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ROLE OF NONTHERMAL VELOCITY FIELDS IN DETERMINING THE Hα WIDTHS IN SUPERGIANT CHROMOSPHERES

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ABSTRACT

We have performed radiative transfer calculations of the Hα line in spherically symmetric, expanding chromospheres to primarily explain the large widths of the line observed in late G and K supergiants. We have illustrated the role of various dynamical processes as well as that of opacity in determining the Hα width. We find that the Hα line profile is basically characterized by large optical depths and large Doppler broadening velocity. The calculations show that the existence of large microturbulence has to be invoked in the chromosphere to understand the observed widths.

Key words: radiative transfer: Hα line–chromosphere: late-type supergiants

1. Introduction

The Hα line is observed to be a very strong absorption feature in the chromospheres of G and K supergiants (Mallik 1982; Zarro and Rodgers 1983; Cram and Mullan 1985). Since in these stars the electron densities are low and the photoionization edge for the level $n = 2$ lies close to where the bulk of the radiation is, the Hα line is most likely photoionization dominated. The Hα line, therefore, does not relate to the specific distribution of densities and temperatures in the chromosphere. As a consequence, despite being strong and easily accessible, the Hα line and its formation in stellar chromospheres have been scantily studied. We shall demonstrate in this paper that the Hα line profile is actually rather sensitive to chromospheric conditions though differently from the way the collision-dominated lines are.

In Section 2 we describe the salient features of the Hα line that we have observed in about 20 G and K supergiants. We also describe the model we have adopted to study the formation of the Hα line in a cool supergiant chromosphere. Section 3 elaborates on the radiative transfer calculations done to explore the extent to which various dynamical processes in conjunction with opacity determine the computed Hα width. We also discuss these results in light of the observed characteristics of Hα absorption in our sample stars. This is followed by discussion in Section 4.

2. Observations and Theory

We have observations of about 20 late G and K supergiants in the Hα region obtained at a dispersion of 7 Å–10 Å mm^{-1} at the 40-inch (1-m) telescope of the VBO using the coudé echelle spectrograph with the image intensifier tube as the detector. These are described in detail in Mallik (1982). Table 1 gives the equivalent widths (EQWs) and the full widths at half-maximum (FWHMs) for these stars in columns (2) and (3). The EQWs range from 1.2 Å to 2.0 Å whereas the FWHMs from 2.0 Å to 3.0 Å which in terms of velocities are in the range from 90 km sec^{-1} to 140 km sec^{-1}. The Hα core reaches very deep; at the line center around 80% of the radiation is extracted out of the continuum. Cram and Mullan (1985) have shown from their LTE model photosphere calculations that the EQW of Hα in cool giants and supergiants (with $T_{\rm eff} = 4000$ K) does not exceed 0.25 Å. The above observations therefore imply that the bulk of the Hα absorption forms in the chromosphere with a large optical depth in that line. Also, the line minimum is shifted to the blue with respect to the line center. This

TABLE 1

Observational data and computed velocity fields for the program stars

star (1)	EQW Å (2)	FWHM Å (3)	estimated T_I(r) model (4)	ξ_t from T_{II}(r) model (5)	V_{exp} $kmsec^{-1}$ (6)
o^1 CMa	1.22	2.4	20	11	8-10
HD 56577	1.47	2.5	21	12	7-9
HD 137709	1.69	2.5	21	12	10-13
β Arae	1.60	2.6	22	13	≈22
λ Vel	1.66	2.6	22	13	13-17
HD 68553	1.51	2.6	22	13	≈35
σ CMa	1.72	2.6	22	13	11-15
33 Sgr	1.67	2.6	22	13	6-7
η Per	1.84	2.8	24	15	8-10
ε Gem	1.77	2.8	24	15	9-11
ξ Cyg	1.93	2.8	24	15	≈10
ε Peg	1.80	2.8	24	15	9-12
ζ Cep	1.81	2.9	25	16	15-20
HD 91056	1.98	2.9	25	16	≈9
HD 4817	1.81	3.0	26	17	13-17
HD 89388	1.79	3.0	26	17	≈26
HD 216946	1.83	3.0	26	17	≈19

indicates that the chromospheres must be expanding.

