)
- Eisloffel, J. & Mundt, R., 1998. Imaging and Kinematic Studies of Young Stellar Object Jets in Taurus, *Astronomical Journal*, **115**, 1554–1575. (Cited on pages 13, 82, 99, 102, 103, and 108.)
- Eisloffel, J., Mundt, R., Ray, T. P., & Rodríguez, L. F., 2000. Collimation and Propagation of Stellar Jets, *Protostars and Planets IV*, p. 815. (Cited on pages 16 and 17.)
- Emerson, J. P., Harris, S., Jennings, R. E., Beichman, C. A., Baud, B., Beintema, D. A., Wesselius, P. R., & Marsden, P. L., 1984. IRAS observations near young objects with bipolar outflows L1551 and HH 46-47, *Astrophysical Journal, Letters*, **278**, L49–L52. (Cited on page 146.)
- Enoch, M. L., Young, K. E., Glenn, J., Evans, II, N. J., Golwala, S., Sargent, A. I., Harvey, P., Aguirre, J., Goldin, A., Haig, D., Huard, T. L., Lange, A., Laurent, G., Maloney, P., Maukopf, P., Rossinot, P., & Sayers, J., 2006. Bolocam Survey for 1.1 mm Dust Continuum Emission in the c2d Legacy Clouds. I. Perseus, *Astrophysical Journal*, **638**, 293–313. (Cited on pages 133, 134, and 143.)
- Enoch, M. L., Corder, S., Dunham, M. M., & Duchêne, G., 2009a. Disk and Envelope Structure in Class o Protostars. I. The Resolved Massive Disk in Serpens Firs 1, *Astrophysical Journal*, **707**, 103–113. (Cited on pages 45, 55, 67, and 75.)
- Enoch, M. L., Evans, II, N. J., Sargent, A. I., & Glenn, J., 2009b. Properties of the Youngest Protostars in Perseus, Serpens, and Ophiuchus, *Astrophysical Journal*, **692**, 973–997. (Cited on pages 45 and 70.)
- Evans, II, N. J., Levreault, R. M., Beckwith, S., & Skrutskie, M., 1987. Observations of infrared emission lines and radio continuum emission from pre-main-sequence objects, *Astrophysical Journal*, **320**, 364–375. (Cited on pages 135, 162, and 163.)
- Ferreira, J., Dougados, C., & Cabrit, S., 2006. Which jet launching mechanism(s) in T Tauri stars?, *Astronomy and Astrophysics*, **453**, 785–796. (Cited on pages 17, 18, 19, 85, and 87.)
- Fischer, W. J., Megeath, S. T., Ali, B., Tobin, J. J., Osorio, M., Allen, L. E., Kryukova, E., Stanke, T., Stutz, A. M., Bergin, E., Calvet, N., di Francesco, J., Furlan, E., Hartmann, L., Henning, T., Krause, O., Manoj, P., Maret, S., Muzerolle, J., Myers, P., Neufeld, D., Pontoppidan, K., Poteet, C. A., Watson, D. M., & Wilson, T., 2010. Herschel-PACS imaging of

- protostars in the HH 1-2 outflow complex, *Astronomy and Astrophysics*, **518**, L122+. (Cited on pages [45](#), [119](#), and [138](#).)
- Frank, A., Ray, T. P., Cabrit, S., Hartigan, P., Arce, H. G., Bacciotti, F., Bally, J., Benisty, M., Eisloffel, J., Güdel, M., Lebedev, S., Nisini, B., & Raga, A., 2014. Jets and Outflows from Star to Cloud: Observations Confront Theory, *Protostars and Planets VI*, pp. 451–474. (Cited on page [17](#).)
- Fridlund, C. V. M., Bergman, P., White, G. J., Pilbratt, G. L., & Tauber, J. A., 2002. The molecular disk surrounding the protostellar binary L1551 IRS5, *Astronomy and Astrophysics*, **382**, 573–582. (Cited on page [97](#).)
- Froebrich, D., 2005. Which Are the Youngest Protostars? Determining Properties of Confirmed and Candidate Class o Sources by Broadband Photometry, *Astrophysical Journal, Supplement*, **156**, 169–177. (Cited on pages [45](#) and [70](#).)
- Garn, T., Green, D. A., Hales, S. E. G., Riley, J. M., & Alexander, P., 2007. Deep 610-MHz Giant Metrewave Radio Telescope observations of the Spitzer extragalactic First Look Survey field - I. Observations, data analysis and source catalogue, *Monthly Notices of the Royal Astronomical Society*, **376**, 1251–1260. (Cited on pages [92](#), [147](#), and [153](#).)
- Gezari, D. Y., Pitts, P. S., & Schmitz, M., 1999. Catalog of Infrared Observations, Edition 5 (Gezari+ 1999), *VizieR Online Data Catalog*, **2225**, 0. (Cited on page [146](#).)
- Ghez, A. M., Neugebauer, G., Gorham, P. W., Haniff, C. A., Kulkarni, S. R., Matthews, K., Koresko, C., & Beckwith, S., 1991. Diffraction limited infrared images of the binary star T Tauri, *Astronomical Journal*, **102**, 2066–2072. (Cited on page [98](#).)
- Gibb, A. G., 1999. A VLA search for embedded young stellar objects and protostellar candidates in L1630, *Monthly Notices of the Royal Astronomical Society*, **304**, 1–7. (Cited on pages [138](#) and [146](#).)
- Gibb, A. G. & Heaton, B. D., 1993. The Star-Forming Region around HH:24-26 - a Revised Morphology, *Astronomy and Astrophysics*, **276**, 511. (Cited on page [53](#).)
- Girart, J. M., Estalella, R., Anglada, G., Torrelles, J. M., Ho, P. T. P., & Rodríguez, L. F., 1997. The Ammonia Core in L723: Hot Spots at the Center of the Quadrupolar Molecular Outflow, *Astrophysical Journal*, **489**, 734. (Cited on page [56](#).)
- Gomez, J. F., Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., & Canto, J., 1993. Upper limits to the detection of ammonia from protoplanetary disks around HL Tauri and L1551-IRS 5, *Astrophysical Journal*, **414**, 333–336. (Cited on page [136](#).)

- Gómez, J. F., Curiel, S., Torrelles, J. M., Rodríguez, L. F., Anglada, G., & Girart, J. M., 1994. The molecular core and the powering source of the bipolar molecular outflow in NGC 2264G, *Astrophysical Journal*, **436**, 749–753. (Cited on pages 54, 66, 74, and 139.)
- Gomez, M., Whitney, B. A., & Kenyon, S. J., 1997. A survey of optical and near-infrared jets in taurus embedded sources., *Astronomical Journal*, **114**, 1138. (Cited on pages 15 and 52.)
- Gramajo, L. V., Whitney, B. A., Gómez, M., & Robitaille, T. P., 2010. Combined Analysis of Images and Spectral Energy Distributions of Taurus Protostars, *Astronomical Journal*, **139**, 2504–2524. (Cited on page 137.)
- Graves, S. F., Richer, J. S., Buckle, J. V., Duarte-Cabral, A., Fuller, G. A., Hogerheijde, M. R., Owen, J. E., Brunt, C., Butner, H. M., Cavanagh, B., Chrysostomou, A., Curtis, E. I., Davis, C. J., Etxaluze, M., Francesco, J. D., Friberg, P., Friesen, R. K., Greaves, J. S., Hatchell, J., Johnstone, D., Matthews, B., Matthews, H., Matzner, C. D., Nutter, D., Rawlings, J. M. C., Roberts, J. F., Sadavoy, S., Simpson, R. J., Tothill, N. F. H., Tsamis, Y. G., Viti, S., Ward-Thompson, D., White, G. J., Wouterloot, J. G. A., & Yates, J., 2010. The JCMT Legacy Survey of the Gould Belt: a first look at Serpens with HARP, *Monthly Notices of the Royal Astronomical Society*, **409**, 1412–1428. (Cited on page 45.)
- Gredel, R. & Reipurth, B., 1994. An infrared counter-flow in the HH 111 jet complex, *Astronomy and Astrophysics*, **289**, L19–L22. (Cited on page 54.)
- Green, D. A., 2007. Comments on the radio spectrum of HB3, *Bulletin of the Astronomical Society of India*, **35**, 77–85. (Cited on page 104.)
- Greene, T. P. & Lada, C. J., 1996. Near-Infrared Spectra and the Evolutionary Status of Young Stellar Objects: Results of a 1.1-2.4 (??) Survey, *Astronomical Journal*, **112**, 2184. (Cited on page 8.)
- Greene, T. P., Wilking, B. A., Andre, P., Young, E. T., & Lada, C. J., 1994. Further mid-infrared study of the rho Ophiuchi cloud young stellar population: Luminosities and masses of pre-main-sequence stars, *Astrophysical Journal*, **434**, 614–626. (Cited on pages 7, 8, and 9.)
- Güdel, M., Telleschi, A., Audard, M., Skinner, S. L., Briggs, K. R., Palla, F., & Dougados, C., 2007. X-rays from jet-driving protostars and T Tauri stars, *Astronomy and Astrophysics*, **468**, 515–528. (Cited on page 82.)
- Güdel, M., Skinner, S. L., Audard, M., Briggs, K. R., & Cabrit, S., 2008. Discovery of a bipolar X-ray jet from the T Tauri star DG Tauri, *Astronomy and Astrophysics*, **478**, 797–807. (Cited on pages 14, 82, and 99.)

