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

You should write a nice summary here...

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)

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1
Introduction

Stellar winds in general ism planets

1.1 The Problem with Cool Evolved Stellar Outflows

lamers and cass intro to outflows

mass loss picture across the HR diagram

Maybe give image in transfer of winds across HR diagram

This thesis is focused on the non-coronal

Introductions in papers

Graham's conf proceedings uv spectra shows gradual acceleration

1.2 Why do Stars have Outflows?

bernoulli (casinelli p95) parker General eqs, bernoulli, solar wind

1.3 Red Giant and Red Supergiant Evolution

Stellar structure Internal and Atmospheric table of scale heights, pressure/density scale height for the Sun, Arctutus, Aldaberan, Betelgeuse Betelgeuse very large scale height resulting in the presence of no more than a few giant and stable convection cells at photospheric level (Schwarzschild 1975, Chiavassa et al. 2010) i.e. schwarychild criteria MOLsphere: explain what it is [tsuji (1988)] Circumstellar environments (Lamers and Cassinelli CO) 'The past present and future evolution of red supergiants' workshop 2012, meynet Stellar Evolution -HR diagram (Boyajian 2013 (Bee's Knees! See print out pile 3))

1.4 Radio Emission from Stellar Atmospheres

give fundamental frequencies

lamors and cass

molecular and free-free

$$F_\nu \approx 0.1 \left(\frac{T_b}{10^6\,K}\right)\left(\frac{\nu}{1\,\mathrm{GHz}}\right)^2\left(\frac{r}{10^{11}\,\mathrm{cm}}\right)^2\left(\frac{1\,\mathrm{pc}}{d}\right)^2 \qquad \mathrm{mJy} \tag{1.1}$$

(Güdel, 2002)

hr radio diagram

1.4.1 Free-free Emission

cite r

1.4.2 Molecular Line Emission

1.4.3 Recombination Line Emission

1.4.4 Non-Thermal Emission

1.5 Radio Observations of Stellar Atmospheres

At this point it is well to draw the distinction between blackbody radiation, where I, = B,, and thermal radiation, where S,, = B,. Thermal radiation becomes blackbody radiation only for optically thick media

1.5.1 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

$$B_\nu(T_e) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT_e}-1} \tag{1.2}$$

and has units of flux per frequency interval per solid angle. One can easily switch to a wavelength scale using $B_\nu d\nu = B_\lambda d\lambda$. When $h\nu \ll kT_e$ Equation 1.2 becomes the *Rayleigh-Jeans Law*

$$B_\nu(T_e) = \frac{2\nu^2 kT_e}{c^2} = I_\nu(T_e). \tag{1.3}$$

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

$$T_\mathrm{b} = \frac{c^2}{2k\nu^2} I_\nu. \tag{1.4}$$

If $h\nu/kT \ll 1$ and if I_ν is emitted by a blackbody, then T_b is the thermodynamic temperature of the source. If non-thermal processes are responsible for the emission or if the frequency is so high that Equation 1.3 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

$$\frac{dI_\nu}{ds} = \varepsilon_\nu - \kappa_\nu I_\nu \tag{1.5}$$

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

$$\frac{dI_\nu}{ds} = 0, \qquad I_\nu = \frac{\varepsilon_\nu}{\kappa_\nu} = \frac{c^2}{2k\nu^2} T_e. \tag{1.6}$$

Equation 1.5 can then be solved by first defining the optical depth, $d\tau_\nu$, as

$$d\tau_\nu = -\kappa_\nu ds, \tag{1.7}$$

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

$$I(s) = I(0)e^{-\tau(s)} + \int_{\tau(s)}^{0} e^{-\tau} \frac{\varepsilon_\nu}{\kappa_\nu} d\tau. \tag{1.8}$$

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

$$I_\nu = I_0 e^{-\tau} + \frac{\varepsilon_\nu}{\kappa_\nu}(1 - e^{-\tau}). \tag{1.9}$$