Both theory and observations suggest that the supergiant chromospheres are geometrically extended (Hartmann and Avrett 1984; Goldberg *et al.* 1982; Drake and Linsky 1986; Hebden, Eckart, and Hege 1987; Carpenter, Brown, and Stencel 1985). They extend up to six or eight times the stellar radius. Extensive observations exist to also suggest that the temperature rises in the chromosphere from a minimum around 3500 K–4000 K to as high as 8500 K or even higher in the outer layers (Brown and Carpenter 1984; Newell and Hjellming 1982; Wischnewski and Wendker 1981). So for a proper interpretation of the observed characteristics, we solve for radiative transfer in the Hα line in spherically symmetric, expanding, nonisothermal chromospheres. The relevant details are described in Mallik (1982, 1986) and Mallik and Mallik (1988). The line-forming region is divided into a number of shells starting from R_*, the stellar radius to an outer radius R_{max} with given velocity $V(r)$, density $n(r)$, and temperature $T(r)$ distributions across it. Because the line core is blueshifted, we assume that the velocity increases outward up to V_{max} at R_{max}. For simplicity, we assume a linear gradient: $V(r) \propto r$. Therefore, to satisfy the equation of continuity, $n(r) \propto r^{-3}$ in a spherically symmetric steady flow. We have tried several plausible temperature structures. These are shown in Figure 1 of Mallik and Mallik (1988). We have used two of them in the present context. $T_{\rm I}(r)$ gives a linear increase of kinetic temperature T with log r from 3400 K at R_* to 8500 K at R_{max}, similar to that adopted by Cram and Mullan (1985). $T_{\rm II}(r)$ follows that of Dupree, Hartmann, and Avrett (1984), with a steep linear increase to 8000 K within a short distance from R_* followed by a broad plateau extending over the rest of the region, the maximum T being 8500 K. These are not based on any theoretical modeling nor detailed observations. However, the above assumed outward rise roughly reflects the consequences of nonradiative heating.

The boundary conditions of the problem are that a Planckian radiation field characterized by a radiation temperature $T_{\rm R}$ = 4000 K is incident on R_* and that there is no radiation incident on R_{max}. Radiation damping contributes little to the width of Hα. Also, collisional broadening is negligible in the low-density atmosphere of supergiants. We therefore assume the Hα line to be Doppler broadened with its profile of the form

$$\phi(x,\delta) = \frac{1}{\delta\sqrt{\pi}} e^{-x^2/\delta^2} ,$$

where

$$x = \frac{\nu - \nu_0}{\Delta\nu_{\rm D}^{\rm ref}}$$

and

$$\delta = \frac{\Delta\nu_{\rm D}(r)}{\Delta\nu_{\rm D}^{\rm ref}} .$$

x is the dimensionless parameter. $\Delta\nu_{\rm D}(r)$ is the Doppler width at a radial point r given by

$$\Delta\nu_{\rm D}(r) = \frac{\nu_0}{c}\sqrt{\frac{2kT(r)}{m} + \xi_t^2} ,$$

where $2kT(r)/m$ is the thermal term and ξ_t^2 is the nonthermal term. $\Delta\nu_{\rm D}^{\rm ref}$ refers to the value at R_{max}.

We have used the formulation of Vernazza, Avrett, and Loeser (1973) suitably modified for a two-level atom with continuum to describe the population of level 2 where we have relaxed the assumption of radiative detailed balance in Lyman-α and the Lyman continuum. Consequently, to solve for Hα transfer, one has to explicitly solve for the transfer of Lyman continuum including the effects of escape of Lα photons. Detailed calculations have shown that there is a substantial change in the distribution of populations in levels 1 and 2 and of the ionization of hydrogen relative to the situation where the condition of radiative detailed balance holds. The ionization decreases significantly and n_1 is drastically overpopulated. These effects are more drastic near the top of the chromosphere. Also, n_2 is overpopulated except at the top where it declines substantially. The Hα line profiles computed from the above model could not, however, reproduce the large observed widths even with ξ_t as high as 15 km sec^{-1}. In fact, the above computations vindicate the fact that the Hα line being photoionization dominated does not respond to the local changes in the population densities of various levels. The scattering term of the Hα line source function is a much more dominant term than the thermal term. A look at the scattering integral

$$J(r) = \int_{-\infty}^{\infty}\int_{-1}^{1} \phi(x,r)I(x,\mu,r)d\mu\, dx$$

tells us that it directly depends on the absorption profile function $\phi(x,r)$ and the radiation field $I(x,\mu,r)$ which are determined by the thermal and nonthermal processes and the optical depth in the chromosphere, respectively. The large discrepancy between the observed and the computed widths led us to investigate the crucial role the above parameters play in determining the widths.