- Gueth, F. & Guilloteau, S., 1999. The jet-driven molecular outflow of HH 211, *Astronomy and Astrophysics*, **343**, 571–584. (Cited on page [15](#).)
- Guilloteau, S., Bachiller, R., Fuente, A., & Lucas, R., 1992. First observations of young bipolar outflows with the IRAM interferometer - 2 arcsec resolution SiO images of the molecular jet in L 1448, *Astronomy and Astrophysics*, **265**, L49–L52. (Cited on pages [49](#) and [143](#).)
- Gullbring, E., Hartmann, L., Briceño, C., & Calvet, N., 1998. Disk Accretion Rates for T Tauri Stars, *Astrophysical Journal*, **492**, 323–341. (Cited on pages [9](#) and [16](#).)
- Gustafsson, M., Kristensen, L. E., Kasper, M., & Herbst, T. M., 2010. The origin, excitation, and evolution of subarcsecond outflows near T Tauri, *Astronomy and Astrophysics*, **517**, A19. (Cited on page [98](#).)
- Haro, G., 1952. Herbig’s Nebulous Objects Near NGC 1999., *Astrophys. J.*, **115**, 572. (Cited on page [5](#).)
- Harris, R. J., Andrews, S. M., Wilner, D. J., & Kraus, A. L., 2012. A Resolved Census of Millimeter Emission from Taurus Multiple Star Systems, *Astrophysical Journal*, **751**, 115. (Cited on page [163](#).)
- Hartigan, P., 1989. The visibility of the Mach disk and the bow shock of a stellar jet, *Astrophysical Journal*, **339**, 987–999. (Cited on page [13](#).)
- Hartigan, P., Morse, J. A., & Raymond, J., 1994. Mass-loss rates, ionization fractions, shock velocities, and magnetic fields of stellar jets, *Astrophysical Journal*, **436**, 125–143. (Cited on page [16](#).)
- Hartigan, P., Edwards, S., & Ghandour, L., 1995. Disk Accretion and Mass Loss from Young Stars, *Astrophysical Journal*, **452**, 736. (Cited on pages [15](#), [85](#), and [86](#).)
- Hartmann, L. & Kenyon, S. J., 1996. The FU Orionis Phenomenon, *Annual Review of Astronomy and Astrophysics*, **34**, 207–240. (Cited on page [8](#).)
- Hartmann, L. & MacGregor, K. B., 1982. Protostellar mass and angular momentum loss, *Astrophysical Journal*, **259**, 180–192. (Cited on page [19](#).)
- Hatchell, J., Fuller, G. A., & Richer, J. S., 2007a. Star formation in Perseus. III. Outflows, *Astronomy and Astrophysics*, **472**, 187–198. (Cited on page [45](#).)
- Hatchell, J., Fuller, G. A., Richer, J. S., Harries, T. J., & Ladd, E. F., 2007b. Star formation in Perseus. II. SEDs, classification, and lifetimes, *Astronomy and Astrophysics*, **468**, 1009–1024. (Cited on pages [42](#), [45](#), [50](#), [56](#), [63](#), [67](#), [68](#), [70](#), [119](#), [134](#), [135](#), [143](#), and [144](#).)

- Herbig, G. H., 1950. Spectra of Variable Stars in the Orion Nebula., *Astrophys. J.*, **111**, 15. (Cited on page [5](#).)
- Herbig, G. H., 1951. The Spectra of Two Nebulous Objects Near NGC 1999., *Astrophysical Journal*, **113**, 697–699. (Cited on page [10](#).)
- Herbst, T. M., Robberto, M., & Beckwith, S. V. W., 1997. Wind-Disk-Ambient Cloud Interactions in the Near Environment of T Tauri, *Astronomical Journal*, **114**, 744. (Cited on page [98](#).)
- Herranz, D., Sanz, J. L., Lopez-Caniego, M., & Gonzalez-Nuevo, J., 2006. A Bayesian approach to flux correction in extragalactic source detection, in *2006 IEEE International Symposium on Signal Processing and Information Technology*, vol. 1, p. 541–544, pp. 541–544. (Cited on page [72](#).)
- Hobson, M. P. & Baldwin, J. E., 2004. Markov-Chain Monte Carlo Approach to the Design of Multilayer Thin-Film Optical Coatings, *Applied Optics*, **43**, 2651–2660. (Cited on pages [58](#) and [100](#).)
- Hogerheijde, M. R., van Dishoeck, E. F., Salverda, J. M., & Blake, G. A., 1999. Envelope Structure of Deeply Embedded Young Stellar Objects in the Serpens Molecular Cloud, *Astrophysical Journal*, **513**, 350–369. (Cited on page [141](#).)
- Hurt, R. L. & Barsony, M., 1996. A Cluster of Class 0 Protostars in Serpens: an IRAS HIRES Study, *Astrophysical Journal, Letters*, **460**, L45. (Cited on page [55](#).)
- Jansky, K. G., 1933a. Radio Waves from Outside the Solar System, *Nature*, **132**, 66. (Cited on page [23](#).)
- Jansky, K. G., 1933b. Electrical phenomena that apparently are of interstellar origin, *Popular Astronomy*, **41**, 548. (Cited on page [23](#).)
- Jennings, R. E., Cameron, D. H. M., Cudlip, W., & Hirst, C. J., 1987. IRAS observations of NGC1333, *Monthly Notices of the Royal Astronomical Society*, **226**, 461–471. (Cited on pages [52](#) and [145](#).)
- Jewitt, D. C., 1994. Submillimeter constraints on dust near Lindroos' POST T Tauri stars, *Astronomical Journal*, **108**, 661–665. (Cited on page [163](#).)
- Jones, B. F. & Cohen, M., 1986. Observations of jets from low-luminosity stars - DG Tauri B, *Astrophysical Journal, Letters*, **311**, L23–L26. (Cited on page [83](#).)
- Jørgensen, J. K., Hogerheijde, M. R., van Dishoeck, E. F., Blake, G. A., & Schöier, F. L., 2004. The structure of the NGC 1333-IRAS2 protostellar system on 500 AU scales. An

