Arcturus

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MODELING LINES FORMED IN THE EXPANDING CHROMOSPHERES OF RED GIANTS

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ABSTRACT. In this paper, I discuss the application of radiative transfer techniques to the study of the physical conditions in the extended, expanding chromospheres of cool giants and supergiants in the spectral ranges K2-M5 (for luminosity type III stars) and G0-M5 (for supergiants). The important diagnostic feature indicating the outflow of chromospheric material in such stars is the presence of blue-shifted absorption components in the h and k resonance lines of Mg II. To model these lines, I use a spherically symmetric co-moving frame solution of the equation of radiative transfer that takes proper account of partial redistribution effects. I give, as a specific example, my preliminary results of the study of the Mg II lines in the K2 III star α Boo.

1. INTRODUCTION

There is a growing body of evidence that late-type giants and supergiants in a wide region of the H-R diagram have geometrically extended, outflowing chromospheres (Stencel 1982; Carpenter et al. 1985). For MK class III stars, the spectral range is approximately from K2 to M5, with giants earlier than K2 having geometrically thin chromospheres and coronae, and giants later than M5 having cool, dusty winds. For MK class I and II stars, the spectral range of stars showing this phenomenon is broader, extending perhaps from G0 to M5. The two basic observational techniques available to study these "warm" (5×10^3 K $\lesssim T_e \lesssim 10 \times 10^3$ K) winds are (a) observations in the radio continuum at centimeter wavelengths and (b) observations of resonance lines of dominant stages of ionization of abundant atoms, e.g., Mg II h and k lines at λ2796 Å and 2803 Å, Ca II H and K lines at λ3933 Å and λ3968 Å, Mg I λ2852 Å.

The winds of K2-4.5 III stars are particularly difficult to study because only the Mg II lines show the blue-shifted absorption components indicating outflow, presumably because the mass loss rates are so small ($\dot{M} \lesssim 10^{-10}$ $M_\odot$ yr^{-1}) that the opacity in the wind for the other lines such as Ca II H and K is insufficient to produce similar

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features. Also, only one such star (α Boo, K2 IIIp) has been detecte as a weak radio continuum source (Drake and Linsky 1984), indicating the limited applicability of the first approach for determining the physical parameters in the wind.

Analysis of the profiles of the Mg II h and k lines in a particular cool star should in principle provide specific information on both the mass flux of the wind and the variation with radius, r, o quantities such as the electron temperature, T_e, and the density, ρ, from the photosphere up to that point in the wind where the lines become optically thin. In practice, it is difficult to "deconvolve" this information uniquely from one observed line profile, and any physical quantities inferred from such an analysis, while "sufficient to reproduce the observed profile may not "necessarily" be the actual ones. Thus, such an analysis should be cross-checked as much as possible with all other pertinent information known about the chromosphere of the star being studied.

If reliable parameters can be established for cool giant winds, however, the resultant information would be valuable in helping t discriminate between the various mechanisms that have been propos for generating such winds (for example, by comparison of theoretical and observationally inferred $T_e(r)$ distributions). Another important application would be in the field of stellar evolution: the observationally inferred mass loss rates of stars in the red giant phase can be compared with the integrated mass loss rates deduced from comparison of theoretical and observational cluster diagrams, and could provide a new constraint or test on the validity of the present evolutionary calculations.

In Sec. 2, I discuss how the previously deduced physical conditions in the Mg II line formation region of cool giants, and the physics of radiative transfer in these resonance lines, determine the particular analytical tools needed to study them. In Sec. 3, I apply these techniques to the Mg II emission lines of the K2 IIIp star α Boo, and, in the final section, I present the conclusions of this study and some suggestions for future work in this area.

2. RADIATIVE TRANSFER METHODOLOGY ADOPTED FOR THIS STUDY

The proper method for solving a line radiative transfer problem in a moving atmosphere is clearly dependent on both the macroscopic proper ties of the wind and on the atomic properties of the particular line being analyzed. The winds of K and M giants of luminosity class III are known to have the following properties:

* (i) The winds are not isothermal -- they originate in the lower chromosphere where $T_e \gtrsim T_{eff}$, further out the temperature reaches a maximum value of $\lesssim 1.5 \times 10^4$ K, and then at greater distances from the star (in the M giants) the temperature must decrease to $\lesssim 5 \times 10^3$ K.