3. Analysis and Results

We first performed transfer calculations to determine the effect of opacity broadening assuming that the profile function has only the thermal term

$$\sqrt{\frac{2kT(r)}{m}} .$$

Both the temperature distributions $T(r) = T_{\rm I}$ and $T_{\rm II}$ as defined earlier were tried. A range of V_{max} was also chosen to describe the expansion of the chromosphere. Our calculations show that at low optical depths τ, FWHM is small, as expected, and it grows steadily as τ is increased until a saturation point is reached. For $T_I(r)$, the maximum FWHM $= 4.8\Delta\nu_D$; the corresponding $n_H(R_*) = 5 \times 10^{11}$ cm^{-3} and $\tau = 5 \times 10^4$ with $R_{max} = 5\,R_*$, and for $T_{II}(r)$, the maximum FWHM $= 6.7\,\Delta\nu_D$ with $n_H(R_*) = 5 \times 10^{10}$ cm^{-3} and $\tau = 1.6 \times 10^4$ and 3.1×10^4, respectively, for $R_{max} = 5\,R_*$ and $2\,R_*$.

If thermal broadening alone were to account for the Hα width, then equating the observed widths to the limits obtained above would lead to $T \geq 60{,}000$ K. Such high values seem highly unrealistic for chromospheres that form Hα. The nonthermal velocity fields must be present in these atmospheres. Following Cram and Mullan (1985) one can estimate the contribution of the nonthermal broadening by equating the upper limit of opacity broadening derived above with the observed FWHMs and then quadratically removing the thermal contribution. This leads to a lower limit to the widths of 20–26 km sec^{-1} for $T_I(r)$ and 12–17 km sec^{-1} for $T_{II}(r)$ caused by nonthermal effects in the Hα profiles of stars under study. The derived lower limits to ξ_t are displayed in columns (4) and (5) of Table 1.

The extent to which stellar winds influence the widths can also be estimated. We find that every 10 km sec^{-1} increase in V_{max} results in an increase of FWHM by 2–4 km sec^{-1}. Since the observed line-core displacements constrain V_{max} to ≤ 40 km sec^{-1}, expansion does not explain the large observed widths either. Column (6) of Table 1 gives the value of V_{max} obtained from the fits with the computed profiles. If the large widths were due to macroturbulence, FWHM would increase without a parallel increase in the EQW. However, the observations suggest to the contrary. Figure 1 shows the plot between the two for about 18 stars. Although the scatter is quite large, there is a clear trend of FWHM increasing with higher EQW. The above exercise thus convinced us that nonthermal velocity fields probably in the form of microturbulence give rise to the large widths of the Hα line.

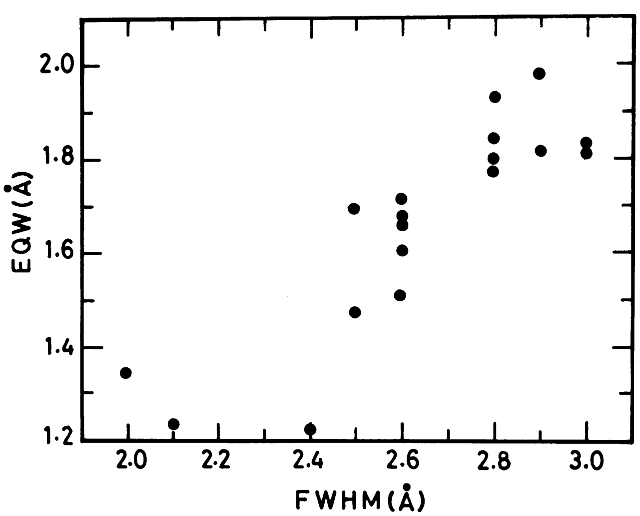

FIG. 1–Correlation between the EQW(Å) and the FWHM(Å) for the stars under study.