- infalling envelope, a circumstellar disk, multiple outflows, and chemistry, *Astronomy and Astrophysics*, **413**, 993–1007. (Cited on pages [144](#) and [145](#).)
- Jørgensen, J. K., van Dishoeck, E. F., Visser, R., Bourke, T. L., Wilner, D. J., Lommen, D., Hogerheijde, M. R., & Myers, P. C., 2009. PROSAC: a submillimeter array survey of low-mass protostars. II. The mass evolution of envelopes, disks, and stars from the Class 0 through I stages, *Astronomy and Astrophysics*, **507**, 861–879. (Cited on page [45](#).)
- Joy, A. H., 1945. T Tauri Variable Stars., *Astrophysical Journal*, **102**, 168. (Cited on pages [9](#) and [98](#).)
- Keene, J. & Masson, C. R., 1990. Detection of A 45 AU radius source around L1551-IRS 5: A possible accretion disk, *Astrophysical Journal*, **355**, 635–644. (Cited on pages [74](#), [135](#), and [136](#).)
- Keene, J. B. & Masson, C. R., 1986. A Compact Density Condensation Around L1551-IRS 5, in *Bulletin of the American Astronomical Society*, vol. 18 of **Bulletin of the American Astronomical Society**, p. 973. (Cited on page [136](#).)
- Kenyon, S. J. & Hartmann, L., 1995. Pre-Main-Sequence Evolution in the Taurus-Auriga Molecular Cloud, *Astrophysical Journal, Supplement*, **101**, 117. (Cited on pages [8](#), [14](#), [74](#), and [83](#).)
- Kenyon, S. J., Dobrzycka, D., & Hartmann, L., 1994. A new optical extinction law and distance estimate for the Taurus-Auriga molecular cloud, *Astronomical Journal*, **108**, 1872–1880. (Cited on pages [45](#) and [89](#).)
- Kirk, H., Johnstone, D., & Tafalla, M., 2007. Dynamics of Dense Cores in the Perseus Molecular Cloud, *Astrophysical Journal*, **668**, 1042–1063. (Cited on page [144](#).)
- Kitamura, Y., Kawabe, R., & Saito, M., 1996a. Aperture Synthesis 13CO (J = 1-0) Observations of the Molecular Gas around DG Tauri: Evidence for a Dispersing Gas Disk, *Astrophysical Journal*, **457**, 277. (Cited on page [164](#).)
- Kitamura, Y., Kawabe, R., & Saito, M., 1996b. Imaging of the Compact Dust Disk around DG Tauri with 1 Resolution, *Astrophysical Journal, Letters*, **465**, L137. (Cited on page [164](#).)
- Königl, A., 1986. Stellar and galactic jets - Theoretical issues, *Canadian Journal of Physics*, **64**, 362–368. (Cited on page [19](#).)
- Königl, A. & Pudritz, R. E., 2000. Disk Winds and the Accretion-Outflow Connection, *Protostars and Planets IV*, p. 759. (Cited on pages [15](#) and [18](#).)
- Koresko, C. D., 2000. A Third Star in the T Tauri System, *Astrophysical Journal, Letters*, **531**, L147–L149. (Cited on page [98](#).)

- Ku, H. H., 1966. Notes on the use of propagation of error formulas, *Journal of Research of the National Bureau of Standards*, **70C**, 263. (Cited on page 97.)
- Kun, M., Balog, Z., Kenyon, S. J., Mamajek, E. E., & Gutermuth, R. A., 2009. Pre-Main-Sequence Stars in the Cepheus Flare Region, *Astrophysical Journal, Supplement*, **185**, 451–476. (Cited on page 45.)
- Lada, C. J., 1987. Star formation - From OB associations to protostars, in *Star Forming Regions*, vol. 115 of **IAU Symposium**, pp. 1–17. (Cited on pages 7, 8, and 9.)
- Lada, C. J. & Fich, M., 1996. The Structure and Energetics of a Highly Collimated Bipolar Outflow: NGC 2264G, *Astrophysical Journal*, **459**, 638. (Cited on page 54.)
- Lada, C. J., Lombardi, M., & Alves, J. F., 2010. On the Star Formation Rates in Molecular Clouds, *Astrophysical Journal*, **724**, 687–693. (Cited on pages 108 and 109.)
- Larson, R. B., 1969. Numerical calculations of the dynamics of collapsing proto-star, *Monthly Notices of the Royal Astronomical Society*, **145**, 271. (Cited on page 5.)
- Lavalley, C., Cabrit, S., Dougados, C., Ferruit, P., & Bacon, R., 1997. Sub-arcsecond morphology and kinematics of the DG Tauri jet in the [O I] λ 6300 line., *Astron. Astrophys.*, **327**, 671–680. (Cited on page 99.)
- Lavalley-Fouquet, C., Cabrit, S., & Dougados, C., 2000. DG Tau: A shocking jet, *Astronomy and Astrophysics*, **356**, L41–L44. (Cited on page 85.)
- Lee, C.-F., Mundy, L. G., Stone, J. M., & Ostriker, E. C., 2002. CO Outflows from Young Stellar Objects, *Astrophysical Journal*, **576**, 294–312. (Cited on page 55.)
- Lim, J. & Takakuwa, S., 2006. Properties and Formation of the Multiple Protostellar System L1551 IRS 5, *Astrophysical Journal*, **653**, 425–436. (Cited on pages 52, 74, and 97.)
- Lis, D. C., Menten, K. M., & Zylka, R., 1999. Dust Continuum Imaging of the HH 24 Region in L1630, *Astrophysical Journal*, **527**, 856–865. (Cited on pages 138 and 146.)
- Livio, M., 2011. Astrophysical Jets, in *American Institute of Physics Conference Series*, vol. 1358 of **American Institute of Physics Conference Series**, pp. 329–333. (Cited on pages 3 and 11.)
- Loinard, L., Rodríguez, L. F., D’Alessio, P., Wilner, D. J., & Ho, P. T. P., 2002. Orbital Proper Motions in the Protobinary System L1527/IRAS 04368+2557?, *Astrophysical Journal, Letters*, **581**, L109–L113. (Cited on pages 52 and 66.)
- Longair, M. S., 2011. *High Energy Astrophysics*, Cambridge University Press, Cambridge. (Cited on pages 105, 107, and 108.)

- Looney, L. W., Mundy, L. G., & Welch, W. J., 2000. Unveiling the Circumstellar Envelope and Disk: A Subarcsecond Survey of Circumstellar Structures, *Astrophysical Journal*, **529**, 477–498. (Cited on pages [83](#), [144](#), and [145](#).)
- Lynch, C., Mutel, R. L., Güdel, M., Ray, T., Skinner, S. L., Schneider, P. C., & Gayley, K. G., 2013. Very Large Array Observations of DG Tau’s Radio Jet: A Highly Collimated Thermal Outflow, *Astrophysical Journal*, **766**, 53. (Cited on pages [77](#), [82](#), [86](#), [99](#), [103](#), [104](#), [105](#), [107](#), [163](#), and [164](#).)
- Maran, S. P., Brown, R. L., Hobbs, R. W., Jura, M., & Knapp, G. R., 1979. On the ionized regions associated with T Tauri stars, *Astronomical Journal*, **84**, 1709–1712. (Cited on page [162](#).)
- Margulis, M. & Lada, C. J., 1986. An unbiased survey for high-velocity gas in the Monoceros OB1 molecular cloud, *Astrophysical Journal, Letters*, **309**, L87–L90. (Cited on page [54](#).)
- Margulis, M., Lada, C. J., & Snell, R. L., 1988. Molecular outflows in the Monoceros OB1 molecular cloud, *Astrophysical Journal*, **333**, 316–331. (Cited on page [54](#).)
- Matt, S. & Pudritz, R. E., 2005. Accretion-powered Stellar Winds as a Solution to the Stellar Angular Momentum Problem, *Astrophysical Journal, Letters*, **632**, L135–L138. (Cited on page [19](#).)
- Maurri, L., Bacciotti, F., Podio, L., Eisloffel, J., Ray, T. P., Mundt, R., Locatelli, U., & Coffey, D., 2014. Physical properties of the jet from DG Tauri on sub-arcsecond scales with HST/STIS, *Astronomy and Astrophysics*, **565**, A110. (Cited on page [85](#).)
- McGroarty, F. & Ray, T. P., 2004. Classical T Tauri stars as sources of parsec-scale optical outflows, *Astronomy and Astrophysics*, **420**, 975–986. (Cited on pages [83](#) and [99](#).)
- McGroarty, F., Ray, T. P., & Froebrich, D., 2007. Proper motion studies of outflows from Classical T Tauri stars, *Astronomy and Astrophysics*, **467**, 1197–1207. (Cited on page [82](#).)
- McMullin, J. P., Mundy, L. G., Wilking, B. A., Hezel, T., & Blake, G. A., 1994. Structure and chemistry in the northwestern condensation of the Serpens molecular cloud core, *Astrophysical Journal*, **424**, 222–236. (Cited on pages [140](#) and [141](#).)
- Meehan, L. S. G., Wilking, B. A., Claussen, M. J., Mundy, L. G., & Wootten, A., 1998. Water Masers in the Circumstellar Environments of Young Stellar Objects, *Astronomical Journal*, **115**, 1599–1609. (Cited on page [56](#).)
- Melis, C., Duchêne, G., Chomiuk, L., Palmer, P., Perrin, M. D., Maddison, S. T., Ménard, F., Stapelfeldt, K., Pinte, C., & Duvert, G., 2011. Microwave Observations of Edge-on

