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Envelopes of Cool Giant Stars: a Hybrid Model

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The mass loss from cool giant stars is considered on the basis of a hybrid mechanism involving chromosphere evaporation and radiation pressure on molecules. Differences between the present model and purely radiative winds are stressed. In particular, average chromospheric temperatures are estimated which are compatible with the previously determined mass loss rate.

A perda de massa de estrelas gigantes vermelhas é considerada, com base em um mecanismo híbrido envolvendo a evaporação de uma cromosfera e a ação da pressão da radiação estelar em moléculas. São assinaladas as principais diferenças entre o presente modelo e modelos de ventos puramente radiativos. Em particular, são obtidos valores médios para a temperatura da cromosfera que sejam compatíveis com a taxa de perda de massa previamente determinada.

1. INTRODUCTION

Late-type giant stars lose mass to the interstellar medium at a rate typically in the range $10^{-8} \lesssim dM/dt\ (M_\odot \mathrm{yr}^{-1}) \lesssim 10^{-5}$ (see for example reference 1). Several mechanisms have been proposed to explain this phenomenon[2,3,4], including the action of radiation pressure on grains[5,1] and molecules[6,7,1]. A detailed study of the latter[6,7] was able to produce a mass loss rate $dM/dt = 1.3\ 10^{-7}\ M_\odot \mathrm{yr}^{-1}$ for a cool M giant with $M_* = 1\ M_\odot$, $T_{ef} = 2000\ K$ and $R = 6.96\ 10^{13}$cm, taking into account infrared molecular absorption bands of CO, H_2O and OH. In that model the cool stellar envelope - as detected for example by displaced circumstellar lines, or OH maser emission (in the case of Mira Variables) - was assumed to begin right above the stellar photosphere, that is, the base R of the envelope was taken to be R R In other words, the possibility of the existence of a chromosphere-corona above the photosphere was not taken into account[7]. As it will be seen in the next section, evidences have been recently gathered on the location on the *HR* diagram and physical characteristics of regions hotter than the stellar photosphere. The main effects of such regions on the envelope structure would be a displacement of the cool layers and some gas acceleration through a purely thermal expansion.

In the present paper, we have considered a simple model chromosphere at the base of the envelope in addition to the cool layer where molecule formation takes place. We have in this way estimated the average chromospheric temperature compatible with the mass loss rate previously determined.

In section 2 recent data on chromospheres of late-type giants is reviewed. In section 3 the envelope structure is developed, and in section 4 the results relating to chromospheric parameters are discussed.

2. CHROMOSPHERES OF COOL GIANT STARS

Traditionally, the presence of warm chromospheres around late-type stars is indicated by emission lines such as Ca II H(A 3968A) and K(λ3934A) [8]. In recent years, however, ultraviolet observations by the International Ultraviolet Explorer (IUE) have considerably extended our knowledge on the location of chromospheres on the HR diagram[9,10]. The main lines detected are the MgII resonance doublet h(λ2803A) and k(λ2796A), Fe II (λ2586A; 2631A), O I (λ1305A, 1355A), and SiII (λ1808A, 1817A). Most observed late-type giants and supergiants present Ca II, Mg II and Fe II in emission, although for the extreme M giants an inverse correlation seems to exist between Ca II emission and infrared excess[10,11]. Empirical temperature estimates from the chromospheric lines indicate an upper limit T $\lesssim$ 20000 K for giants and supergiants later than about K5. Some examples are presented in table 1. The upper limits given (references 9,12,14,15,16) indicate the absence of hotter chromospheric UV lines from IUE observations. The average temperature of 5000 K for a Ori was estimated by Lambert and Snell[13] on the basis of a chromospheric contribution to the observed infared excess. The temperature range for this star comes from model calculations matching the Ca II and Mg II lines••. Table 1 illustrates well the feeling that average chromospheric temperatures do not exceed $\sim 10^4 K$ for the late M giants and supergiants. The giants of spectral type later than about *M5*, in particular, do not present temperatures greater than $\sim$ 8000 K, which is supported by the absence of Mg II emission in W Hya[15].

