Radio Interferometric Studies of Cool Evolved Stellar Winds

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

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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.

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Summary

Mass-loss becomes significant for most stars as they approach the end of their lives and become either red giants or red supergiants. This continuous mass-loss, which occurs in the form of a relatively dense and slow-moving wind, can have a significant impact on the evolution of gas and dust in galaxies, on surrounding planets, and indeed on the very evolution of the star itself. Despite the importance of this phenomenon and decades of study, the fundamental mechanisms responsible for producing these winds remain unknown. The main reason for this is due to our lack of understanding of the dynamics and thermodynamics of the stellar outflow environment. Isolated giants and supergiants do not contain the expected additional complexities encountered by binaries, making them ideal targets for understanding the nature of these outflows. Traditionally, observations have provided only limited disk-averaged information about the outflow environments of these stars, making it difficult to infer the outflow properties. However, the latest suite of radio interferometers now have the capability to provide essential spatial information on these outflow environments.

This thesis first presents the results of a radio interferometric study into the dynamics of the two unique flows in the circumstellar environment of the M2 red supergiant, Betelgeuse. The Combined Array for Research in Millimeter-wave Astronomy (CARMA) was used in multiple configurations to observe the CO($J = 2 - 1$) emission line allowing spatial scales as small as $0''.9$ ($\sim 40\,R_\star$) to be traced over a $32''$ ($\sim 1500\,R_\star$) field of view. The outer flow known as S2, was found to have outflow velocities of -15.4 and +13.2 km s^{-1} with respect to the stellar rest frame and extend out to $17''$, while the inner

flow known as S1, was found to have outflow velocities of -9.0 and +10.6 km s^{-1} and extend out to between $4 - 6''$. Both flows were found to be inhomogeneous down to the resolution limit, but when azimuthally averaged, their intensity falloff was found to be consistent with an optically thin, spherically symmetric, constant velocity outflow. High resolution multi-epoch centimter continuum observations of Betelgeuse which probe its inner atmosphere ($< 10\,R_\star$) are also presented. The radio flux density is found to vary on time scales of $\lesssim 14$ months at all wavelengths, and again evidence for inhomogeneities in the outflow is found.

This thesis also presents Karl G. Jansky Very Large Array (VLA) multi-wavelength ($0.7 - 20$ cm) observations of two non-dusty, non-pulsating K spectral-type red giants, Arcturus and Aldebaran. Detections at 10 cm (3.0 GHz: S-band) and 20 cm (1.5 GHz: L-band) represent the first isolated luminosity class III red giants to be detected at these long wavelengths. These thermal continuum observations provide a snapshot of the different stellar atmospheric layers and are independent of any long-term variability. The long wavelength data sample Arcturus' outer atmosphere where the wind velocity is approaching its terminal value and the ionization balance is becoming *frozen-in*. For Aldebaran, the data samples its inner atmosphere where the wind is still accelerating. Our data is in conflict with published semi-empirical models based on ultraviolet data. Spectral indices are used to discuss the possible properties of the stellar atmospheres. Evidence for a rapidly cooling wind in the case of Arcturus is found and a new analytical wind model is developed for this star. This model is used as the basis to compute a thermal energy balance of Arcturus' outflow by investigating the various heating and cooling processes that control its thermal structure. The analysis focuses on distances between $1.2 \rightarrow 10\,R_\star$ and includes the wind acceleration zone. We find that an additional substantial heating mechanism is required to maintain the inner thermal structure of the outflow.

For Mum and Dad,
a constant source of inspiration and guidance.

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List of Publications

Refereed

1. **O'Gorman, E.**, Harper, G. M., Brown, A., Brown, A., Drake, S., and Richards, A. M. S.
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2. 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"
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"CARMA CO(J = 2 - 1) Observations of the Circumstellar Envelope of Betelgeuse"
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A

List of Abbreviations Used in this Thesis.

Table A.1: List of Abbreviations

Acronym	Meaning
ALMA	The Atacama Large Millimeter/submillimeter Array
AGB	Asymptotic Giant Branch
ALC	Automatic Level Control
BIMA	Berkeley Illinois Maryland Association
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CASA	Common Astronomy Software Application
CSE	Circumstellar Envelope
DDT	Director's Discretionary Time
e-MERLIN	e-Multi-Element Radio Linked Interferometer Network
FFT	Fast Fourier Transform
FITS	Flexible Image Transport System
FOV	Field of View
GBT	Robert C. Byrd Green Bank Telescope
GHRS	Goddard High-Resolution Spectrograph
GREAT	German Receiver for Astronomy at Terahertz Frequencies
HIFI	Heterodyne Instrument for the Far Infrared
HPBW	Half Power Beamwidth
H-R	Hertzsprung-Russell

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Table A.1 – *Continued from previous page*