- Protoplanetary Disks: Program Overview and First Results, *Astrophysical Journal, Letters*, **739**, L7. (Cited on pages [52](#) and [137](#).)
- Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A., 2007. The distance to the Orion Nebula, *Astronomy and Astrophysics*, **474**, 515–520. (Cited on page [45](#).)
- Mestel, L., 1968. Magnetic braking by a stellar wind-I, *Monthly Notices of the Royal Astronomical Society*, **138**, 359. (Cited on page [19](#).)
- Mitchell, G. F., Hasegawa, T. I., Dent, W. R. F., & Matthews, H. E., 1994. A molecular outflow driven by an optical jet, *Astrophysical Journal, Letters*, **436**, L177–L180. (Cited on page [83](#).)
- Morgan, J. A., Snell, R. L., & Strom, K. M., 1990. Radio continuum emission from young stellar objects in L1641, *Astrophysical Journal*, **362**, 274–283. (Cited on page [137](#).)
- Moriarty-Schieven, G. H. & Wannier, P. G., 1991. A second outflow from L1551/IRS 5?, *Astrophysical Journal, Letters*, **373**, L23–L26. (Cited on page [98](#).)
- Moriarty-Schieven, G. H., Butner, H. M., & Wannier, P. G., 1995. The L1551NE molecular outflow, *Astrophysical Journal, Letters*, **445**, L55–L58. (Cited on page [52](#).)
- Moriarty-Schieven, G. H., Powers, J. A., Butner, H. M., Wannier, P. G., & Keene, J., 2000. L1551NE-Discovery of a Binary Companion, *Astrophysical Journal, Letters*, **533**, L143–L145. (Cited on page [145](#).)
- Moriarty-Schieven, G. H., Johnstone, D., Bally, J., & Jenness, T., 2006. Multigenerational Star Formation in L1551, *Astrophysical Journal*, **645**, 357–368. (Cited on page [146](#).)
- Motte, F. & André, P., 2001. The circumstellar environment of low-mass protostars: A millimeter continuum mapping survey, *Astronomy and Astrophysics*, **365**, 440–464. (Cited on pages [70](#), [133](#), [136](#), [141](#), [143](#), [144](#), and [145](#).)
- Mundt, R. & Fried, J. W., 1983. Jets from young stars, *Astrophysical Journal, Letters*, **274**, L83–L86. (Cited on pages [10](#), [79](#), [83](#), [85](#), and [99](#).)
- Mundt, R., Ray, T. P., & Raga, A. C., 1991. Collimation of Stellar Jets - Constraints from the Observed Spatial Structure - Part Two - Observational Results, *Astronomy and Astrophysics*, **252**, 740. (Cited on pages [17](#), [83](#), and [85](#).)
- Myers, P. C. & Ladd, E. F., 1993. Bolometric temperatures of young stellar objects, *Astrophysical Journal, Letters*, **413**, L47–L50. (Cited on page [8](#).)
- Nisini, B., Giannini, T., & Lorenzetti, D., 2002. Evolution in the Far-Infrared Spectra of Low-Mass Young Embedded Sources, *Astrophysical Journal*, **574**, 246–257. (Cited on page [45](#).)

- Nutter, D. & Ward-Thompson, D., 2007. A SCUBA survey of Orion - the low-mass end of the core mass function, *Monthly Notices of the Royal Astronomical Society*, **374**, 1413–1420. (Cited on pages 138 and 146.)
- Ohashi, N., Kawabe, R., Ishiguro, M., & Hayashi, M., 1991. Observations of 11 protostellar sources in Taurus with Nobeyama millimeter array - Growth of circumstellar disks, *Astronomical Journal*, **102**, 2054–2065. (Cited on pages 136 and 164.)
- Ohashi, N., Hayashi, M., Ho, P. T. P., & Momose, M., 1997. Interferometric Imaging of IRAS 04368+2557 in the L1527 Molecular Cloud Core: A Dynamically Infalling Envelope with Rotation, *Astrophysical Journal*, **475**, 211. (Cited on pages 52 and 137.)
- Orlando, E. & Strong, A., 2013. Cosmic rays: interstellar gamma-ray and radio emission, *Nuclear Physics B Proceedings Supplements*, **239**, 64–69. (Cited on page 108.)
- Panagia, N. & Felli, M., 1975. The spectrum of the free-free radiation from extended envelopes, *Astronomy and Astrophysics*, **39**, 1–5. (Cited on pages 19, 20, 29, and 71.)
- Perley, R. A. & Butler, B. J., 2013. An Accurate Flux Density Scale from 1 to 50 GHz, *Astrophysical Journal, Supplement*, **204**, 19. (Cited on page 78.)
- Persson, M. V., 2014a. Current view of protostellar evolution (ENG). https://figshare.com/articles/Current_view_of_protostellar_evolution/654555. (Cited on page 6.)
- Persson, M. V., 2014b. SEDs of the different protostellar evolutionary stages. https://figshare.com/articles/SEDs_of_the_different_protostellar_evolutionary_stages/1121574. (Cited on page 7.)
- Phillips, R. R., Gibb, A. G., & Little, L. T., 2001. Dense cores in the L1630 molecular cloud: discovering new protostars with SCUBA, *Monthly Notices of the Royal Astronomical Society*, **326**, 927–936. (Cited on page 146.)
- Podio, L., Kamp, I., Flower, D., Howard, C., Sandell, G., Mora, A., Aresu, G., Brittain, S., Dent, W. R. F., Pinte, C., & White, G. J., 2012. Herschel/PACS observations of young sources in Taurus: the far-infrared counterpart of optical jets, *Astronomy and Astrophysics*, **545**, A44. (Cited on pages 85 and 86.)
- Pound, M. W. & Bally, J., 1991. Two new molecular outflows in L1551?, *Astrophysical Journal*, **383**, 705–713. (Cited on page 98.)
- Pravdo, S. H., Rodríguez, L. F., Curiel, S., Canto, J., Torrelles, J. M., Becker, R. H., & Sellgren, K., 1985. Detection of radio continuum emission from Herbig-Haro objects 1 and 2 and from their central exciting source, *Astrophysical Journal, Letters*, **293**, L35–L38. (Cited on pages 53, 75, 137, and 138.)