We recomputed the Hα line profiles incorporating both the thermal and the nonthermal terms in the profile function. Each such profile is characterized by an integrated line center optical depth (or $n_H(R_*)$), the extent of the chromosphere $\Delta R = R_{max} - R_*$, the rms nonthermal velocity ξ_t and given velocity and temperature distributions. Computer runs were carried out for a variety of the above parameters in order to cover the range of the observed characteristics of the line profiles. Figures 2a–f show the superposition of several such theoretical profiles over the observed profile for six stars. Details of the fits are given in Table 2. Profiles with $T_I(r)$ fit the observed widths quite well with the estimated ξ_t of 20–25 km sec^{-1}. However, profiles with $T_{II}(r)$ did not fit the observed with the estimated range of 12–17 km sec^{-1} in ξ_t. Increasing τ or V_{max} did not change the situation either. On the basis of a large number of numerical runs, we arrived at the conclusion that the widths could only be matched with ξ_t as high as 20–25 km sec^{-1}, even for $T_{II}(r)$. Our calculations thus reinforce the idea that the large Hα widths can only be reproduced by the substantial nonthermal velocity fields prevailing in cool chromospheres irrespective of the temperature structure chosen and in spite of large optical depths. They are, in fact, higher than the thermal motion of hydrogen atoms in these atmospheres which lie between 8–11 km sec^{-1} for the temperature structures chosen.

4. Discussion

Our emphasis has been on explaining the large observed widths of Hα in cool supergiants. No attempt has been made to do a point-to-point profile fitting. Better fits with the observed profiles could perhaps be obtained by tuning parameters like $n_H(R_*)$ or, in other words, τ, V_{max}, $T(r)$, etc. more finely. A different velocity law that fits the shape of the observed profiles better could be tried. However, it is unlikely that any of these would change the widths tangibly. We conclude, therefore, that within the framework of the chosen model, the shape and the width

TABLE 2

Parameter fits for a sample of program stars

	Model	T_I(r)		Model	T_{II}(r)	
Star	$n_H(R_*)$ (cm^{-3})	ξ_t ($kmsec^{-1}$)	V_{max} ($kmsec^{-1}$)	$n_H(R_*)$ (cm^{-3})	ξ_t ($kmsec^{-1}$)	V_{max} ($kmsec^{-1}$)
ϵ Peg	5×10^{10}	25	10	5×10^{9}	20	10
η Per	10^{11}	25	10	5×10^{9}	20	10
λ Vel	5×10^{10}	25	10	10^{9}	25	10
HD 137709	5×10^{10}	20	20	10^{9}	25	20
HD 91056	5×10^{10}	25	10	5×10^{9}	20	10
σ CMa	5×10^{10}	20	10	10^{9}	25	10