* (ii) The winds have maximum outflow velocities, V_{wind}, that are typically in the range 10-50 km s^{-1}.

*(iii) The microturbulence, V_{Dopp}, deduced for the chromospheric lines is of order 5-20 km s^{-1}.

* (iv) The chromospheres extend out to at least a few stellar radii.

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The low ratio of systematic to random velocities, which is commonly true for the winds of cool giants, means that approximate radiative transfer solutions of the Sobolev type (valid in the high velocity limit) will not be reliable, and that an exact method must be used. As discussed by Drake and Linsky (1983a), for these cases it is also not appropriate to assume complete frequency redistribution in the radiative transfer for a resonance line, and the correct redistribution function should be used, viz.:

$$R(\nu',\nu) = \gamma \, R_{II}(\nu',\nu) + (1-\gamma)\, \phi_\nu \phi_\nu' \quad ,$$

where I have used the standard notation [cf. Mihalas 1978, eq. (13-72)].

I have therefore adopted a spherically symmetric co-moving frame (CMF) technique for the radiative transfer, based on an original program kindly provided by Paul Kunasz, and modified it to include partial redistribution of this particular type (see Drake and Linsky 1983a for further details). I have used a two-level atom to represent the upper and lower level of the resonance line.

I have used angle-averaged redistribution functions in this analysis, but as Milkey et al. (1975) point out, this approximation may be inaccurate for the case of extended chromospheres with velocity fields. To the best of my knowledge, no detailed wind model calculations have yet been done using the full angle-dependent partial redistribution functions to verify this supposition. Another limitation of the particular CMF formulation used is that it can correctly handle only monotonic velocity laws such as accelerating outflows, but this restriction is probably not too important for this particular study.

3. MODELING THE Mg II k LINE OF ARCTURUS

I have adopted a semi-empirical approach in applying the techniques discussed in Sec. 2 to fitting an observed Mg II profile. I have not attempted to adopt $T_e(r)$ and $V_{wind}(r)$ laws predicted by specific theoretical wind models as Hartmann and Avrett (1984) did in their study of the wind of α Orionis (M2 Iab). For the photosphere and temperature minimum region of the atmosphere of α Boo where $V_{wind} \ll V_{Dopp}$, I have adopted the Ayres and Linsky (1975) plane parallel model atmosphere. This assumption has little effect on the modeling of the Mg II k line emission core. For the outer region of the chromosphere where the outflow velocity is significant, I choose on a trial and error basis the following quantities: $T_e(r)$, $V_{wind}(r)$, $V_{Dopp}(r)$, and $\dot{M}$. (The density $\rho(r)$ is implicitly fixed, given $\dot{M}$ and $V_{wind}(r)$, by the equation of continuity.) Since all of these parameters help determine the resultant line profile, it is difficult to determine the actual atmospheric structure uniquely and more than one valid solution that fits the observed profile well might exist.

Given this input model atmosphere, the radiative transfer in the specified line is carried out in the co-moving frame (CMF) or fluid frame, and the emergent line profile calculated after a transformation into the observer's frame (Mihalas et al. 1976). The theoretical line profile of say, the k line, is then compared with the observed line profile (see Fig. 1), and the nature of the discrepancies between the two usually helps one to produce a new "improved" set of input parameters. This procedure is repeated for many iterations until "optimal" agreement is reached between the two profiles. Because of the number of free parameters and the wide range of parameter space that has to be explored, this iterative process requires a large amount of time and the decision as to when the "optimal" or best fit has been reached is clearly subjective. Since this process may not lead to unique atmospheric parameters, I believe that it is crucial to compare the predicted properties of the "optimal" fit model(s) with as many other observational constraints as possible.

