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Stellar winds from red supergiants stars accelerated by Alfvén waves

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Abstract. In this work, we investigate the influence of resonant damping of a surface Alfvén-wave flux as a mechanism for accelerating the winds of red supergiant stars. We present results for Alpha Orionis for both the isothermal and non-isothermal cases. The non-isothermal treatment reduces the terminal velocity, bringing the model closer to observations, indicating that these winds reach terminal speeds of about half the escape velocity.

Resumo. Neste trabalho investigamos a influência do amortecimento ressonante de um fluxo de ondas Alfvén de superfície como mecanismo de aceleração do vento de estrelas supergigantes vermelhas. Apresentamos resultados para Alpha Orionis, tanto no caso isotérmico quanto no caso não isotérmico. O tratamento não isotérmico reduz a velocidade terminal, aproximando-a da observação de a velocidade destes ventos é cerca de metade da velocidade de escape.

Keywords. winds – supergiants – plasmas

1. Introduction

Mass loss via stellar winds is a key ingredient in the evolution of massive stars. Red supergiants stars (RSGS) exhibit dense, cool outflows with comparatively low terminal velocities, typically satisfying $u_\infty < v_{\rm esc}$ and often $u_\infty < (0.5)\, v_{\rm esc}$. Standard driving mechanisms (thermal pressure gradients, line driving, dust driving) face difficulties in reproducing RSGS wind properties under the observational constraints.

Several studies in the literature deal not only with the diagnosis of mass loss but also with the construction of models to explain it. Jatenco-Pereira & Opher (1989) (JPO from now on) proposed a model for mass loss in red supergiant stars in which the damping of an Alfvén wave flow, generated in the turbulent region of the star serves as the principal wind acceleration mechanism.

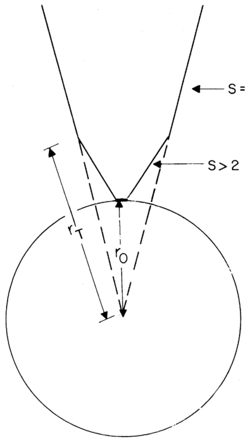

Figure 1. Rapidly divergent magnetic field geometry, where r_T defines the transition radius from divergent geometry $S > 2$ to radial $S = 2$, from JPO.

The proposed model is based on the geometry of the Sun's coronal holes, which, when observed in X-rays, reveal a rapidly diverging structure (Figure 1). Just like the work done in JPO, we used an Alfvén wave flux localized at the base of the stellar wind, propagating out of the star along the magnetic field lines. These waves are damped with a damping length, L, transferring momentum to the plasma, accelerating it. Thus, the velocity profile is given by:

(1)

where u is the velocity of the wind, V_T, thermal speed, M_A is the Alfvén Mach number given by $M_A = \frac{u}{V_A}$ (where V_A is the Alfvén velocity) and lastly, Z is a constant that takes the values for the divergent geometry as a function of the radius, as illustrated in Figure 1, whose dynamics are governed by the Equation 2:

$$Z = \begin{cases} S, & \text{for } r \le r_T \\ 2, & \text{for } r > r_T \,. \end{cases} \tag{2}$$

For the wind temperature, we adopt the behavior described in Holzer, Fla & Leer (1983). For a plasma composed predominantly of hydrogen and helium, with a characteristic Alfvén frequency $\bar{\omega} = 10^{-4}$ s^{-1}, the thermal distribution is given by:

$$T \simeq T_0 \, e^{\left[-\frac{(r-10r_0)}{26r_0}\right]}, \tag{3}$$

where, T_0 is the initial temperature and r_0, the star radius.

Therefore, it was necessary to develop a numerical code to obtain the terminal wind velocity by solving Equation 1 for both the isothermal and non-isothermal cases.

2. Methodology and Procedure

Still following JPO, an isothermal wind model was used with the same objective: to reproduce the low terminal wind velocity of cold supergiant stars.

For the wave damping, we considered the resonant absorption of surface Alfvén waves (Lee & Roberts 1986), where within an inhomogeneity, such as a divergent geometry of an open magnetic field, there exists an Alfvén wave with frequency ω_2, and outside the inhomogeneity, an Alfvén wave with frequency ω_1, which is lower than ω_2, so assuming a linear variation of the wave frequency $\omega_A^2 = k^2 v_A^2(x)$, we have:

$$\omega_A^2 = \bar{\omega}^2 + \left(\omega_2^2 - \omega_1^2\right)\left(\frac{x}{2a}\right), \tag{4}$$

where $\bar{\omega}$ is given by:

$$\bar{\omega}^2 = \frac{\left(\omega_2^2 - \omega_1^2\right)}{2}, \tag{5}$$

and x is the distance along the inhomogeneity,which has width a. This implies the concentration of surface wave energy within a thin resonant layer, where we assume the energy is dissipated locally as heat over a damping length L.