- Pudritz, R. E. & Norman, C. A., 1983. Centrifugally driven winds from contracting molecular disks, *Astrophysical Journal*, **274**, 677–697. (Cited on pages [3](#) and [16](#).)
- Pudritz, R. E. & Norman, C. A., 1986. Bipolar hydromagnetic winds from disks around protostellar objects, *Astrophysical Journal*, **301**, 571–586. (Cited on page [16](#).)
- Pudritz, R. E., Ouyed, R., Fendt, C., & Brandenburg, A., 2007. Disk Winds, Jets, and Outflows: Theoretical and Computational Foundations, *Protostars and Planets V*, pp. 277–294. (Cited on pages [18](#), [77](#), and [82](#).)
- Raga, A. C., Binette, L., Canto, J., & Calvet, N., 1990. Stellar jets with intrinsically variable sources, *Astrophysical Journal*, **364**, 601–610. (Cited on page [13](#).)
- Raga, A. C., Mundt, R., & Ray, T. P., 1991. Collimation of stellar jets: Constraints from the observed spatial structure. I - Data analysis methods. II - Observational results, *Astronomy and Astrophysics*, **252**, 733–761. (Cited on page [85](#).)
- Raga, A. C., Reipurth, B., Cantó, J., Sierra-Flores, M. M., & Guzmán, M. V., 2011. An overview of the observational and theoretical studies of HH 1 and 2, *Revista Mexicana de Astronomía y Astrofísica*, **47**, 425–437. (Cited on page [75](#).)
- Ray, T., 2010. Cosmic Rays from Cosmic Birth, *Science*, **330**, 1184–. (Cited on pages [3](#) and [108](#).)
- Ray, T. P., 2007. The generation of jets from young stars: an observational perspective, in *IAU Symposium*, vol. 243 of **IAU Symposium**, pp. 183–194. (Cited on page [77](#).)
- Ray, T. P., 2009. Getting to Grips with the Unknown: How Important are Magnetic Fields in Outflows from Young Stars?, in *Revista Mexicana de Astronomía y Astrofísica Conference Series*, vol. 36 of **Revista Mexicana de Astronomía y Astrofísica Conference Series**, pp. 179–185. (Cited on pages [3](#) and [105](#).)
- Ray, T. P., Mundt, R., Dyson, J. E., Falle, S. A. E. G., & Raga, A. C., 1996. HST Observations of Jets from Young Stars, *Astrophysical Journal, Letters*, **468**, L103. (Cited on pages [17](#) and [83](#).)
- Ray, T. P., Muxlow, T. W. B., Axon, D. J., Brown, A., Corcoran, D., Dyson, J., & Mundt, R., 1997. Large-scale magnetic fields in the outflow from the young stellar object T Tauri S, *Nature*, **385**, 415–417. (Cited on pages [21](#) and [105](#).)
- Reber, G. & Conklin, E. H., 1938. UHF receivers, *Radio*, **225**, 112. (Cited on page [23](#).)
- Rebull, L. M., Padgett, D. L., McCabe, C.-E., Hillenbrand, L. A., Stapelfeldt, K. R., Noriega-Crespo, A., Carey, S. J., Brooke, T., Huard, T., Terebey, S., Audard, M., Monin, J.-L.,

- Fukagawa, M., Güdel, M., Knapp, G. R., Menard, F., Allen, L. E., Angione, J. R., Baldwin-Saavedra, C., Bouvier, J., Briggs, K., Dougados, C., Evans, N. J., Flagey, N., Guieu, S., Grosso, N., Glauser, A. M., Harvey, P., Hines, D., Latter, W. B., Skinner, S. L., Strom, S., Tromp, J., & Wolf, S., 2010. The Taurus Spitzer Survey: New Candidate Taurus Members Selected Using Sensitive Mid-Infrared Photometry, *Astrophys. J. Suppl. Ser.*, **186**, 259–307. (Cited on page 108.)
- Reipurth, B., 1989. The HH111 jet and multiple outflow episodes from young stars, *Nature*, **340**, 42–45. (Cited on page 54.)
- Reipurth, B. & Bally, J., 2001. Herbig-Haro Flows: Probes of Early Stellar Evolution, *Annual Review of Astronomy and Astrophysics*, **39**, 403–455. (Cited on pages 10, 11, 13, and 14.)
- Reipurth, B., Raga, A. C., & Heathcote, S., 1992. Structure and kinematics of the HH 111 jet, *Astrophysical Journal*, **392**, 145–158. (Cited on pages 13, 14, and 54.)
- Reipurth, B., Chini, R., Krugel, E., Kreysa, E., & Sievers, A., 1993. Cold Dust around Herbig-Haro Energy Sources - a 1300-MICRON Survey, *Astronomy and Astrophysics*, **273**, 221. (Cited on pages 63, 136, 138, 139, 141, 142, and 162.)
- Reipurth, B., Bally, J., & Devine, D., 1997. Giant Herbig-Haro Flows, *Astronomical Journal*, **114**, 2708. (Cited on pages 54 and 98.)
- Reipurth, B., Yu, K. C., Rodríguez, L. F., Heathcote, S., & Bally, J., 1999. Multiplicity of the HH 111 jet source: it Hubble Space Telescope NICMOS images and VLA maps, *Astronomy and Astrophysics*, **352**, L83–L86. (Cited on page 54.)
- Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J., 2002. Radio Continuum Maps of Deeply Embedded Protostars: Thermal Jets, Multiplicity, and Variability, *Astronomical Journal*, **124**, 1045–1053. (Cited on pages 52, 133, 143, 144, and 145.)
- Reipurth, B., Rodríguez, L. F., Anglada, G., & Bally, J., 2004. Radio Continuum Jets from Protostellar Objects, *Astronomical Journal*, **127**, 1736–1746. (Cited on pages 56 and 142.)
- Reynolds, S. P., 1986. Continuum spectra of collimated, ionized stellar winds, *Astrophysical Journal*, **304**, 713–720. (Cited on pages 19, 20, 29, 65, 66, 71, 72, 82, 98, and 100.)
- Richer, J. S., Shepherd, D. S., Cabrit, S., Bachiller, R., & Churchwell, E., 2000. Molecular Outflows from Young Stellar Objects, *Protostars and Planets IV*, p. 867. (Cited on page 15.)
- Robitaille, T. P. & Whitney, B. A., 2010. The Present-Day Star Formation Rate of the Milky Way Determined from Spitzer-Detected Young Stellar Objects, *Astrophysical Journal, Letters*, **710**, L11–L15. (Cited on page 108.)

- Rodríguez, L. F., 1995. Subarcsecond Observations of Radio Continuum from Jets and Disks, in *Revista Mexicana de Astronomía y Astrofísica Conference Series*, vol. 1 of **Revista Mexicana de Astronomía y Astrofísica**, vol. 27, p. 1. (Cited on page 19.)
- Rodríguez, L. F., 1998. Recent Advances in the Study of Thermal Radio Jets, in *Revista Mexicana de Astronomía y Astrofísica Conference Series*, vol. 7 of **Revista Mexicana de Astronomía y Astrofísica**, vol. 27, p. 14. (Cited on page 52.)
- Rodríguez, L. F. & Canto, J., 1983. Stellar Winds and Molecular Clouds - a Search for Ionized Stellar Winds, *Revista Mexicana de Astronomía y Astrofísica*, 8, 163. (Cited on page 161.)
- Rodríguez, L. F. & Curiel, S., 1989. A candidate for the exciting source of the powerful molecular outflow NGC 2264G, *Revista Mexicana de Astronomía y Astrofísica*, 17, 115–119. (Cited on pages 66 and 139.)
- Rodríguez, L. F. & Reipurth, B., 1994. The exciting source of the Herbig-Haro 111 jet complex: VLA detection of a one-sided radio jet, *Astronomy and Astrophysics*, 281, 882–888. (Cited on page 139.)
- Rodríguez, L. F. & Reipurth, B., 1998. VLA Detection of the Exciting Sources of HH 83, HH 117, HH 124, HH 192, HH 300, HH 366, and HH 375, *Revista Mexicana de Astronomía y Astrofísica*, 34, 13. (Cited on page 53.)
- Rodríguez, L. F., Canto, J., Torrelles, J. M., & Ho, P. T. P., 1986. The double radio source associated with L1551 IRS 5 - Binary system or ionized circumstellar torus?, *Astrophysical Journal, Letters*, 301, L25–L28. (Cited on page 135.)
- Rodríguez, L. F., Canto, J., Mirabel, I. F., & Ruiz, A., 1989a. VLA observations of the high-velocity bipolar OH absorption in L1551, *Astrophysical Journal*, 337, 712–719. (Cited on page 135.)
- Rodríguez, L. F., Curiel, S., Moran, J. M., Mirabel, I. F., Roth, M., & Garay, G., 1989b. Large proper motions in the remarkable triple radio source in Serpens, *Astrophysical Journal, Letters*, 346, L85–L88. (Cited on pages 21, 55, 65, and 140.)
- Rodríguez, L. F., Ho, P. T. P., Torrelles, J. M., Curiel, S., & Canto, J., 1990. VLA observations of the Herbig-Haro 1-2 system, *Astrophysical Journal*, 352, 645–653. (Cited on pages 53, 75, 137, and 138.)
- Rodríguez, L. F., Anglada, G., & Curiel, S., 1997. Is SVS 13 the Exciting Source of the HH 7-11 Flow?, *Astrophysical Journal, Letters*, 480, L125. (Cited on page 51.)