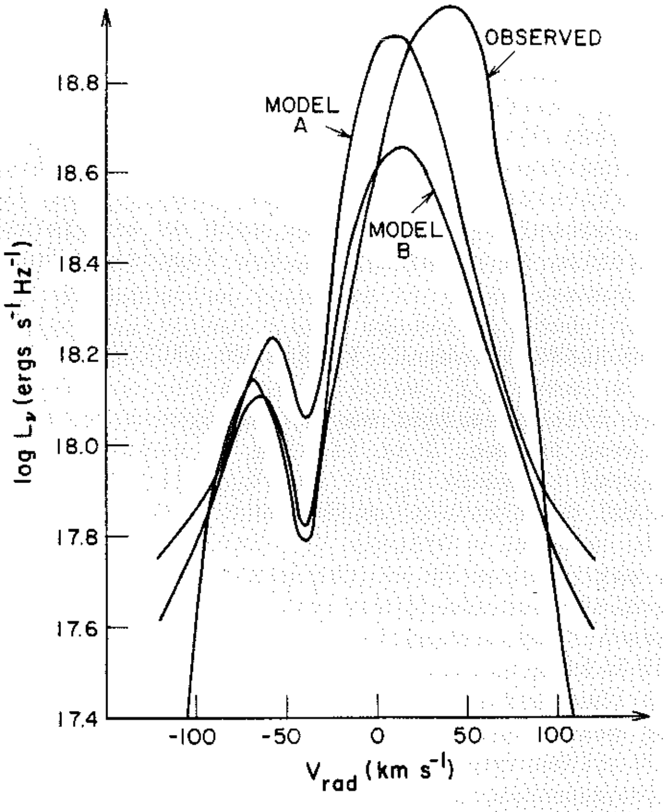

Figure 1. The observed profile of Mg II K in α Boo is compared with two calculated profiles. The ordinate is monochromatic luminosity in ergs s^{-1} Hz^{-1} and the abscissa is radial velocity relative to the stellar photosphere in km s^{-1}. The models are discussed in the text.

In Figure 1, I compare the observed Mg II k profile in α Boo with that predicted by two model atmospheres. The agreement is not perfect: Model A has about the right peak emission but the blue-shifted absorption is weaker than is observed, while model B fits the absorption well but underestimates the peak emission by a factor of 2. In Figure 2, the temperature and velocity structure of model B is shown. The other properties of this particular model atmosphere can be summarized as follows:

(i) The wind velocity and electron temperature climb steeply to their maximum values of 40 km s^{-1} and 8400 K, respectively, in a fairly short distance above the photosphere.

(ii) There is a broad high temperature plateau with $T_e \gtrsim 7 \times 10^3$ K extending from 1.2 to ~13 r_*.

(iii) There is a region further out, extending from 13 to 50-100 r_*, where the temperature is rather cooler ($T_e \sim 5 \times 10^3$ K).

(iv) The mass loss rate is 2×10^{-10} $M_\odot$ yr^{-1}, and the ionization fraction of the outer atmosphere is about 50%.

(v) The maximum microturbulence reached is 5 km s^{-1}.

