A HOT CORONA MODEL FOR O-STARS AND WR STARS

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ABSTRACT

Atmospheric models are presented for the outer layers of hot stars, O, Of and Wolf-Rayet stars. The model is a two component hybrid model, consisting of a rapidly expanding component and a slower component. For the rapidly expanding component the energy sources are radiation pressure, a deposit of internally generated and stored energy, and radiation cooling. In this way a coronal layer with temperatures of the order of 4-7 million K is generated, with an extent of 1 to 2 stellar radii. The mass loss rates range between 10^{-6} and 10^{-4} $M_{\odot}$ yr^{-1}. The stellar wind velocity at infinity is of the order of 4000 km s^{-1}. It is assumed that this rapid component interacts with the slow component, and gives rise to shocks. The corona as well as the shocks generated by the interaction of the two components can explain the observed X-rays.

INTRODUCTION

X-ray emission has been detected for O-stars and Wolf-Rayet stars, indicating the presence of a hot corona. Our aim is to construct atmospheric models for the outer layers of these stars.

The given two component hybrid model consists of a rapidly expanding component and a cooler one, which interactions generate shocks producing X-rays. We assume the fast component to have the following characteristics :

1. the mass outflow starts at the photosphere and the wind velocity increases to maximum values of 4000 km s^{-1};
2. the flow is determined by radiation pressure and by a given energy deposit, produced below the photosphere;
3. radiative cooling is taken into account.

Models for stars of 30-100 $M_{\odot}$, with mass loss rates up to 4.41 10^{-6} and 6.85 10^{-6} $M_{\odot} yr^{-1}$ have been constructed. The first one could account for the hot component in O stars, while the second one could represent the

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atmosphere of a Wolf-Rayet star. The outflow velocities, v_∞ are 4000 km s^{-1} and 2700 km s^{-1} respectively. The coronal temperatures are 4.1 to 6.6 10^6 and 5.0 10^6 K respectively.

THE BASIC EQUATIONS

a) mass conservation :

$$\dot{M} = 4\pi\, r^2\, \rho\, v = \text{constant} \tag{1}$$

b) conservation of momentum :

$$v \frac{dv}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM}{r^2} \tag{2}$$

c) energy conservation :

$$v \frac{de}{dr} + p\, v \frac{d}{dr}\left(\frac{1}{\rho}\right) = \frac{1}{\rho}\left(Q_A + Q_R - \nabla \vec{q}_c\right) \tag{3}$$

where Q_A = energy per unit volume and per unit of time produced below the photosphere and liberated above
Q_R = radiation energy per unit volume and per unit of time
q_c = conductive flux.

These equations are adapted for the stellar wind. Adding the radiative acceleration to equation (2) and using the force multiplier of Castor, Abbott and Klein gives :

$$v \frac{dv}{dr} + \frac{1}{\rho}\frac{dp}{dr} + \frac{GM'}{r^2} = C \frac{1}{r^2}\left(r^2\, v \frac{dv}{dr}\right)^{\alpha} \tag{2'}$$

with $M' = M(1-\Gamma)$ and $C = \Gamma\, G\, M\, k \left(\frac{4\pi}{\sigma\, v_{th}\, \dot{M}}\right)^{\alpha}$

The energy equation (3), omitting conduction and radiation, can be written :

$$\frac{3}{2}\rho\, v\, r^2 \frac{d}{dr}\left(\frac{p}{\rho}\right) + p\, \rho\, v\, r^2 \frac{d}{dr}\left(\frac{1}{\rho}\right) = r^2\, Q_A \tag{3'}$$

Introducing the square of the adiabatic sound velocity s ($s=\gamma p/\rho$) and the continuity equation into (2') and (3') leads to a set of two equations equivalent to the basic ones :

$$F(r,v,v',s) \equiv \left(v - \frac{5}{3}\frac{s}{\gamma v}\right)\frac{dv}{dr} - \frac{10}{3}\frac{s}{\gamma r} + \frac{GM'}{r^2} + \frac{2}{3}P(r) - \frac{C}{r^2}\left(r^2 v \frac{dv}{dr}\right)^{\alpha} = 0 \tag{4}$$