- Rodríguez, L. F., D'Alessio, P., Wilner, D. J., Ho, P. T. P., Torrelles, J. M., Curiel, S., Gómez, Y., Lizano, S., Pedlar, A., Cantó, J., & Raga, A. C., 1998. Compact protoplanetary disks around the stars of a young binary system, *Nature*, **395**, 355–357. (Cited on page 97.)
- Rodríguez, L. F., Anglada, G., & Curiel, S., 1999. The Nature of the Radio Continuum Sources Embedded in the HH 7-11 Region and Its Surroundings, *Astrophysical Journal, Supplement*, **125**, 427–438. (Cited on pages 51, 52, 134, 144, and 145.)
- Rodríguez, L. F., Delgado-Arellano, V. G., Gómez, Y., Reipurth, B., Torrelles, J. M., Noriega-Crespo, A., Raga, A. C., & Cantó, J., 2000. New VLA Observations of the HH 1-2 Region: Evidence for Density Enhancements Moving along the Axis of the VLA 1 Radio Jet, *Astronomical Journal*, **119**, 882–889. (Cited on pages 20, 53, and 75.)
- Rodríguez, L. F., Curiel, S., Cantó, J., Loinard, L., Raga, A. C., & Torrelles, J. M., 2003a. Very Large Array Observations of Proper Motions in L1551 IRS 5, *Astrophysical Journal*, **583**, 330–333. (Cited on pages 19, 52, 74, and 135.)
- Rodríguez, L. F., Porras, A., Claussen, M. J., Curiel, S., Wilner, D. J., & Ho, P. T. P., 2003b. The Binary Jet in L1551 IRS 5, *Astrophysical Journal, Letters*, **586**, L137–L139. (Cited on pages 52 and 97.)
- Rodríguez, L. F., Moran, J. M., Franco-Hernández, R., Garay, G., Brooks, K. J., & Mardones, D., 2008a. The Collimated Jet Source in IRAS 16547-4247: Time Variation, Possible Precession, and Upper Limits to the Proper Motions Along the Jet Axis, *Astronomical Journal*, **135**, 2370–2379. (Cited on page 53.)
- Rodríguez, L. F., Torrelles, J. M., Anglada, G., & Reipurth, B., 2008b. High-Angular Resolution Observations at 7 MM of the Core of the Quadrupolar HH 111/121 Outflow, *Astronomical Journal*, **136**, 1852–1856. (Cited on pages 20, 54, and 139.)
- Rodríguez, L. F., González, R. F., Raga, A. C., Cantó, J., Riera, A., Loinard, L., Dzib, S. A., & Zapata, L. A., 2012. Radio continuum emission from knots in the DG Tauri jet, *Astronomy and Astrophysics*, **537**, A123. (Cited on pages 77, 99, 104, and 163.)
- Rosvick, J. M. & Davidge, T. J., 1995. An infrared embedded source in the L1251 molecular cloud, *Publications of the Astronomical Society of the Pacific*, **107**, 49–57. (Cited on pages 142 and 143.)
- Sadavoy, S. I., Di Francesco, J., Bontemps, S., Megeath, S. T., Rebull, L. M., Allgaier, E., Carey, S., Gutermuth, R., Hora, J., Huard, T., McCabe, C.-E., Muzerolle, J., Noriega-Crespo, A., Padgett, D., & Terebey, S., 2010. The Mass Distribution of Starless and Protostellar Cores in Gould Belt Clouds, *Astrophysical Journal*, **710**, 1247–1270. (Cited on page 163.)

- Sandell, G., Knee, L. B. G., Aspin, C., Robson, I. E., & Russell, A. P. G., 1994. A molecular jet and bow shock in the low mass protostellar binary NGC 1333-IRAS2, *Astronomy and Astrophysics*, **285**, L1–L4. (Cited on pages [52](#), [144](#), and [145](#).)
- Sargent, A. & Beckwith, S., 1989. Molecular disks around young stars, in *IAU Colloq. 120: Structure and Dynamics of the Interstellar Medium*, vol. 120 of **Springer-Verlag**, p. 215. (Cited on page [164](#).)
- Sargent, A. & Beckwith, S., 1994. Disks Around T Tauri Stars, in *IAU Colloq. 140: Astronomy with Millimeter and Submillimeter Wave Interferometry*, vol. 59 of **Astronomical Society of the Pacific Conference Series**, p. 203. (Cited on page [164](#).)
- Sato, F. & Fukui, Y., 1989. Two molecular outflows in L1251, *Astrophysical Journal*, **343**, 773–778. (Cited on pages [56](#) and [143](#).)
- Sauty, C., Tsinganos, K., & Trussoni, E., 1999. Nonradial and nonpolytropic astrophysical outflows. IV. Magnetic or thermal collimation of winds into jets?, *Astronomy and Astrophysics*, **348**, 327–349. (Cited on page [19](#).)
- Scaife, A. M. M., 2013. Anomalous Microwave Emission from Star Forming Regions, *Advances in Astronomy*, **2013**. (Cited on pages [21](#) and [28](#).)
- Scaife, A. M. M., Curtis, E. I., Davies, M., Franzen, T. M. O., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A. N., Olamaie, M., Pooley, G. G., Rodríguez-Gonzálvez, C., Saunders, R. D. E., Schammel, M., Scott, P. F., Shimwell, T., Titterington, D., Waldram, E., & Zwart, J. T. L., 2011a. AMI Large Array radio continuum observations of Spitzer c2d small clouds and cores, *Monthly Notices of the Royal Astronomical Society*, **410**, 2662–2678. (Cited on pages [21](#), [41](#), [57](#), [67](#), [70](#), [72](#), [73](#), [89](#), [111](#), and [112](#).)
- Scaife, A. M. M., Hatchell, J., Davies, M., Franzen, T. M. O., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A. N., Olamaie, M., Perrott, Y. C., Pooley, G. G., Rodríguez-Gonzálvez, C., Saunders, R. D., Schammel, M. P., Scott, P. F., Shimwell, T., Titterington, D., & Waldram, E., 2011b. AMI-LA radio continuum observations of Spitzer c2d small clouds and cores: Perseus region, *Monthly Notices of the Royal Astronomical Society*, **415**, 893–910. (Cited on pages [41](#), [57](#), [67](#), [69](#), [70](#), [72](#), [133](#), [143](#), [144](#), and [145](#).)
- Scaife, A. M. M., Buckle, J. V., Ainsworth, R. E., Davies, M., Franzen, T. M. O., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A. N., Olamaie, M., Perrott, Y. C., Pooley, G. G., Ray, T. P., Richer, J. S., Rodríguez-Gonzálvez, C., Saunders, R. D. E., Schammel, M. P., Scott, P. F., Shimwell, T., Titterington, D., & Waldram, E., 2012a. Radio continuum observations of Class I protostellar discs in Taurus: constraining the greybody tail at centimetre wavelengths, *Monthly Notices of the Royal Astronomical Society*, **420**, 3334–3343. (Cited on pages [20](#), [52](#), [59](#), [63](#), [66](#), [77](#), [82](#), [83](#), [99](#), [137](#), and [164](#).)

