Radio Interferometric Studies of Cool Evolved Stellar Outflows

A dissertation submitted to the University of Dublin
for the degree of Doctor of Philosophy

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Summary

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A dedication if you wish...

Acknowledgements

Some sincere acknowledgements...

List of Publications

Refereed

1. Richards, A. M. S., Davis, R. J., Decin, L., Etoka, S., Harper, G. M., Lim, J. J., Garrington, S. T., Gray, M. D., McDonald, I., **O'Gorman, E.**, Wittkowski, M.
   "e-MERLIN resolves Betelgeuse at wavelength 5 cm"
   Monthly Notices of the Royal Astronomical Society Letters, 432, L61 (2013)

2. **O'Gorman, E.**, Harper, G. M., Brown, J. M., Brown, A., Redfield, S., Richter, M. J., and Requena-Torres, M. A.
   "CARMA CO(J = 2 - 1) Observations of the Circumstellar Envelope of Betelgeuse"
   The Astronomical Journal, 144, 36 (2012)

3. Sada, P. V., Deming, D., Jennings, D. E., Jackson, B. K., Hamilton, C. M., Fraine, J., Peterson, S. W., Haase, F., Bays, K., Lunsford, A., and **O'Gorman, E.**
   "Extrasolar Planet Transits Observed at Kitt Peak National Observatory"
   Publications of the Astronomical Society of the Pacific, 124, 212 (2012)

4. Sada, P. V., Deming, D., Jackson, B. K., Jennings, D. E., Peterson, S. W., Haase, F., Bays, K., **O'Gorman, E.**, and Lundsford, A.
   "Recent Transits of the Super-Earth Exoplanet GJ 1214b"
   The Astrophysical Journal Letters, 720, L215 (2010)

Non-Refereed

1. **O'Gorman, E.**, & Harper, G. M.
   "What is Heating Arcturus' Wind?",
   Proceedings of the 16th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun. Astronomical Society of the Pacific Conference Series, 448, 691 (2011)

Contents

List of Figures

List of Tables

1 Introduction

Here is the introduction of the thesis, complete with a few references (Prothero & Buell, 2007; Sagan, 1997). Section 1.2 contains Equation ??, Section ?? has Figure ?? and Section ?? has Table ??. Chapter ?? has pretty much nothing in it.

1.1 The problem

1.2 History

1.3 Radio Emission from Stellar Atmospheres

lamors and cass give example of flux from nearest star into hr radio diagram

1.3.1 Brightness Temperature

In thermodynamic equilibrium the spectral distribution or brightness, B_ν, of the radiation of a black body with temperature T_e is given by the Planck law

$$B_\nu(T_e) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT_e} - 1} \tag{1.1}$$

and has units of flux per frequency interval per solid angle. One can easily switch to a wavelength scale using $B_\nu(T)d\nu = B_\lambda(T)d\lambda$. When $h\nu \ll kT$ Equation 1.1 becomes the *Rayleigh-Jeans Law*

$$B_\nu(T_e) = \frac{2\nu^2 kT_e}{c^2} = I_\nu(T_e). \tag{1.2}$$

This equation does not contain Plank's constant and therefore is the classical limit of the Planck Law. We have also include the specific intensity, I_ν, here as it has the same units of the spectral brightness and is regularly used instead. This equation is valid for all thermal radio sources except in the millimeter or sub-millimeter regime at low temperatures (Rohlfs & Wilson, 1996). In the Rayleigh-Jeans relation, the brightness is strictly proportional to the thermodynamic temperature of the black body. In radio astronomy it is customary to measure the brightness of an object by its *brightness temperature*, T_b. Therefore, the brightness temperature is the temperature at which a blackbody would have to be in order to reproduce the observed brightness of an object at frequency ν and is defined as

$$T_\mathrm{b} = \frac{c^2}{2k\nu^2}B_\nu = \frac{c^2}{2k\nu^2}I_\nu. \tag{1.3}$$

If $h\nu/kT \ll 1$ and if B_ν is emitted by a blackbody, then T_b is the thermodynamic temperature of the source. If other processes are responsible for the emission or if the frequency is so high that Equation 1.2 is not valid, then T_b is different from the thermodynamic temperature of a black body.