Equation 1 was integrated with a 4th-order Runge–Kutta scheme (RK4), enforcing the piecewise magnetic geometry across r_T. We apply the model to α Orionis using representative parameters from Schuller et al. (2004): stellar radius $r = 608.3\ R_\odot$, stellar mass $M = 10\ M_\odot$, initial temperature $T_0 = 3640$ K, initial density $\rho_0 = 6.0 \times 10^{-13}$ g cm^{-3}, $B_0 = 10$ G, initial damping length $L_0 = 0.2\, r_0$, Alfvén wave flux $\phi_0 = 3.36 \times 10^6$ erg cm^{-2} s^{-1}, and geometry opening $S = 4.8$. The escape velocity obtained was $v_{\rm esc} = 79.2$ km s^{-1}.

3. Results

3.1. Isothermal solution

For the isothermal case, the model yields an accelerating solution that becomes supersonic beyond a critical point and reaches a terminal speed:

$$u_{\infty_{isothermal}} \approx 51.3 \text{ km s}^{-1}, \tag{6}$$

satisfying the observational constraint $u_\infty < v_{\rm esc}$ given by Weymann (1962). We also verified that the rapidly divergent geometry strongly impacts the terminal speed: by decreasing it, we obtain an increasingly higher final velocity, as shown in the Figure 2.

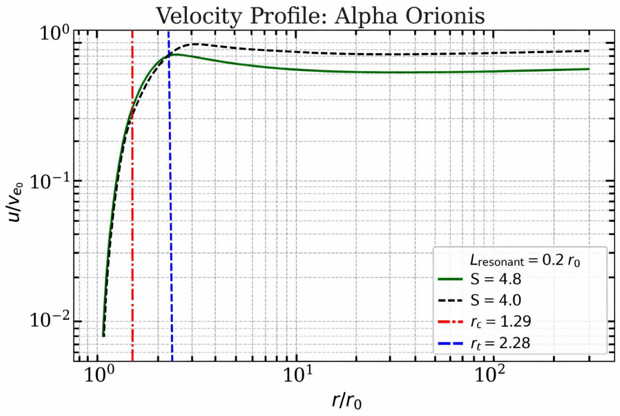

Figure 2. Wind velocity profile of *Alpha Orionis* as a function of distance for $S = 4.0$ (dotted line) and $S = 4.8$ (solid line). The critical radius r_c marks the transition to supersonic flow, while r_t denotes the radius at which the magnetic-field geometry becomes radial.

3.2. Non-isothermal solution

Including the temperature decay given by Equation 3 modifies the thermal velocity $V_T(r)$ and, consequently, the wind temperature decreases as it expands outward into the interstellar medium, leading to a lower terminal velocity:

$$u_\infty \approx 39.2 \text{ km s}^{-1}, \tag{7}$$

which is remarkably close to half the escape velocity, agreeing with the observations. Therefore, replacing the isothermal approximation with a more physically consistent model improves agreement with observations of cold supergiant winds and provides a more physically consistent description of both wind acceleration and thermal structure. The non-isothermal velocity profile is shown in Figure 3.

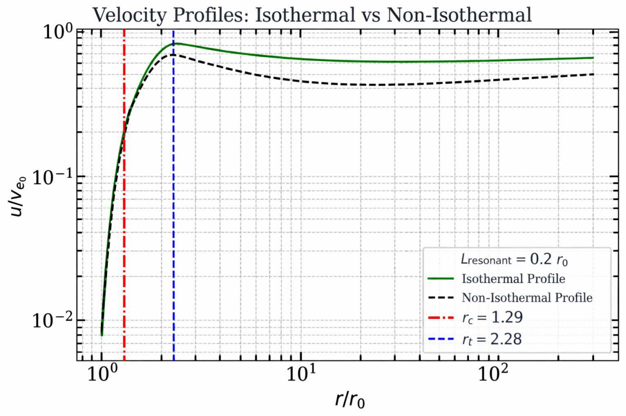

Figure 3. Comparison of the wind velocity profile of *Alpha Orionis* as a function of distance for $S = 4.8$, for the isothermal case (solid line) and for the non-isothermal case (dashed line).

4. Conclusions

We modeled the wind of the red supergiant α Orionis, driven by the damping of an Alfvén wave flux in a rapidly diverging open magnetic-field geometry. The isothermal treatment yields $u_\infty \simeq 51$ km s^{-1}, whereas a non-isothermal temperature profile yields $u_\infty \simeq 39$ km s^{-1}, consistent with the observational expectation that RSGS terminal velocities are of order half the escape speed. We also demonstrate that the divergent magnetic-field geometry plays a key role in setting the wind's terminal velocity.

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