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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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

A Thermal Energy Balance for Arcturus' Outflow

The chapter investigates the various heating and cooling processes that control the thermal structure of Arcturus' mass outflow region. We use the hybrid chromosphere and wind model derived in Section **??** as the basis to derive the magnitude of these processes as function of distance from the star. The effect of adiabatic expansion cooling and cooling by various lines are investigated. This work is a continuation of the initial findings of O'Gorman & Harper (2011).

1.1 Motivation for a Thermal Energy Balance

We have shown in Chapter **??** that for a monotonic ideal gas, the energy per unit mass, $u(r)$, is the sum of the kinetic and gravitational energies, and the enthalpy

$$u(r) = \frac{v(r)^2}{2} - \frac{GM_\star}{r} + \frac{5\Re T}{2\mu}. \tag{1.1}$$

The lower boundary of a stellar outflow is the photosphere which is gravitationally bound to the star. This implies that the energy in Equation 1.1 must be negative at this point. If a star is to have an outflow, then its energy must become positive at large r to escape the gravitational well [i.e., $v(r)^2 \geq v_{\rm esc}(r)^2$]. Therefore, energy must be added to the gas if its velocity is to reach (or exceed) the local escape velocity. The addition of this energy can be either in the form of heat input per unit mass, $q(r)$, or in the form of momentum input [i.e., an outward force, $f(r)$]. In other words, differentiating Equation 1.1 with respect to r gives the change in energy per distance from the star, and this becomes

$$\frac{d\,u(r)}{dr} = f(r) + q(r), \tag{1.2}$$

which is just a form of the *Bernoulli* equation. The unknown fundamental mechanisms responsible for driving the winds of cool evolved stars must therefore manifest themselves in either one or both of the quantities on the right hand side of Equation 1.2. Therefore, studying the heating deposition , $q(r)$, taking place in Arcturus's outflow is a valuable exercise and should provide insight into its wind driving mechanism(s).

Our multi-wavelength radio study of Arcturus allowed us to refine its existing atmospheric model. We found that our long wavelength VLA flux density measurements could be reproduced by the existing model if the almost isothermal outflow was replaced with an outflow that contained a large thermal gradient. This new hybrid model is graphically summarized in Figure **??**. The goal in this chapter is to use this new model as a foundation to study the thermal energy balance in Arcturus's atmosphere. The simple idea behind this is that all the heating and cooling processes taking place in the outflow should combine to produce the derived thermal profile from Chapter ??. Knowing the main mechanisms through which the plasma can cool thus allows us to examine the possible mechanisms which heat the plasma to the known temperature. Investigating the magnitude of the heating deposition of various mechanisms then then tells us if such a mechanism can play a part in the mass loss process.

1.2 Thermal Model for a Spherically Symmetric Outflow

In this section we derive an expression to describe how the temperature in a stellar outflow changes as a function of distance from the star. In doing so, we also present the notation that is used in subsequent sections to describe the magnitude of the heating and cooling taking place at certain regions in a stellar outflow. We assume all quantities vary radially (i.e, spherical symmetry) and that the mass loss rate is constant (i.e., time independent). The continuity equation can then be written as

$$v\frac{d\rho}{dr} = -\rho\left(\frac{dv}{dr} + \frac{2v}{r}\right) \tag{1.3}$$

where v and ρ are the flow velocity and mass density at a distance r from the star. The first law of thermodynamics tells us that the change in internal energy of a system is equal to the heat added to the system minus the work done by the system on its environment. For a reversible process in a closed system the work done is PdV, where P and V are the pressure and volume of the system. Writing the first law of thermodynamics in terms of rates per unit mass then gives

$$\frac{du}{dt} = \frac{dq}{dt} - \frac{P}{m}\frac{dV}{dt} \tag{1.4}$$

where u is the internal energy per unit mass and q is the net heat gained per unit mass. The time dependence in the first and last terms can be switched to a radial dependence via $v = dr/dt$, and m/ρ can be substituted for V to get

$$v\frac{du}{dr} = -\frac{P}{\rho}\left(v\frac{d\rho}{dr}\right) + \frac{dq}{dt}. \tag{1.5}$$

Substituting in Equation 1.3 and using $u = 3nkT/2\rho$ and $P = nkT$ gives

$$v\left(\frac{3nk}{2\rho}\frac{dT}{dr}\right) = -\frac{nkT}{\rho}\left(\frac{dv}{dr} + \frac{2v}{r}\right) + \frac{dq}{dt}. \tag{1.6}$$

If we define Γ and Λ are the heating and cooling rates per unit volume respectively, then we can rearrange this equation to get

$$\frac{dT}{dr} = -\frac{4T}{3r} - \frac{2T}{3v}\frac{dv}{dr} + \frac{2(\Gamma - \Lambda)}{3nkv}. \tag{1.7}$$