- Scaife, A. M. M., Hatchell, J., Davies, M., Franzen, T. M. O., Grainge, K. J. B., Hobson, M. P., Hurley-Walker, N., Lasenby, A. N., Olamaie, M., Perrott, Y. C., Pooley, G. G., Rodríguez-González, C., Saunders, R. D., Schammel, M. P., Scott, P. F., Shimwell, T., Titterton, D., & Waldrum, E., 2012b. AMI-LA radio continuum observations of Spitzer c2d small clouds and cores: Serpens region, *Monthly Notices of the Royal Astronomical Society*, **420**, 1019–1033. (Cited on pages [41](#), [55](#), [56](#), [57](#), [67](#), [70](#), [74](#), [75](#), and [140](#).)
- Schulz, N. S., 2005. *From Dust To Stars Studies of the Formation and Early Evolution of Stars*. (Cited on page [10](#).)
- Schwartz, P. R. & Spencer, J. H., 1977. Observations of radio stars at 3.3 MM, *Monthly Notices of the Royal Astronomical Society*, **180**, 297–303. (Cited on page [162](#).)
- Schwartz, P. R., Simon, T., Zuckerman, B., & Howell, R. R., 1984. The T Tauri radio source, *Astrophysical Journal, Letters*, **280**, L23–L26. (Cited on pages [161](#) and [162](#).)
- Schwartz, P. R., Simon, T., & Campbell, R., 1986. The T Tauri radio source. II - The winds of T Tauri, *Astrophysical Journal*, **303**, 233–238. (Cited on pages [161](#) and [162](#).)
- Schwartz, P. R., Gee, G., & Huang, Y.-L., 1988. CO pedestal features from IRAS sources in dark clouds, *Astrophysical Journal*, **327**, 350–355. (Cited on page [56](#).)
- Schwartz, R. D., 1975. T Tauri Nebulae and Herbig-Haro Nebulae - Evidence for excitation by a strong stellar wind, *Astrophysical Journal*, **195**, 631–642. (Cited on page [10](#).)
- Schwartz, R. D., 1983. Herbig-Haro Objects - an Overview, *Revista Mexicana de Astronomia y Astrofisica*, **7**, 27. (Cited on page [10](#).)
- Shang, H., 2004. Modeling Outflows from Young Stars, in *Star Formation at High Angular Resolution*, vol. 221 of **IAU Symposium**, p. 351. (Cited on page [85](#).)
- Shang, H., Lizano, S., Glassgold, A., & Shu, F., 2004. Free-free Radio Emission from Young Stellar Objects, *Astrophysical Journal, Letters*, **612**, L69–L72. (Cited on page [22](#).)
- Shang, H., Li, Z.-Y., & Hirano, N., 2007. Jets and Bipolar Outflows from Young Stars: Theory and Observational Tests, *Protostars and Planets V*, pp. 261–276. (Cited on page [18](#).)
- Shirley, Y. L., Evans, II, N. J., Rawlings, J. M. C., & Gregersen, E. M., 2000. Tracing the Mass during Low-Mass Star Formation. I. Submillimeter Continuum Observations, *Astrophysical Journal, Supplement*, **131**, 249–271. (Cited on pages [134](#), [141](#), [142](#), [143](#), and [144](#).)
- Shirley, Y. L., Evans, II, N. J., & Rawlings, J. M. C., 2002. Tracing the Mass during Low-Mass Star Formation. III. Models of the Submillimeter Dust Continuum Emission from Class 0 Protostars, *Astrophysical Journal*, **575**, 337–353. (Cited on page [63](#).)

- Shirley, Y. L., Claussen, M. J., Bourke, T. L., Young, C. H., & Blake, G. A., 2007. The Detection and Characterization of Centimeter Radio Continuum Emission from the Low-Mass Protostar L1014-IRS, *Astrophysical Journal*, **667**, 329–339. (Cited on page 67.)
- Shirley, Y. L., Mason, B. S., Mangum, J. G., Bolin, D. E., Devlin, M. J., Dicker, S. R., & Korngut, P. M., 2011. Mustang 3.3 mm Continuum Observations of Class 0 Protostars, *Astronomical Journal*, **141**, 39. (Cited on pages 133, 134, and 143.)
- Shu, F. H., Najita, J. R., Shang, H., & Li, Z.-Y., 2000. X-Winds Theory and Observations, *Protostars and Planets IV*, p. 789. (Cited on pages 18 and 87.)
- Skinner, S. L. & Brown, A., 1994. The enigmatic T Tauri radio source, *Astronomical Journal*, **107**, 1461–1468. (Cited on pages 161 and 162.)
- Snell, R. L. & Bally, J., 1986. Compact radio sources associated with molecular outflows, *Astrophysical Journal*, **303**, 683–701. (Cited on pages 75 and 140.)
- Snell, R. L., Loren, R. B., & Plambeck, R. L., 1980. Observations of CO in L1551 - Evidence for stellar wind driven shocks, *Astrophysical Journal, Letters*, **239**, L17–L22. (Cited on page 97.)
- Snell, R. L., Bally, J., Strom, S. E., & Strom, K. M., 1985. Radio and optical observations of the jets from L1555 IRS 5, *Astrophysical Journal*, **290**, 587–595. (Cited on page 135.)
- Spencer, J. H. & Schwartz, P. R., 1974. Radio Emission from Pre-Main Stars, *Astrophysical Journal, Letters*, **188**, L105. (Cited on pages 161 and 162.)
- Stapelfeldt, K. R. & Scoville, N. Z., 1993. Circumstellar molecular gas of the HH 34 and HH 111 exciting stars, *Astrophysical Journal*, **408**, 239–250. (Cited on page 139.)
- Stapelfeldt, K. R., Burrows, C. J., Krist, J. E., Watson, A. M., Ballester, G. E., Clarke, J. T., Crisp, D., Evans, R. W., Gallagher, III, J. S., Griffiths, R. E., Hester, J. J., Hoessel, J. G., Holtzman, J. A., Mould, J. R., Scowen, P. A., Trauger, J. T., & Westphal, J. A., 1998. Hubble Space Telescope Imaging of the Circumstellar Nebulosity of T Tauri, *Astrophysical Journal*, **508**, 736–743. (Cited on page 98.)
- Stojimirović, I., Narayanan, G., Snell, R. L., & Bally, J., 2006. Entrainment Mechanisms for Outflows in the L1551 Star-forming Region, *Astrophysical Journal*, **649**, 280–298. (Cited on pages 97 and 98.)
- Straižys, V., Černis, K., & Bartašiūtė, S., 1996. Interstellar extinction in the area of the Serpens Cauda molecular cloud., *Baltic Astronomy*, **5**, 125–147. (Cited on page 45.)
- Strom, K. M., Strom, S. E., & Grasdalen, G. L., 1974a. An infrared source associated with a Herbig-Haro object., *Astrophysical Journal*, **187**, 83–86. (Cited on page 10.)