Acronym	Meaning
HST	Hubble Space Telescope
IF	Intermediate Frequency
IOTA	Infrared Optical Telescope Array
IR	Infrared
IRAM	Institut de Radioastronomie Millimétrique
ISM	Interstellar Medium
IUE	International Ultraviolet Explorer
LNA	Low Noise Amplifier
LO	Local Oscillator
LSR	Local Standard of Rest
LTE	Local Thermodynamic Equilibrium
MEM	Maximum Entropy Method
MERLIN	Multi-Element Radio Linked Interferometer Network
MHD	Magnetohydrodynamic
OVRO	Owens Valley Radio Observatory
OSRO	Open Shared Risk Observing
RF	Radio Frequency
RFI	Radio Frequency Interference
RGC	Red Giant Clump
RGB	Red Giant Branch
RSG	Red Supergiant
S/N	signal-to-noise ratio
SB	Scheduling Block
SGB	Subgiant Branch
SOFIA	Stratospheric Observatory for Infrared Astronomy
SMA	Submillimeter Array
SZA	Sunyaev-Zel'dovich Array
SIS	Superconductor Insulator Superconductor
UV	Ultraviolet
VLA	Karl G. Jansky Very Large Array
VLBA	Very Long Baseline Array
VLT	Very Large Telescope
W-R	Wolf-Rayet

B
Discrete Absorption Feature

During this study we analyzed *HST* STIS spectra of Arcturus from the online StarCAT catalog (Ayres, 2010b). The Mg II h and k lines from data obtained in 2001 show a wind velocity $\sim 30-40$ km s^{-1}, which is similar to that adopted in the Drake models for this star Drake (1985). A narrow discrete absorption feature was found at -49 km s^{-1} in the broad blue-shifted wind absorption component of both lines as shown in Figure B.1. For this discrete feature we find a most probable turbulent velocity of 3.4 km s^{-1} and a Mg II column density[1] of 1.4×10^{12} cm^{-2}. A Mg II column density of 10^{15} cm^{-2} is required to produce the blueward absorption components in the h and k lines (**?**). Therefore, this discrete absorption feature accounts for only $\sim 0.1\%$ of the total wind column density and is probably a result of a discrete ejection event.