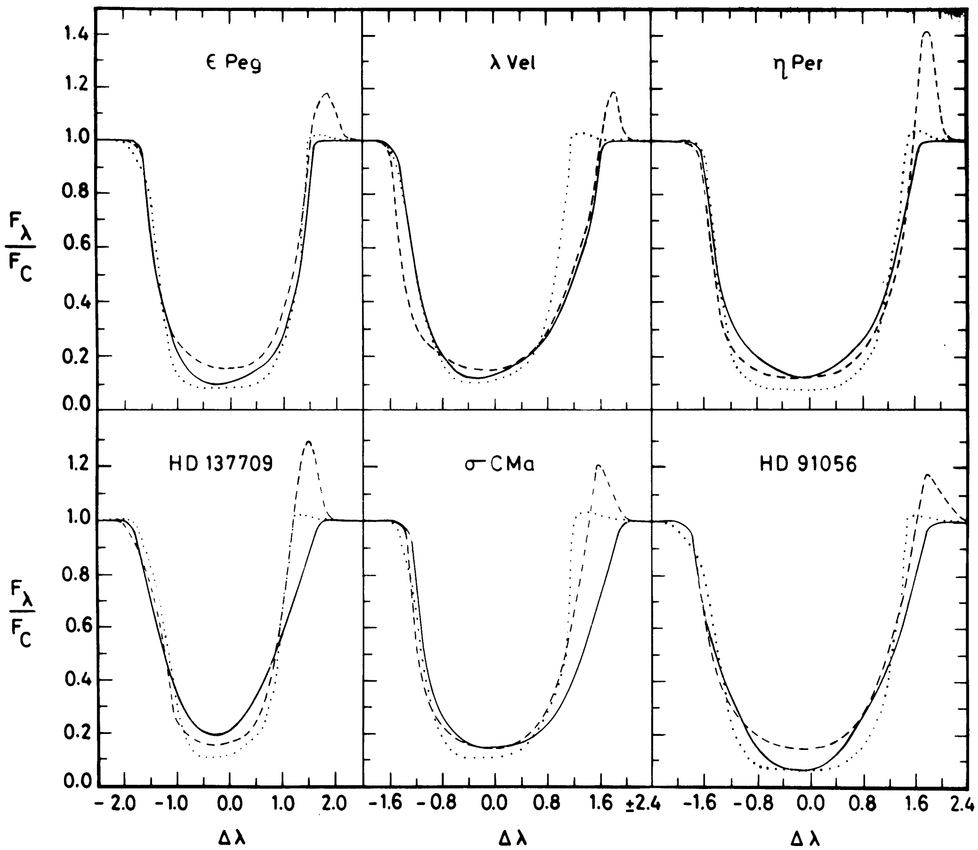

FIG. 2a–f–Superposition of the observed profile for six stars over the theoretical profiles computed for various models described in the text (see Table 2). ____, observed line; - - - -, theoretical with $T_{\rm I}(r)$; ...., theoretical with $T_{\rm II}(r)$. $R_{max} = 5\,R_*$.

of the Hα line are basically dictated by a large optical depth and a large value of the nonthermal velocity. The expansion of the chromosphere also contributes to the broadening; the amount is, however, limited by the observed blue displacement of the line core. Cram and Mullan (1985) in their analysis of Hα in the chromospheres of cool stars also estimated the nonthermal velocity amplitudes to be as large as ≈ 25 km sec^{-1}. Hartmann and Avrett (1984) concluded from their analysis of the chromospheric profiles of Ca II, Mg II, and Hα in α Orionis that the most probable turbulent velocity reached values as high as 22 km sec^{-1} in the outer layers. There are very few direct observations to yield information on the turbulence in the supergiant chromospheres. In ζ Aurigae-type systems, where the primary is usually a K supergiant, analyses of the spectral line data during the secondary eclipse have yielded rather large stochastic motions between 10–20 km sec^{-1} (Wright 1980; Linsky 1985; Che, Hempe, and Reimers 1983).

In the present work we have discussed the effect of a variable Doppler width on line formation due to a variation of the temperature alone in the chromosphere. It is appropriate also to include the depth dependence of microturbulence in the study of the Doppler width gradient. There is some indication that turbulence increases with height in the chromospheres of giants and supergiants (Jordan and Linsky 1987). Fosbury (1973) discussed the Ca II K and Mg II k width-luminosity relations in giants and supergiants and observed that the Mg II emission widths were systematically higher. If the widths are attributed to nonthermal velocity broadening, then, since the Mg II emission forms higher in the chromosphere than the Ca II emission, this would imply an outward increase in nonthermal velocities. More extensive IUE data on the Mg II k emission widths have confirmed Fosbury's observation. The IUE satellite has further been utilized to study the chromospheric structure of ζ Aur systems during eclipse. Extensive observations at different phases of the secondary eclipse have indicated that nonthermal velocities in the primary K supergiant chromosphere increase with height (Schröder 1985). Hartmann and Avrett (1984) also used a variable turbulent velocity parameter in their study of α Ori. In a simple analytical approach, Zarro (1984) equated ξ_t to the local isothermal sound speed and let it increase in proportion to the rising temperature in the chromosphere. Since ξ_t enters as a square term under the root in the expression for $\Delta\nu_{\rm D}$, $\Delta\nu_{\rm D}$ is more sensitive to its variation than it is to that of temperature. Preliminary calculations of line profiles with an ad hoc depth-dependent microturbulence reveal that the profiles change drastically in response to the variation in ξ_t. It is hoped that further observations and modeling of the ζ Aur-type systems at different phases of the secondary eclipse would provide valuable insights into the velocity and temperature structures of the chromospheres of K supergiants. Such inputs would lead to significant improvement in the modeling and interpretation of the Hα line.

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