- Strom, S. E., Grasdalen, G. L., & Strom, K. M., 1974b. Infrared and optical observations of Herbig-Haro objects., *Astrophysical Journal*, **191**, 111–142. (Cited on page [10](#).)
- Terebey, S. & Padgett, D. L., 1997. Millimeter Interferometry of Class o Sources: Rotation and Infall Towards L1448N, in *Herbig-Haro Flows and the Birth of Stars*, vol. 182 of **IAU Symposium**, pp. 507–514. (Cited on page [49](#).)
- Testi, L., Bacciotti, F., Sargent, A. I., Ray, T. P., & Eisloffel, J., 2002. The kinematic relationship between disk and jet in the DG Tauri system, *Astronomy and Astrophysics*, **394**, L31–L34. (Cited on page [82](#).)
- Thompson, A. R., Moran, J. M., & Swenson, Jr., G. W., 2001. *Interferometry and Synthesis in Radio Astronomy, 2nd Edition*. (Cited on pages [33](#) and [34](#).)
- Tobin, J. J., Hartmann, L., & Loinard, L., 2010. The Inner Envelope and Disk of L1527 Revealed: Gemini L'-band-scattered Light Imaging, *Astrophysical Journal, Letters*, **722**, L12–L17. (Cited on pages [52](#) and [66](#).)
- Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., & Canto, J., 1985. VLA observations of ammonia and continuum in regions with high-velocity gaseous outflows, *Astrophysical Journal*, **288**, 595–603. (Cited on page [136](#).)
- van Kempen, T. A., van Dishoeck, E. F., Güsten, R., Kristensen, L. E., Schilke, P., Hogerheijde, M. R., Boland, W., Menten, K. M., & Wyrowski, F., 2009. APEX-CHAMP⁺ high-J CO observations of low-mass young stellar objects. II. Distribution and origin of warm molecular gas, *Astronomy and Astrophysics*, **507**, 1425–1442. (Cited on page [45](#).)
- Ward-Thompson, D., Eiroa, C., & Casali, M. M., 1995. Confirmation of the driving source of the NGC 2264G bipolar outflow: a Class o protostar, *Monthly Notices of the Royal Astronomical Society*, **273**, L25–L28. (Cited on pages [54](#) and [140](#).)
- Watson, D. M., Kemper, F., Calvet, N., Keller, L. D., Furlan, E., Hartmann, L., Forrest, W. J., Chen, C. H., Uchida, K. I., Green, J. D., Sargent, B., Sloan, G. C., Herter, T. L., Brandl, B. R., Houck, J. R., Najita, J., D'Alessio, P., Myers, P. C., Barry, D. J., Hall, P., & Morris, P. W., 2004. Mid-infrared Spectra of Class I Protostars in Taurus, *Astrophysical Journal, Supplement*, **154**, 391–395. (Cited on page [83](#).)
- Weintraub, D. A., Sandell, G., & Duncan, W. D., 1989a. Submillimeter measurements of T Tauri and FU Orionis stars, *Astrophysical Journal, Letters*, **340**, L69–L72. (Cited on pages [163](#) and [164](#).)
- Weintraub, D. A., Zuckerman, B., & Masson, C. R., 1989b. Measurements of Keplerian rotation of the gas in the circumbinary disk around T Tauri, *Astrophysical Journal*, **344**, 915–924. (Cited on page [162](#).)

- Wendker, H. J., 1995. Radio continuum emission from stars: a catalogue update., *Astronomy and Astrophysics, Supplement*, **109**, 177–179. (Cited on pages [58](#), [133](#), and [161](#).)
- White, S. M., Pallavicini, R., & Kundu, M. R., 1992. Radio flares and magnetic fields on weak-line T Tauri stars, *Astronomy and Astrophysics*, **259**, 149–154. (Cited on pages [9](#) and [21](#).)
- Willing, B. A., Blackwell, J. H., Mundy, L. G., & Howe, J. E., 1989. A millimeter-wave spectral-line and continuum survey of cold IRAS sources, *Astrophysical Journal*, **345**, 257–264. (Cited on pages [136](#) and [139](#).)
- Wilson, T. L., Rohlfs, K., & Hüttemeister, S., 2013. *Tools of Radio Astronomy*. (Cited on pages [23](#), [24](#), [25](#), [26](#), [27](#), and [28](#).)
- Wolf-Chase, G. A., Barsony, M., & O’Linger, J., 2000. Giant Molecular Outflows Powered by Protostars in L1448, *Astronomical Journal*, **120**, 1467–1478. (Cited on pages [49](#) and [50](#).)
- Woody, D. P., Scott, S. L., Scoville, N. Z., Mundy, L. G., Sargent, A. I., Padin, S., Tinney, C. G., & Wilson, C. D., 1989. Interferometric observations of 1.4 millimeter continuum sources, *Astrophysical Journal, Letters*, **337**, L41–L44. (Cited on page [164](#).)
- Wright, A. E. & Barlow, M. J., 1975. The radio and infrared spectrum of early-type stars undergoing mass loss, *Monthly Notices of the Royal Astronomical Society*, **170**, 41–51. (Cited on page [19](#).)
- Wu, J., Dunham, M. M., Evans, II, N. J., Bourke, T. L., & Young, C. H., 2007. SHARC-II Mapping of Spitzer c2d Small Clouds and Cores, *Astronomical Journal*, **133**, 1560–1584. (Cited on page [142](#).)
- Wu, P.-F., Takakuwa, S., & Lim, J., 2009. Multiple Bipolar Molecular Outflows from the L1551 IRS5 Protostellar System, *Astrophysical Journal*, **698**, 184–197. (Cited on page [97](#).)
- Yamamura, I., Makiuti, S., Ikeda, N., Fukuda, Y., Oyabu, S., Koga, T., & White, G. J., 2010. AKARI/FIS All-Sky Survey Point Source Catalogues (ISAS/JAXA, 2010), *VizieR Online Data Catalog*, **2298**, 0. (Cited on page [164](#).)
- Yang, J., Ohashi, N., Yan, J., Liu, C., Kaifu, N., & Kimura, H., 1997. Detection of Infall Motion from the Circumstellar Disk Associated with the Exciting Source of HH 111, *Astrophysical Journal*, **475**, 683. (Cited on page [54](#).)
- Yorke, H. W., Bodenheimer, P., & Laughlin, G., 1995. The formation of protostellar disks. 2: Disks around intermediate-mass stars, *Astrophysical Journal*, **443**, 199–208. (Cited on page [8](#).)

- Young, C. H., Shirley, Y. L., Evans, II, N. J., & Rawlings, J. M. C., 2003. Tracing the Mass during Low-Mass Star Formation. IV. Observations and Modeling of the Submillimeter Continuum Emission from Class I Protostars, *Astrophysical Journal, Supplement*, **145**, 111–145. (Cited on page [63](#).)
- Zacharias, N., Finch, C. T., Girard, T. M., Henden, A., Bartlett, J. L., Monet, D. G., & Zacharias, M. I., 2013. The Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4), *Astronomical Journal*, **145**, 44. (Cited on pages [79](#), [99](#), and [103](#).)
- Zwart, J. T. L., Barker, R. W., Biddulph, P., Bly, D., Boysen, R. C., Brown, A. R., Clementson, C., Crofts, M., Culverhouse, T. L., Czeres, J., Dace, R. J., Davies, M. L., D’Alessandro, R., Doherty, P., Duggan, K., Ely, J. A., Felvus, M., Feroz, F., Flynn, W., Franzen, T. M. O., Geisbüsch, J., Génova-Santos, R., Grainge, K. J. B., Grainger, W. F., Hammett, D., Hills, R. E., Hobson, M. P., Holler, C. M., Hurley-Walker, N., Jilley, R., Jones, M. E., Kaneko, T., Kneissl, R., Lancaster, K., Lasenby, A. N., Marshall, P. J., Newton, F., Norris, O., Northrop, I., Odell, D. M., Petencin, G., Pober, J. C., Pooley, G. G., Pospieszalski, M. W., Quay, V., Rodríguez-Gonzálvez, C., Saunders, R. D. E., Scaife, A. M. M., Schofield, J., Scott, P. F., Shaw, C., Shimwell, T. W., Smith, H., Taylor, A. C., Titterington, D. J., Velić, M., Waldram, E. M., West, S., Wood, B. A., Yassin, G., & AMI Consortium, 2008. The Arcminute Microkelvin Imager, *Monthly Notices of the Royal Astronomical Society*, **391**, 1545–1558. (Cited on pages [35](#) and [46](#).)