

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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Acknowledgements

Some sincere acknowledgements...

List of Publications

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1. Richards, A. M. S., Davis, R. J., Decin, L., Etoke, 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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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”
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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”
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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

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

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., $v(r)^2 \geq v_{\text{esc}}(r)^2$]. 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

$$\frac{du(r)}{dr} = f(r) + q(r), \quad (1.2)$$

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 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

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

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

$$\frac{du}{dt} = \frac{dq}{dt} - \frac{P}{m} \frac{dV}{dt} \quad (1.4)$$

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

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

1.2 Thermal Model for a Spherically Symmetric Outflow

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

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

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

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

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:

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

where

$$\mathcal{H}_i = \frac{2r}{3nk v T} \Gamma_i \quad (1.9)$$

and

$$\mathcal{L}_j = \frac{2r}{3nk v T} \Lambda_j \quad (1.10)$$

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 ,

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

where

$$\lambda = \lambda_0 + \sum_{i=1} \lambda_i \quad (1.12)$$

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

The three ways in which the gas in Arcturus' partially ionized outflow can cool are through adiabatic expansion, radiative recombination, and collisional excitation of neutral and ionized atoms. We now assess the importance of each of these cooling processes 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

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

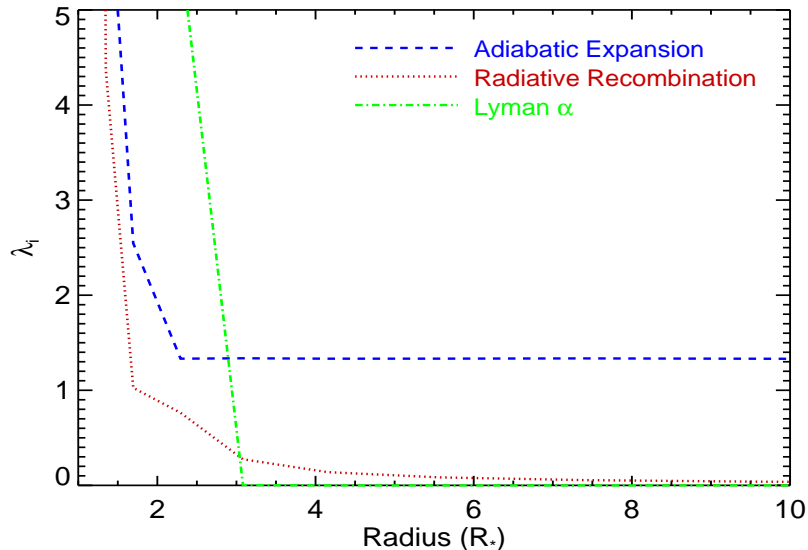


Figure 1.1: The effects of adiabatic expansion, radiative recombination, and Lyman α cooling in Arcturus' outflow. For adiabatic expansion cooling, the dominant term close to the photosphere is the velocity gradient term from Equation 1.8 due to the rapid wind acceleration, while further out where the wind reaches its terminal velocity, the geometric term becomes dominant. Radiative recombination is also an important cooling mechanism between $\sim 1 - 4 R_*$. The Lyman α cooling function is very sensitive to T and is the dominant cooling process out to $2.8 R_*$.

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

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

$\phi_2(\beta)$ 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

At temperatures of a few thousand degrees, the excited levels in neutral H can become populated from electron collisions and thus can be a source of cooling. The analytical expression for the resulting net cooling rate per volume is

$$\Lambda_{\text{eH}} = 7.3 \times 10^{-19} n_e n_{\text{HI}} e^{-118,400/T(K)} \quad \text{erg s}^{-1} \text{cm}^{-3} \quad (1.15)$$

Spitzer (1978). Most of the resulting radiation comes from the $n = 2$ level (Lyman α) and this is why the cooling rate is almost proportional to $\exp(-E_{12}/kT)$, where $E_{12}/k = 118319 \text{ K}$. Equation 1.15 is a very sensitive function of the gas temperature and as can be seen from Figure 1.1, is the dominant cooling process out to $2.8 R_\star$. The sharp falloff in temperature in Arcturus' outflow post $2.3 R_\star$ results in this mechanism going from being a very efficient cooling process within $2.3 R_\star$ to having a negligible effect by $\sim 3.1 R_\star$.

1.3.4 Other Line Coolants

Due to its large abundance, H is expected to be the most efficient line cooling mechanism in the inner atmosphere of Arcturus. Nevertheless, it is also worth investigating the effects of line cooling from heavier elements which may become important at lower temperature further out in the atmosphere where line cooling from H has almost ceased. Line cooling from these heavy elements is due mainly to electron impact excitation of electronic levels of the neutral and ionized species at high temperatures, while at lower temperatures (i.e. further out in the CSE) line cooling is mainly due to the electron impact excitation of fine structure levels of the neutral and ionized constituents (Dalgarno & McCray, 1972). Table 1.1 lists the most relevant heavy elements for this study based on abundance and suitable line transitions. All heavy elements with an ionization potential (IP) lower than O were assumed fully ionized, while the ionization balance of O was based on the IUE line profile analysis of Judge (1986).