The first two terms on the right account for adiabatic expansion cooling. The second term is important in the wind acceleration region but is zero once the wind has reached its terminal velocity. The third term accounts for all other heating and cooling processes. This equation is equivalent to Equation 8 in Goldreich & Scoville (1976) and can also be written in dimensionless form (Rodgers & Glassgold, 1991) by multiplying across by r/T as follows:

$$\frac{d(\ln T)}{d(\ln r)} = -\frac{4}{3} - \frac{2}{3}\frac{d(\ln v)}{d(\ln r)} + \sum_{i=1}\mathcal{H}_i - \sum_{j=1}\mathcal{L}_j \tag{1.8}$$

where

$$\mathcal{H}_i = \frac{2r}{3nkvT}\Gamma_i \tag{1.9}$$

and

$$\mathcal{L}_j = \frac{2r}{3nkvT}\Lambda_j \tag{1.10}$$

are the various heating and cooling contributions respectively, normalized to constant velocity adiabatic expansion cooling. Finally this equation can be expressed in terms of the gas kinetic temperature's local power law slope, λ,

$$\frac{d(\ln T)}{d(\ln r)} = -\lambda \tag{1.11}$$

where

$$\lambda = \lambda_0 + \sum_{i=1}\lambda_i \tag{1.12}$$

which contains all of the wind heating and cooling processes, including that from adiabatic expansion cooling, λ_0. We note that positive and negative λ's represent cooling and heating, respectively. This notation will be used throughout this chapter and allows the various heating and cooling process to be easily compared to the 4/3 exponent, characteristic of a constant velocity outflow undergoing adiabatic expansion cooling.

1.3 Cooling Processes

We now assess the important cooling processes which take place in Arcturus' atmosphere between $\sim 1 - 10\,R_\star$.

1.3.1 Adiabatic Expansion Cooling

Adiabatic expansion cooling is the thermodynamic process in which a fixed quantity of gas cools as it expands into a larger volume of gas. It is composed of a geometric term and a velocity gradient term; these being the first two terms on the right of Equation 1.8. As shown in Figure 1.1, the dominant term close to the photosphere is the velocity gradient term due to the rapid wind acceleration while further out where the wind reaches its terminal velocity, the geometric term becomes dominant. Adiabatic expansion cooling is a very efficient cooling mechanism in the atmospheres of all stars. To show this we take the atmosphere of Arcturus as an example and assume the absence of all heating mechanisms. The geometric factor alone then will lower the gas temperature to decrease by a factor of 10^4 by $1500\,R_\star$ which is below the cosmic background temperature.

1.3.2 Radiative Recombination Cooling

Radiative recombination is the process by which an electron is captured by an ion into a bound state n with the emission of a photon. The overwhelming abundance of H along with it having a similar cross section for capture to heavier ions, means that it is by far the most important species to consider for this cooling process. The radiative recombination cooling rate is

$$\Lambda = n_{HII} n_e \alpha^n \left(\frac{3}{2}kT\right) \qquad \mathrm{erg\,s^{-1}\,cm^{-3}} \tag{1.13}$$

where $\frac{3}{2}kT$ is the average thermal energy of a captured electron and α^n is the hydrogen recombination rate coefficient summed over n levels. The hydrogen

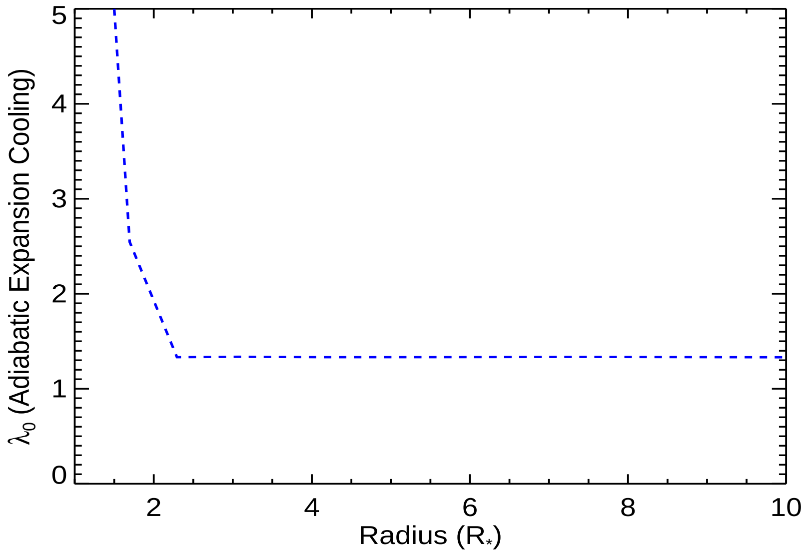

Figure 1.1: The effect of adiabatic expansion cooling in Arcturus' outflow. The dominant term close to the photosphere is the velocity gradient term from Equation 1.8 due to the rapid wind acceleration, while further out where the wind reaches its terminal velocity, the geometric term becomes dominant.

recombination rate coefficient excluding captures to the $n = 1$ level is given as

$$\alpha_B = \frac{2.06 \times 10^{-11}}{T^{1/2}} \phi_2(\beta) \qquad \mathrm{s}^{-1}\,\mathrm{cm}^{-3}. \tag{1.14}$$

$\phi_2(\beta)$ is a function that varies with temperature and has been tabulated for various temperatures by (Spitzer, 1978). Recombination to the ground state is excluded because the process produces another ionizing photon that can be easily absorbed again, producing the net effect that the recombination had not occurred. The radiative recombination cooling contribution can then be calculated using Equation 1.10.

1.3.3 Lyman-alpha Cooling

1.3.4 Other Line Cooling

1.4 Heating Mechanisms

Table 1.1: Ionized

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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