[1]Assuming all Mg to be Mg II

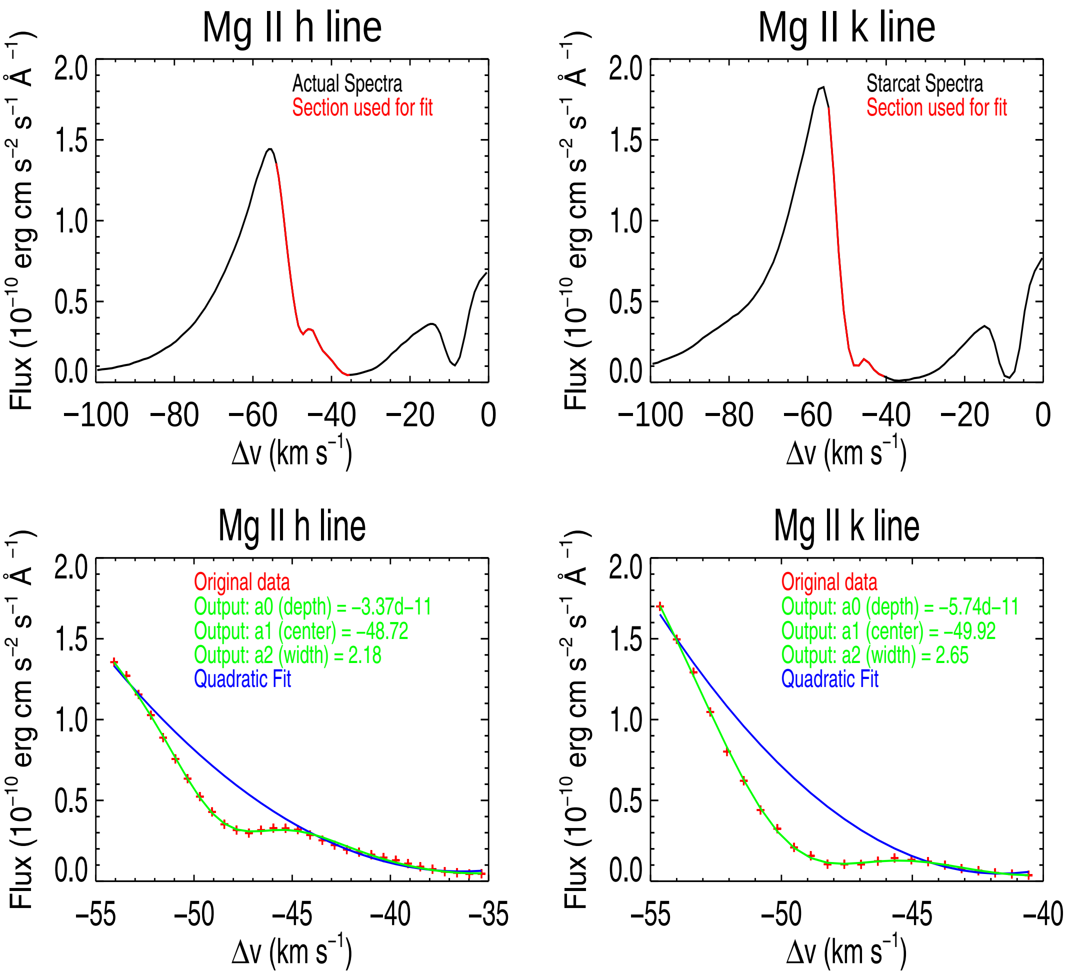

Figure B.1: Analysis on the absorption feature found in the Mg II *h* and *k* lines. A function composed of a linear combination of a Gaussian and a quadratic fitted the discrete absorption feature the best. The red data in the upper row shows the data that is used in this analysis.

C
Ambipolar Diffusion Heating

Considering a steady flow accelerating in an inertial frame, the equation of motion can be written as

$$\rho_n \boldsymbol{a}_n = \rho_n \boldsymbol{g} + \boldsymbol{f}_d \tag{C.1}$$

for the neutral species n, and

$$\rho_i \boldsymbol{a}_i = \rho_i \boldsymbol{g} - \boldsymbol{f}_d + \boldsymbol{f}_L \tag{C.2}$$

for the ion species, i. The flow acceleration is defined as $\boldsymbol{a} \equiv (\boldsymbol{v}.\nabla)\boldsymbol{v}$ and the gravitational acceleration is $\boldsymbol{g} \equiv \nabla(GM_\star/r)$. The volumetric drag force of the ions on the neutrals is defined as

$$\boldsymbol{f}_d = \gamma \rho_n \rho_i (\boldsymbol{v}_i - \boldsymbol{v}_n) \tag{C.3}$$

and $\boldsymbol{f}_L$ is the volumetric Lorentz force. The equation of motion for the combined ion-neutral fluid is found by the addition of Equations C.1 and C.2

$$\rho \boldsymbol{a} = \rho \boldsymbol{g} + \boldsymbol{f}_L \tag{C.4}$$

where $\rho \equiv \rho_n + \rho_i$ is the mass density without the electrons and $\boldsymbol{a} \equiv (\rho_n \boldsymbol{a}_n + \rho_i \boldsymbol{a}_i)/\rho$ is the total acceleration.

The gravitational acceleration term can then be eliminated from Equations C.1 and C.2 to give

$$\boldsymbol{a}_n - \boldsymbol{a}_i = \left(\frac{1}{\rho_n} + \frac{1}{\rho_i}\right) \boldsymbol{f}_d - \frac{1}{\rho_i} \boldsymbol{f}_L. \tag{C.5}$$

Assuming then that the acceleration of the neutrals and ions are the same we get

$$\boldsymbol{f}_d = \left(\frac{\rho_n}{\rho_n + \rho_i}\right) \boldsymbol{f}_L. \tag{C.6}$$

This equation tells us that for a lightly ionized outflow the drag force is almost equal to the Lorentz force. We can now obtain an expression for the slip velocity, $\boldsymbol{w}$, by subbing this equation into Equation C.3

$$\boldsymbol{w} = \boldsymbol{v}_i - \boldsymbol{v}_n = \frac{\boldsymbol{f}_L}{\gamma \rho_i (\rho_n + \rho_n)}. \tag{C.7}$$

The slip velocity becomes large when the ion density becomes small, but does not become large when the neutral density becomes small because the large density of ions drag the few neutrals that are present along with the rest of the mostly ionized plasma. The heating rate per unit volume due to ambipolar diffusion heating is

$$\Gamma = \boldsymbol{f}_d . \boldsymbol{w} \tag{C.8}$$

and substitution of Equations C.6 and C.7 gives

$$\Gamma = \frac{\rho_n |\boldsymbol{f}_L|^2}{\gamma \rho_i (\rho_n + \rho_i)^2}, \tag{C.9}$$

and so for a completely ionized plasma, $\Gamma = 0$.