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	O stars	$k=0.012$ $\alpha=0.8$		$x_{CP}=1.08$	$X=0.7$	$Z=0.03$		$\mu=0.6182$	
$M/M_\odot$	$\log L/L_\odot$	$\log T_{eff}$	$R/R_\odot$	$\dot{M}$ $(10^{-6} M_\odot yr^{-1})$	P_o $(x10^4)$	$\log T_{max}$	v_∞ $(km\ s^{-1})$	$\log g_{eff}$	
100	6.06	4.716	13.28	4.41	1.075	6.78	4162	4.045	
80	5.90	4.706	11.54	2.86	1.202	6.77	4106	4.095	
60	5.67	4.676	10.22	1.58	1.212	6.72	3895	4.103	
50	5.52	4.658	9.30	1.05	1.261	6.69	3794	4.122	
40	5.32	4.633	8.28	0.62	1.321	6.66	3668	4.144	
30	5.04	4.594	7.20	0.30	1.361	6.61	3477	4.159	
	WR star	$\alpha=0.83$		$x_{CP}=1.08$	$X=0$	$Z=0.03$		$\mu=1.347$	k
40	5.319	4.441	20.20	0.791	0.265	6.69	2719	3.395	0.012
40	"	"	"	1.824	0.268	6.70	2724	"	0.024
40	"	"	"	6.849	0.274	6.71	2735	"	0.072

Table 1. The change of the mass loss rate, energy input, temperature and v_∞ for different O-stars and one WR star.

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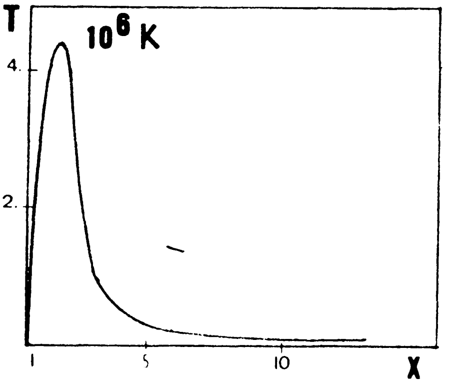

Figure 1. The temperature of the outer regions as a function of the distance X (expressed in stellar radii) for a ZAMS 40 $M_\odot$ star.

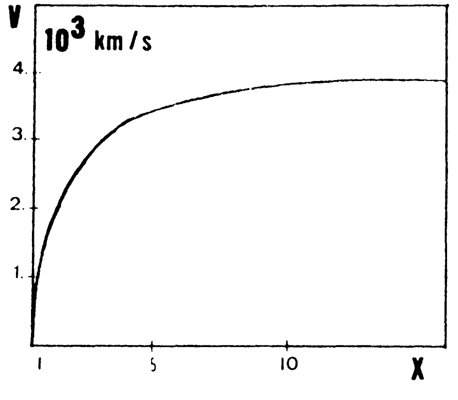

Figure 2. The outflow velocity for a 40 $M_\odot$ star as a function of the distance X.

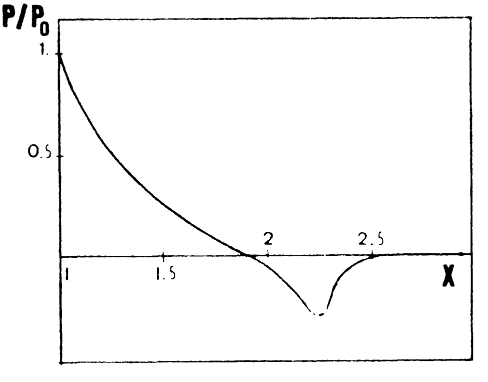

Figure 3. The energy deposit and the cooling as a function of the distance X.

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$$\frac{3}{2}\frac{ds}{dr} + \frac{2s}{r} + \frac{s}{v}\frac{dv}{dr} = \gamma P(r) \qquad (5)$$

with $P(r) = 4\pi r^2 Q_A/\dot{M}$

For given values of r and C, F is a function of v, v' and s and not linear in v'. Moreover for s a complementary condition is given by the linear differential equation (5).
In addition two supplementary conditions, the locus of singular points and the continuity condition, define a critical point. It can be seen as the solution of a non linear equation in s :

$$\frac{2}{3}s^2 + B(x) + \frac{8}{3}W(s,x)\left[s - \frac{5}{12}P(x)R_*x + W(s,x)\right] = 0 \qquad (6)$$

where non dimensional distance units $x = r/R_*$ are used.
The heat deposition takes the form :

$$P(x) = P_o x^2 \left[e^{-\beta(x-1)} - \gamma\, e^{-\frac{(x-\lambda)^2}{\omega}} + \varepsilon\, e^{-\frac{(x-\nu)^2}{\eta}}\right]$$

with β an inverted scale height.
The first term works before and in the neighbourhood of the critical point; the last two terms, simulating cooling, are only affecting the temperature beyond his maximum.

CONCLUSIONS

1. Radiation pressure is the dominant factor in the mass loss machanisms.
2. The velocity structure is completely determined by the model and has not to be assumed à priori
3. Hot coronae with temperatures of the order of 4-6 10^6K are generated.
4. The temperature profile and T_{max} depend strongly on the energy deposition.
5. The velocity structure and the mass loss determined by radiation pressure and the temperature and T_{max} determined by energy deposit and radiative cooling can be considered as disconnected.

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