Table 1 - Average chromospheric temperatures

Star	Spectral type	temperature (K)	reference
a Tau	K5 III	< 20000	12
a Cet	M0 III	< 20000	12
α Ori	M2 Iab	< 20000	9
		2700-7000	11
		5000	13
β Gru	M2 II	< 20000	14
R Aql	M5e-M8e III	6000-8000	15
R Aqr	M7 III	$\lesssim$ 10000	16
W Hya	M8e-M9e III	8000	13
		< 8000	15

The presence of transition regions around stars has been indicated by IUE observations of C II (λ1335A), Si IV (λ1394A, 1403A), among other lines[10]. IUE can detect such regions up to $\sim 2\ 10^5$ K, and recent investigations show that essentially no star to the right of the Linsky-Haisch dividing line exhibits transition regions[10,11]. Although the exact position of the dividing line may be uncertain, it seems that no transition regions are present around M giants and supergiants. The same is true regarding the still hotter coronae ($T \gtrsim 10^6$ K), which can be detected through soft X-ray flux as observed by the Einstein X-ray observatory (HEAO-2)[4,11]. Recent investigations have failed to detect such regions on giant/supergiants later than about $K5$. As an example, the upper limits of the X-ray flux for α Ori ($M2$ Iab) and a Sco ($M1$ Ib) are about 10^3 times lower than the flux of the solar coronal holes[4,10]. This result can be interpreted as either no corona is present or the coronal emission measure is too small to be observed.

3. ENVELQPE STRUCTURE

Figure 1 shows schematically the assumed model geometry. The hybrid envelope consists of a warm chromosphere above the stellar photosohere, surrounded by a cool layer containing atomic gas and molecules. The structure of the cool part of the envelope has been descrited in detail elsewhere[6]. Steadystate flow with spherical symmetry is assumed, and at large distances from the sear the gas expands adiabatically. Since we are primarily interested in a rough estimate of chromospheric parameters, we will assume the chromosphere to be optically

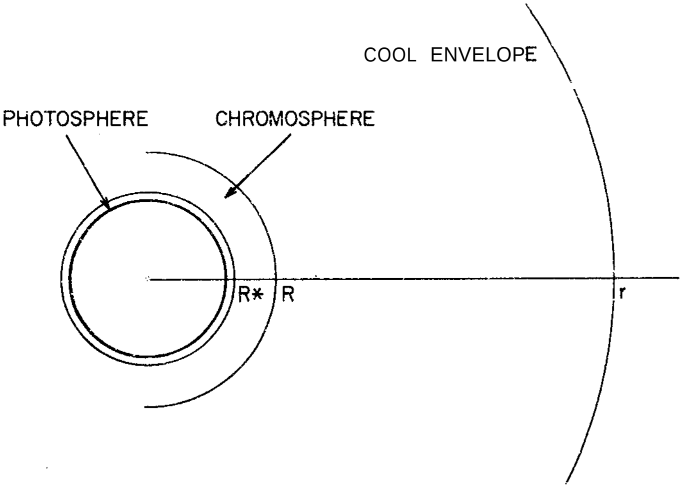

Fig.1 - Schematic view of thr model geometry.

thin and isothermal at a temperature T. Naturally, this implies the existence of an energy source for the chromosphere, which is not specified in our model. For a more detailed discussion on non-thermal energy input in stellar chromospheres the reader is referred to reviews 8 and 17.

According to figure 1, the depth of the chromosphere is $\Delta r =$ $= R-R_*$, so that in the present model R characterizes the point where temperature decrease takes place.

Apart from the equation of state (T = constant) for $R_* < r < R$, the main difference in the model equations from the previous model[6] is the absence of the radiation pressure term in the momentum equation, as no molecules are expected to survive the high chromospheric temperatures. The equation can be written as

$$V\frac{dV}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM_*}{r^2} \tag{1}$$

where V, P and ρ are the gas velocity, pressure and density, respectively.