In order to calculate the ambipolar diffusion heating, we need to find a value for the ion-neutral momentum transfer coefficient, γ (in units $\mathrm{cm^3\,s^{-1}\,g^{-1}}$) which depends on the collisional coefficient rates, cross sections, slip speed, and gas composition. Shang *et al.* (2002) give the following expression

$$\gamma = \frac{2.13 \times 10^{14}}{1 - 0.714 x_e} \left(\left[3.23 + 41.0 T_4^{0.5} \times \left(1 + 1.338 \times 10^{-3} \frac{w_5^2}{T_4} \right)^{0.5} \right] x_{HI} + 0.243 \right) \tag{C.10}$$

where T_4 is the temperature in units of 10^4 K, and w_5 is the slip velocity in units of $\mathrm{km\,s^{-1}}$. We have assumed no molecular hydrogen to be present and the fractional abundance of He, $x_{He} = 0.1$. Subbing Equation C.7 into Equation C.10 gives a quartic equation for γ, i.e.,

$$\gamma^4 - (2AE + 2ABx_{HI})\gamma^3 + (A^2E^2 + 2A^2BEx_{HI} + A^2B^2x_{HI}^2 - A^2C^2x_{HI}^2)\gamma^2 - GA^2C^2x_{HI}^2 = 0$$

where
$A = \frac{2.13\times10^{14}}{1-0.714x_e}$, $B = 3.23$, $C = 41.0T_4^{0.5}$, $D = \frac{1.338\times10^{-3}}{T_4}$, $E = 0.243$, $F = \frac{\boldsymbol{f}_L}{\rho_i(\rho_n+\rho_i)}$, and $G = \frac{DF^2}{1\times10^{10}}$. Finally the components of the Lorentz force and thus the corresponding volumetric ambipolar heating rates can be calculated by using the following expressions for the flow and gravitational accelerations:

$$\boldsymbol{a} = v\frac{dv}{dr}\boldsymbol{r} + \frac{v}{r}\frac{dv}{d\theta}\boldsymbol{\theta} + \frac{v}{r\sin\theta}\frac{dv}{d\phi}\boldsymbol{\phi} \tag{C.11}$$

and

$$\boldsymbol{g} = -\frac{GM_\star}{r^2}\boldsymbol{r} + \frac{1}{r}\frac{d}{d\theta}\left(\frac{GM_\star}{r}\right)\boldsymbol{\theta} + \frac{1}{r\sin\theta}\frac{d}{d\phi}\left(\frac{GM_\star}{r}\right)\boldsymbol{\phi}. \tag{C.12}$$

D
Turbulent Heating

By including time dependence and shear viscosity, μ, into the stellar wind momentum equation we get the Navier-Stokes equation

$$\rho\left(\frac{\partial v}{\partial t}+v.\nabla v\right)=-\nabla P+\mu\nabla^2 v-\frac{GM_\star}{r}+f_{\rm other} \tag{D.1}$$

where $f_{\rm other}$ represents all other forces, and ∇^2 is the vector Laplace operator. In most astronomical settings we expect the viscous term to be unimportant. This can be seen by considering the ratio of the inertial term to the viscous term in the Navier-Stokes equation **?**:

$$\frac{\rho v.\nabla v}{\mu\nabla^2 v}\sim\frac{\rho U^2/L}{\mu U/L^2}=\frac{UL}{\nu}\equiv Re, \tag{D.2}$$

where U is a typical flow speed, L is the macroscopic length of the problem, R_e is the Reynolds number, and $\nu\equiv\mu/\rho$ is called the kinematic viscosity. The shear viscosity is defined as

$$\mu\sim mv_T/\sigma \tag{D.3}$$

where v_T is the thermal speed and σ is the typical collision cross section. Therefore the kinematic viscosity has the unit of velocity times length where,

$$\nu \sim v_T l \tag{D.4}$$

and l is the collision mean free path. The Reynolds number can then be written as

$$Re \sim \frac{UL}{v_T l} \gg 1 \quad \text{when} \quad U \sim v_T. \tag{D.5}$$

In other words, in stellar winds where the flow speeds are sonic or supersonic, the Reynolds number must be large and viscous forces are much less important than inertial effects. These high Reynolds number values (i.e., $Re \gg 10^3$ to 10^4) are associated with the onset of turbulence (**?**) and produce turbulent flows resulting in the formation of eddies and other flow instabilities.

The rate at which energy is fed into the largest eddies per unit mass equals

$$\epsilon \sim \frac{U^2}{L/U} = \frac{U^3}{L}. \tag{D.6}$$

This energy can neither accumulate nor dissipate viscously, so the only other route for it is to be progressively transferred to eddies of smaller and smaller scales. If these smaller eddies have a scale λ and velocity v_λ then the energy that cascades from the large to the small per unit mass is

$$\epsilon \sim v_\lambda^3/\lambda. \tag{D.7}$$

Combining equation D.6 and D.7 gives Kolmogorov's law:

$$v_\lambda \sim U \left(\frac{\lambda}{L}\right)^{1/3} \tag{D.8}$$

The process of transferring energy from large eddies down to smaller eddies continues until the scale of the turbulance is small enough for viscous action to become important and dissipation as heat to occur.

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