The line cooling rate per unit volume due to the transition ul in a medium

Table 1.1: Elemental Abundance in Arcturus's Outflow

Element	Abundance	IP (eV)	Reference
O	4.7×10^{-4}	13.6	Ramírez & Allende Prieto (2011)
C	2.1×10^{-4}	11.3	Ramírez & Allende Prieto (2011)
N ¹	6.7×10^{-5}	14.5	Asplund <i>et al.</i> (2009)
Mg	3.0×10^{-5}	7.6	Ramírez & Allende Prieto (2011)
Si	2.0×10^{-5}	8.2	Ramírez & Allende Prieto (2011)
Fe	1.0×10^{-5}	7.9	Decin <i>et al.</i> (2003)

¹ Assumed solar abundance.

where the optical depth is not negligible is

$$\Lambda_{\text{line}} = \sum_{u \rightarrow l} n_u A_{ul} E_{ul} \rho(\tau) \quad \text{erg s}^{-1} \text{ cm}^{-3} \quad (1.16)$$

where n_u is the population of the upper level, A_{ul} is the spontaneous emission coefficient of the transition, and E_{ul} is the energy of the radiated photon. Here, the sum is over all possible upper to lower transitions and $\rho(\tau)$ is the probability the photon will escape the gas without being reabsorbed. This function lowers the line cooling rate and can be written as

$$\rho(\tau) = \frac{1 - \exp(-3\tau/2)}{3\tau/2} \quad (1.17)$$

(Castor, 2004). The level populations were found by simultaneously solving the statistical equilibrium equations and the non-LTE fractional fractional populations formula, i.e.,

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp\left(\frac{-E_{21}}{kT}\right) \left(1 + \frac{n_{\text{cr}}}{n_{\text{tot}}}\right)^{-1}. \quad (1.18)$$

Here g_u and g_l are the degeneracy (the number of states with the same energy) of the levels and n_{tot} is the total number density of all particles in the gas. The critical density, n_{cr} , is the ratio of the radiative and collisional rates

$$n_{\text{cr}} = \frac{A_{ul} \rho_{ul}}{C_{ul}}. \quad (1.19)$$

and tells us whether LTE is an accurate approximation at that point in the outflow.

The line cooling from these heavy elements was found to be only significant within $1.5 R_\star$, the most efficient of which being the $\text{C II } ^2P \rightarrow ^2P$ semi-forbidden transition (2326 \AA). Line cooling due to the fine structure levels of these elements was found to be negligible due to the high temperature regime. In Figure 1.2 we plot the sum of all the cooling mechanisms taking place in Arcturus' outflow. The cooling taking place within the first $3 R_\star$ is mainly due to Lyman Alpha emission line while the cooling further out is mainly due to gas expansion, with a small contribution from radiative recombination.

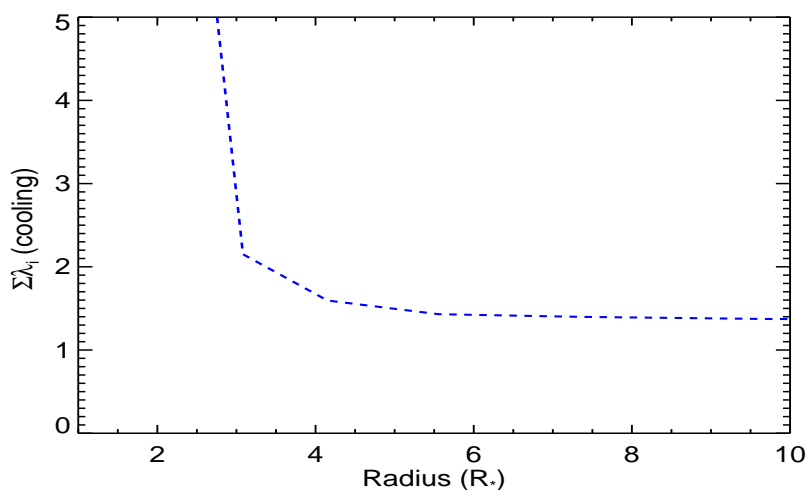


Figure 1.2: Summation of all the cooling mechanisms taking place in Arcturus' outflow. The cooling taking place within the first $3 R_\star$ is mainly due to Lyman Alpha emission line while the cooling further out is from gas expansion, with a small contribution from radiative recombination.

1.4 Heating Mechanisms

In the following sections we investigate various possible heating mechanisms taking place in Arcturus's outflow and the overall efficiency of these mechanisms at various distance from the star.

1.4.1 Photoionization Heating



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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