As discussed in reference 18, the flow equations in the isothermal case can be solved analytically, and for the so-called type 3 solution[18] ($dV/dr > 0$ at $r = r$ and $V > V_c$ for $r > r_c$) the velocity structure is given by

$$\left(\frac{V}{V_c}\right)^2 - \ln\left(\frac{V}{V_c}\right)^2 = 4\ln\left(\frac{r}{r_c}\right) + 4\left(\frac{r_c}{r}\right) - 3 \tag{2}$$

where the subscript c refers to the critical point, at which V equals the speed of sound

$$V_c = \sqrt{\frac{P}{\rho}} = \sqrt{\frac{kT}{\mu m_H}} \tag{3}$$

and r_c is equal to the critical radius

$$r_c = \frac{GM_*\mu m_H}{2kT} \tag{4}$$

where μ is the mean molecular weight.

4. RESULTS AND DISCUSSION

In the previous model[6], the derived mass loss rate implied that the gas is moving at $V \cong 3.3$ km/s at r/R 1. In the present work we assume that the gas acceleration up to this pointiscaused by chromospheric evaporation. It is then interesting to determine the chromospheric parameters compatible with this situation, that is, under which circumstances chronosphere evaporation would provide initial acceleration without appreciably disturbing the structure of the cool envelope. Therefore, we should look for chromospheric temperatures for which $\Delta r/R_\star << 1$, since in this case the changes on the physical parameters would be small. The chromosphere is then assumed to extend up to $V \simeq$ $\simeq 3.34$ km/s, where acceleration by radiation pressure on molecules takes over.

Figure 2 shows the chromospheric depth $\Delta r/R_\star$ as a function of the average temperature T. It can be seen that

$$\frac{\Delta r}{R_\star} < 1 \qquad (5)$$

for

$$T > 3800\ K.$$

On the other hand, for

$$T > 6500\ K \qquad (6)$$

$$\frac{\Delta r}{R_\star} < 0$$

that is, for $T > 6500\ K$ our assumption that the base of the chromosphere coincides witti the photospheric radius is not valid. Therefore, the average chromospheric temperature is given by

$$6500 \gtrsim T\ (K) \gtrsim 3800 \qquad (7)$$

if the general characteristics of the cool envelope are to be maintained. In other words, chromosphere hotter than about 6500 K would imply more substancial alterations on the envelope structure.

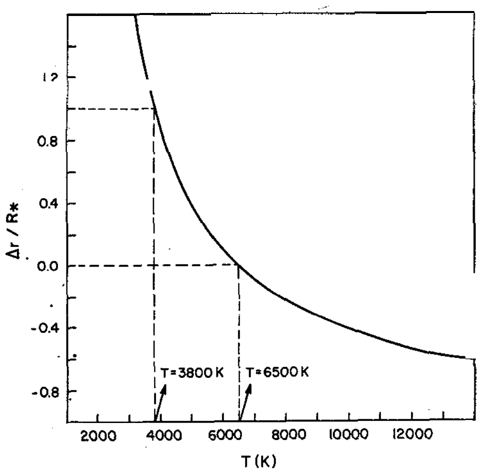

Fig.2 - Chromospheric depth ($\Delta r/R_*$) as a function of the average temperature of the chromosphere.

It is difficult to determine T better than given by (7) since the present model involves rather crude assumptions on the envelope structure. However, if the gas is assumed to be nearly at rest at the base of the chromosphere, T would be near the lower limit of (7), namely $T < 4000$ K. Naturally, the initial velocity cannot be exactly zero, since in our model continuous mass loss is assumed.

The average temperatures given by (7) are quite reasonable, in view of our discussion in Section 3. It should be kept in mind that the present model applies essentially to the cool, late M giants, for which available evidences indicate $T \lesssim 8000$ K. In conclusion, the presente of such a rather cool chromosphere would be compatible with mass loss by radiation pressure, providing in addition an initial pull at the base of the stellar envelope.

It is interesting to investigate the relationship between chromospheres and mass loss in greater detail, by considering a more varied set of stellar parameters. This is expected soon to become possible, as more data on chromospheric indicators on the HR diagram accumulate.

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