Using Equations 1.4 and 1.6 one obtains

$$T_b = T_0 e^{-\tau} + T_e(1 - e^{-\tau}) \tag{1.10}$$

which assumes thermodynamic equilibrium and so only holds for a thermal source. If T_e is replaced with $T_{\text{eff}} = h\nu/k$ then this equation becomes valid for a homogeneous nonthermal sources so that

$$T_b = T_0 e^{-\tau} + T_{\text{eff}}(1 - e^{-\tau}). \tag{1.11}$$

For an isolated source, there are two limiting cases:

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

and

$$T_b = \tau T_e \quad \text{(i.e., for optically thin } \tau \ll 1). \tag{1.13}$$

In these equations, T_e can also be replaced by T_{eff} if the radio emission emission is non-thermal. Also, these equations are only valid if the source is spatially resolved. If the source is unresolved then an upper limit to T_e/T_{eff} is found.

1.5.2 Brightness Temperature and Flux Density

The flux density, F_ν, is a fundamental quantity measured by a radio telescope and is usually measured in Janskys (Jy) where 1 Jy= $1 \times 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$. The observed flux density measured by the radio telescope is

$$F_\nu = \int_\Omega I_\nu \, d\Omega \tag{1.14}$$

where Ω is the solid angle subtended by the star. The radio emission from evolved cool stars is almost purely thermal and so Equation 1.14 becomes

$$F_\nu = \frac{\pi R_\star^2}{d^2} \frac{2k\nu^2 T_b}{c^2}. \tag{1.15}$$

The angular diameter of a star in radians is $\phi_\star = 2R_\star/d$ and so

$$F_\nu = \frac{\pi k \phi_\star^2 T_b}{2\lambda^2} \tag{1.16}$$

If $\phi_\star$ has major and minor axes $\phi_{\rm maj}$ and $\phi_{\rm min}$ then

$$T_b(K) = 1.96 F_\nu(\rm mJy) \left(\frac{\lambda}{\rm cm}\right)^2 \left(\frac{\phi_{\rm min}}{\rm arcsec}\frac{\phi_{\rm min}}{\rm arcsec}\right)^{-1}. \tag{1.17}$$

Therefore, if an optically thick stellar atmosphere can be spatially resolved (i.e., $\phi_{\rm maj}$ and $\phi_{\rm min}$ can be measured) then the flux density at a particular wavelength tells gives the brightness temperature and therefore the electron temperature. Unfortunately, the number of stars that can have their atmospheres spatially resolved at radio wavelengths is low due to their relatively small angular diameters. However, different layers of stellar atmospheres can still be probed due to the nature of the free-free radio opacity which is discussed in the next section.

1.5.3 Thermal Free-free Radio Opacity

In Section 1.4.1 we derived an expression for the thermal free-free emissivity of an ionized gas. Since we assumed LTE at some temperature T, we can use Kirchoff's law to find the thermal radio free-free opacity (absorption coefficient):

$$\kappa_\nu^{ff} = \frac{\epsilon_\nu^{ff} c^2}{2kT\nu^2} \tag{1.18}$$

Substituting in Equation **??** then gives a value for the radio opacity

$$\kappa_\nu^{ff} = \frac{0.018 Z^2 n_e n_i g_{ff}}{T^{1.5}\nu^2} \tag{1.19}$$

The Gaunt factor is slightly dependent on temperature and frequency and at cm-wavelengths is given by

$$g_{ff}^{cm} = 11.96 T_e^{0.15} \nu^{-0.1} \tag{1.20}$$

(Altenhoff *et al.*, 1960), while in the sub-millimeter regime it is slightly different

$$g_{ff}^{sub-mm} = 24.10 T_e^{0.26} \nu^{-0.17} \tag{1.21}$$

(Hummer, 1988). The abundant species in the atmospheres of cool evolved stars are either neutral or single ionized so that $Z = 1$ and $n_e = n_i$. Focusing on centimeter wavelengths, the radio opacity is then

$$\kappa_\nu^{ff} = \frac{0.212 n_e^2}{T^{1.35}\nu^{2.1}} \qquad \mathrm{cm}^{-1}. \tag{1.22}$$

Therefore, the free-free opacity increases towards lower frequencies as $\kappa_\nu^{ff} \propto \nu^{-2.1}$ (or longer wavelengths as $\kappa_\lambda^{ff} \propto \lambda^{2.1}$). This means that the optical depth, $\tau_\lambda = \int \kappa_\lambda dr$, also increases towards longer wavelengths implying that the effective radius (i.e., the radius where $\tau_\lambda = \tau_{\mathrm{radial}}$) will increase with longer wavelengths. This means that different layers of unresolved stellar atmospheres can be probed by observing them at different radio wavelengths.

