Radio Interferometric Studies of Cool Evolved Stellar Winds

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Declaration

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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 $0''.9$ to be traced over a $32''$ field of view. The outer flow known as S2, was found to have outflow velocities of -15.4 and 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 -15.4 and and +13.2 km s^{-1} and extend out to $4 \rightarrow 6''$. 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 ($\sim 1-5\,R_{\star}$) 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 its wind velocity is approaching its terminal value and the ionization balance is becoming *frozen-in*. For Aldebaran the data still sampling 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.
   "Multi-wavelength Radio Continuum Emission Studies of Dust-free Red Giants"
   The Astronomical Journal, 146, 98, (2013)

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"
   Monthly Notices of the Royal Astronomical Society Letters, 432, L61 (2013)

3. **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)

4. 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)

5. 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 Conclusions and Future Work

The goal of this thesis was to broaden our understanding of the outflow environments of red giants and red supergiants. To achieve this goal, we observed these stars with the most sensitive radio interferometers available, allowing their atmospheres to be probed with exquisite detail. The first part of this thesis described the results of our multi-wavelength high spatial resolution campaign to enhance our understanding of Betelgeuse's complex outflow environment. The second part of this thesis focused on the analysis of multi-wavelength centimeter continuum emission from Arcturus and Aldebaran which provided a snapshot of the different stellar atmospheric layers. In this chapter, the primary findings and conclusions of these two studies are presented along with possible directions for future work.

1.1 Principle Results

1.1.1 Multi-wavelength Study of Betelgeuse's Extended Atmosphere

- The two distinct velocity components seen by Bernat *et al.* (1979) in CO absorption against the stellar spectrum at 4.6 μm were both detected at 230 GHz for the first time. The extended CARMA C configuration resolved out almost all of the S2 emission leaving us with an approximate line profile for the S1 flow. From this profile a blueshifted outflow velocity of -9.0 km s^{-1} and a slightly greater redshifted outflow velocity of $+10.6$ km s^{-1} was inferred; in good agreement with Bernat *et al.*'s (1979) value of 9 km s^{-1}.

- The line profiles obtained with the D and E configurations were found to be wider than the C configuration line profile with the notable appearance of an extreme blue wing feature which was associated with the S2 flow. The high spectral resolution multi-configuration spectrum was used to determine S2 outflow velocities of -15.4 km s^{-1} and $+13.2$ km s^{-1} which are in good agreement with Bernat *et al.*'s (1979) value of 16 km s^{-1}.

- In the blueshifted channels of the multi-configuration image cube the emission is compact at high absolute velocities and becomes more extended at lower absolute velocities indicating that the S2 flow has a shell like structure. This is less clear in the redshifted channels indicating an asymmetrical shell. These multi-configuration maps provide the first direct measurements on the spatial extent of the S2 flow, which we derive to have a radius of $17''$; a value that is higher than most previous estimates.

- A well defined outer edge for the S1 flow is not obvious. The emission at low absolute velocities is resolved out in the S1 line profile and because the resolving out scale of the C configuration is $\sim 6''$, this tells us that the spatial extent of the emission must be at least $\sim 3''$. From the intensity distribution of the S1 emission, we infer that the extent of the S1 emission is between $4 - 6''$.

- Both flows were found to be inhomogeneous down to the resolution limit with a notable clump of emission $\sim 5''$ S-W of the star, at low absolute velocities. However, when azimuthally averaged, the intensity falloff of both flows was found to be consistent with an optically thin, spherically symmetric constant velocity outflow.

- Previous single dish observations of the CO line with small HPBWs do not show the classical resolved signature of high emission at large absolute velocities and low emission at low absolute velocities for two main reasons. Firstly, the S1 flow is still unresolved in these single dish observations and thus contributes emission and at the lower absolute velocities. As well as this, the multi-configuration CARMA maps show that the S2 emission is brighter in the higher absolute velocity maps than at lower absolute velocities and so when the emission from the fainter rings is neglected (i.e. when observed with a small HPBW), the overall line profile does not change significantly.

- The various CO rotational line profiles get narrower with increasing excitation energies indicating that the higher excitation lines are formed mainly in the S1 flow. Therefore the high frequency bands of ALMA will preferentially trace the S1 flow.

- Assuming a mean outflow velocity of $14.3\ \mathrm{km\,s^{-1}}$ and $9.8\ \mathrm{km\,s^{-1}}$ for the S2 and S1 flows, respectively, then their ages are ~ 1100 yr and $\sim 400 \rightarrow 600$ yr. The S1 flow may be an extension of the current wind phase seen at UV and centimeter wavelengths but higher spatial resolution data is needed to confirm this (see Section 1.2.1).

- The thermal continuum emission of Betelgeuse's inner atmosphere has been imaged at 6 cm with e-MERLIN, revealing two unresolved hotspots separated by 90 mas, with brightness temperatures 5400 ± 600 and 3800 ± 500 K. The astrometric solutions of Harper *et al.* (2001) place the optical photospheric position almost directly at the position of the weaker feature meaning that the hotter feature is $\sim 2\,R_\star$ above the optical photosphere. Existing 1-D atmospheric models are capable of almost reproducing the low resolution e-MERLIN image but are inadequate at the highest e-MERLIN resolution. 1-D atmospheric models are probably not a realistic representation of Betelgeuse's inner atmosphere.