The equation of radiative transfer describes the change in specific intensity of a ray along the line of sight in a slab of material of thickness ds

$$\frac{dI_\nu}{ds} = \varepsilon_\nu - \kappa_\nu I_\nu \tag{1.4}$$

where ε_ν and κ_ν are the emissivity (in $\mathrm{erg\,s^{-1}\,cm^{-3}\,Hz^{-1}\,sr^{-1}}$) and the absorption coefficient (i.e., opacity) (in $\mathrm{cm^{-1}}$) of the plasma. In thermodynamic equilibrium the radiation is in complete equilibrium with its surroundings and the brightness distribution is described by the Planck function

$$\frac{dI_\nu}{ds} = 0, \qquad I_\nu = \frac{\varepsilon_\nu}{\kappa_\nu} = \frac{c^2}{2k\nu^2}T_e. \tag{1.5}$$

Equation 1.4 can then be solved by first defining the optical depth, $d\tau_\nu$ as

$$d\tau_\nu = -\kappa_\nu ds, \tag{1.6}$$

and then integrated by parts between 0 to s, and τ to 0, to give

$$I(s) = I(0)e^{-\tau(s)} + \int_{\tau(s)}^{0} e^{-\tau}\frac{\varepsilon_\nu}{\kappa_\nu}d\tau. \tag{1.7}$$

The second term within the integral is known as the source function, S_ν, and this can be taken outside of the integral in the case of a homogeneous source, i.e. one for which both the emissivity and absorption coefficient are constant along the ray path. The solution then to the equation of radiative transfer for a homogeneous source is

$$I_\nu = I_0 e^{-\tau} + \frac{\varepsilon_\nu}{\kappa_\nu}(1 - e^{-\tau}). \tag{1.8}$$

Using Equations 1.3 and 1.5 one obtains

$$T_b = T_0 e^{-\tau} + T_e(1 - e^{-\tau}) \tag{1.9}$$

which assumes thermodynamic equilibrium and so only holds for a thermal source.

If T_e is replaced with $T_{\rm eff} = h\nu/k$ then this equation becomes valid for a homogeneous nonthermal sources so that

$$T_b = T_0 e^{-\tau} + T_{\rm eff}(1 - e^{-\tau}). \tag{1.10}$$

For an isolated source, there are two limiting cases:

$$T_b = T_e \quad \text{(i.e., for optically thick } \tau \gg 1) \tag{1.11}$$

and

$$T_b = \tau T_e \quad \text{(i.e., for optically thin } \tau \ll 1). \tag{1.12}$$

In these equations, T_e can also be replaced by $T_{\rm eff}$ if the radio emission emission is non-thermal and are only valid if the source is resolved.

1.3.2 Brightness Temperature and Flux Density

In the previous section we have shown that at radio wavelengths, we are able to directly measure the gas temperature if we are able to spatially resolve an optically thick stellar atmosphere which emits thermal radiation. Unfortunately, the number of stars that can have their atmospheres spatially resolved at radio wavelengths is low due to their relatively small angular diameters. Moreover, the number of stars whose radio emission is mainly thermal and can be spatially resolved are even smaller due to their lower brightness temperatures compared to the non-thermal emitters and thus sensitivity becomes an issue.

1.3.3 Radio Free-free Opacity

optically thick/ thin (notes)

derive radio opacity and plot a graph as in notes

1.3.4 Radio Excess from Stellar Winds

1.4 Stellar Radio Emission Mechanisms

A
List of Abbreviations

Table A.1: List of Abbreviations

Abbreviation	Meaning
BIMA	Berkeley Illinois Maryland Association
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CSE	Circumstellar Envelope
DDT	Director's Discretionary Time
e-MERLIN	e-Multi-Element Radio Linked Interferometer Network
FOV	Field of View
GREAT	German Receiver for Astronomy at Terahertz Frequencies
HPBW	Half Power Beamwidth
HST	Hubble Space Telescope
IOTA	Infrared Optical Telescope Array
IR	Infrared
IRAM	Institut de Radioastronomie Millimétrique
IUE	International Ultraviolet Explorer
LSR	Local Standard of Rest
MEM	Maximum Entropy Method
OVRO	Owens Valley Radio Observatory
RFI	Radio Frequency Interference
S/N	signal-to-noise
SOFIA	Stratospheric Observatory for Infrared Astronomy
SMA	Submillimeter Array
UV	Ultraviolet
VLA	Karl G. Jansky Very Large Array
VLBA	Very Long Baseline Array
VLT	Very Large Telescope

References

PROTHERO, D. & BUELL, C. (2007). *Evolution: what the fossils say and why it matters*. Columbia University Press. (Cited on page 1.)

ROHLFS, K. & WILSON, T.L. (1996). *Tools of Radio Astronomy*. (Cited on page 2.)

SAGAN, C. (1997). *The Demon-Haunted World: Science as a Candle in the Dark*. Ballantine Books. (Cited on page 1.)