In LTE, the solution to the equation of radiative transfer (i.e, Equation 1.9) for a plasma with no background source can be written as

$$I_\nu = B_\nu(1 - e^{-\tau}). \tag{1.23}$$

An example of such a source is an isolated H II region. At long enough wavelengths the H II region becomes opaque so that $\tau_\nu \gg 1$. Equation 1.23 then tells us that the spectrum approaches that of a black body with a flux density varying as $F_\nu \propto \nu^2$. At short wavelengths where $\tau_\nu \ll 1$, the H II region is almost transparent, and the flux density becomes

$$F_\nu \propto \frac{2kT\nu^2}{c^2}\tau_\nu \propto \nu^{-0.1}. \tag{1.24}$$

These two scenarios are shown in Figure 1.1 along with the point where these two slopes intersect which corresponds to the frequency at which $\tau \simeq 1$. When the radio spectrum is plotted on a log-log plot the spectral slope is often referred to as the spectral index, α, and is defined:

$$\alpha = \frac{d\log F_\nu}{d\log\nu} \tag{1.25}$$

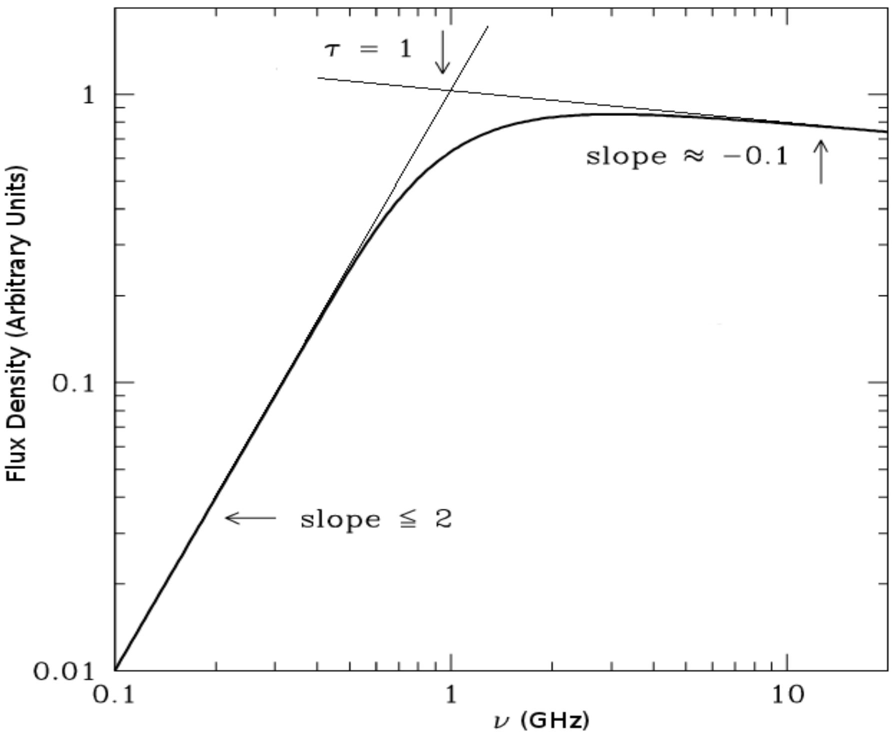

Figure 1.1: The radio spectrum for a hypothetical H II region with no background illuminating source. At long wavelengths the source becomes opaque and has a black body like spectrum with $\alpha = 2$. At short wavelengths where $\tau_\nu \ll 1$, the H II region is almost transparent and $\alpha = -0.1$. (Image Credit: NRAO)

1.5.4 Radio Excess from Stellar Winds

Derive 0.6 wind (easy version)

give spectrum of betelgeuse from 1st radio paper

1.6 Thesis Outline

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

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Rohlfs, K. & Wilson, T.L. (1996). *Tools of Radio Astronomy*. (Cited on page 3.)