- variability
- no sign of hot spots but possible q-band features

1.1.2 Multi-wavelength Radio Continuum Emission Studies of Dust-free Red Giants

- x
- y
- z

1.2 Future Work

1.2.1 y

1.2.2 y

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
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
GHRS	Goddard High-Resolution Spectrograph
GREAT	German Receiver for Astronomy at Terahertz Frequencies
HPBW	Half Power Beamwidth
H-R	Hertzsprung-Russell
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

Continued on next page

Table A.1 – *Continued from previous page*

Acronym	Meaning
LTE	Local Thermodynamic Equilibrium
MEM	Maximum Entropy Method
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
SGB	Subgiant Branch
SOFIA	Stratospheric Observatory for Infrared Astronomy
SMA	Submillimeter Array
SZA	Sunyaev-Zel'dovich Array
SIS	superconductorinsulatorsuperconductor
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

The temperature equation outlined in Chapter ?? assumes that the wind is homogenous, but this may not be the case for Arcturus. During this study we analyzed STIS spectra of Arcturus from the online StarCAT catalog (Ayres, 2010). 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 is 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 column density[1] of 1.4×10^{12} cm^{-2}. A Mg column density of 10^{15} cm^{-2} is required to produce the blueward absorption components in the h and k lines (McClintock *et al.*, 1978). Therefore, this discrete absorption feature accounts for $\sim 0.1\%$ of the total wind column density.

[1]Assuming all Mg to be Mg II

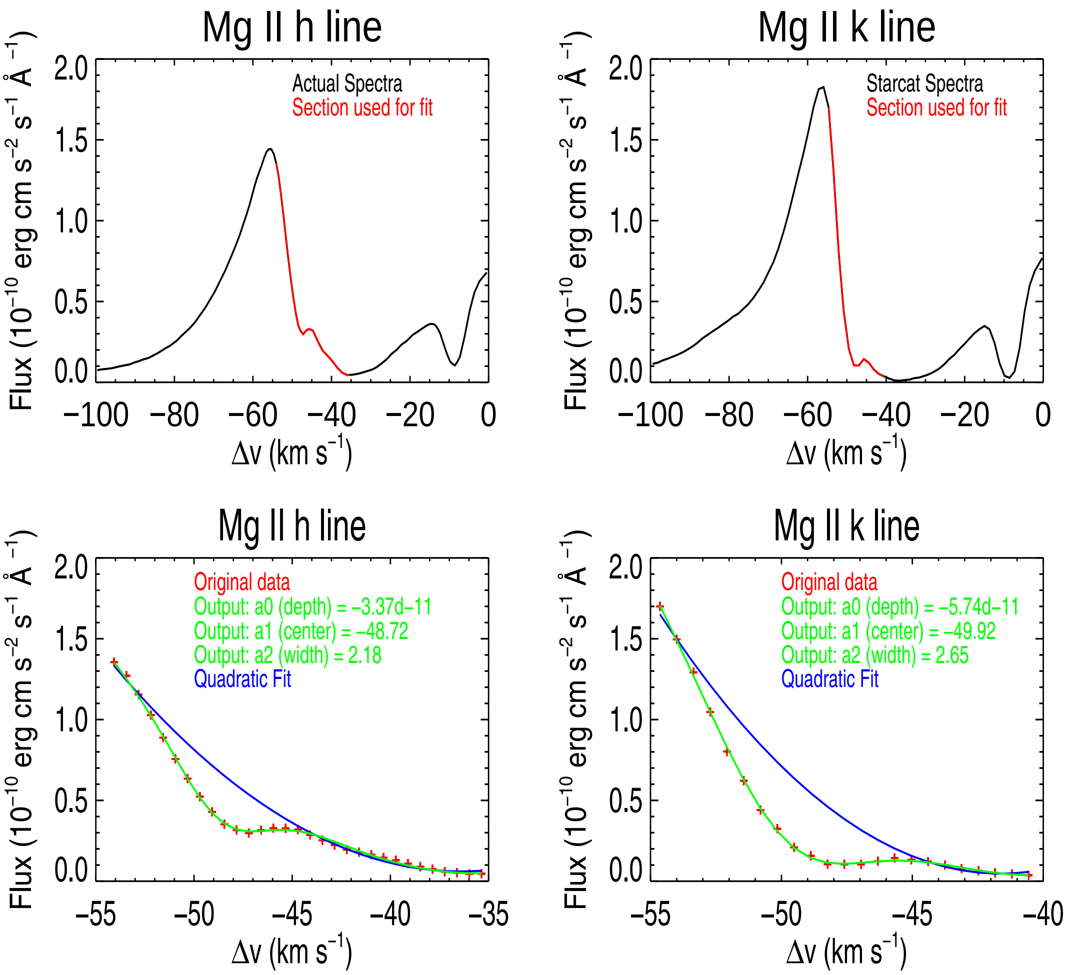

Figure B.1: Analysis on the absorption feature found in the Mg II h and k lines. A function composed of a linear combination of a Gaussian and a quadratic fitted the discrete absorption feature the best. The red data in the upper row shows the data that is used in this analysis.

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