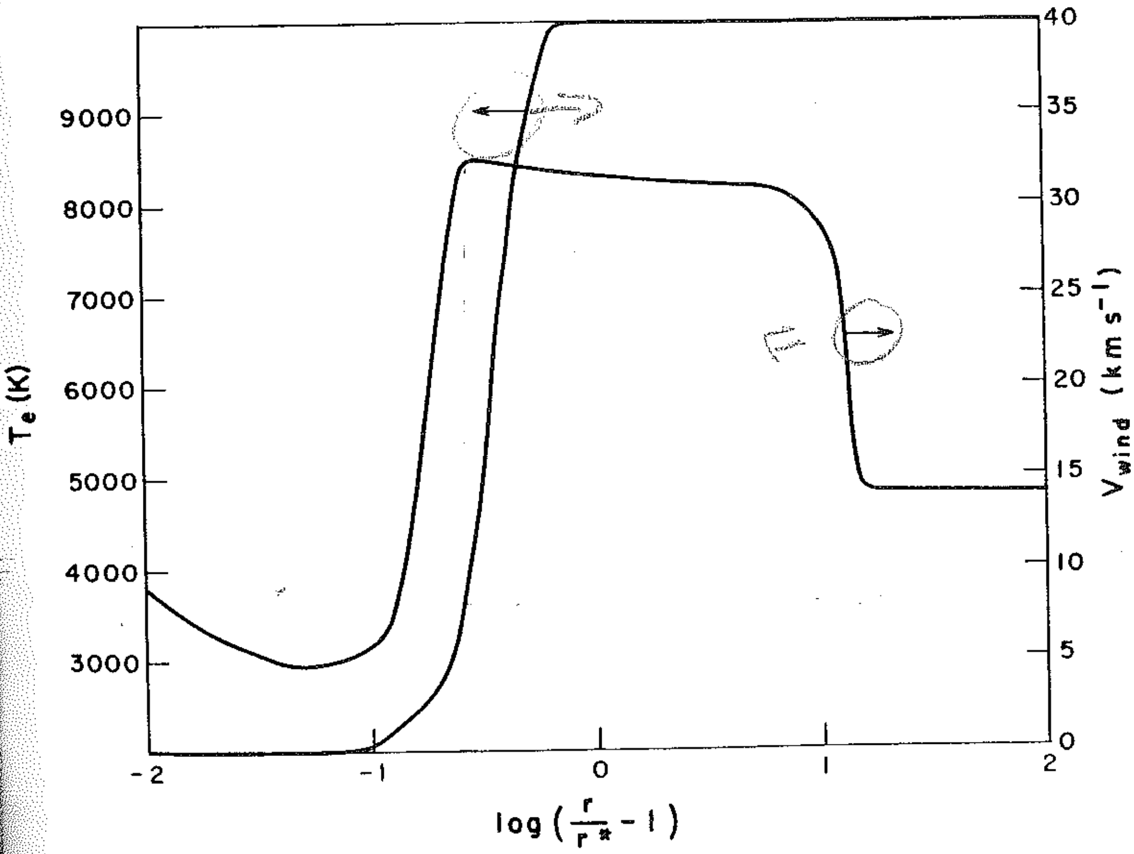

Figure 2. The wind velocity and electron temperature for Model B are shown as a function of radial distance above the photosphere (see text).

The major difference between Model B and Model A is that the latter has an even more extensive high temperature plateau region extending as far as 35 r_* (required to produce the stronger Mg II peak emission of this model). Specific predictions that can be made based on Model B are:

(i) The angular size of Arcturus in the Mg II k line is large: assuming a photospheric angular diameter of 0".021, the predicted size of α Boo in the integrated Mg II emission is ~0".27.

(ii) The free-free emission from the ionized wind of α Boo should make it a radio continuum source of ~0.4 mJy at 6 cm.

(iii) The angular size of Arcturus imaged in the blue absorption component of Mg II k is ~1".

The only one of the above predictions that has been tested to date is that α Boo should be radio source: Drake and Linsky (1983b) have detected α Boo as a 0.25 mJy source at 6 cm, in good agreement with the predicted value. The remaining predictions should be easily verifiable or disproven by the Faint Object Camera on Space Telescope.

An independent estimate of the chromospheric temperature can be obtained from the ratio of the C II resonance and intersystem lines. Brown and Carpenter (1984) estimated $\langle T_e \rangle \simeq 8 \times 10^3$ K (±500 K) for α Boo, which is also consistent with the models discussed above. Using the same PRD program, I also plan to calculate the Lyman-α profile for α Boo and to compare it with the observed profile (e.g., McClintock et al. 1978). Although Lyα is strongly affected by both interstellar absorption and geocoronal emission, any realistic Mg II model atmosphere should be able to reproduce approximately the observed Lyα strength and shape.

One final property of these models is that the line profiles calculated assuming CRD are nearly the same as those shown in Fig. 1 (where PRD is assumed). This is presumably due to the fairly high V_{wind}/V_{Dopp} ratio in these particular models. It may also be due in part to the Gaussian smearing by 25 km s^{-1} FWHM that has been performed on the theoretical profiles in order to reproduce the instrumental resolution of the observed IUE profile.

4. SUMMARY

I have described a technique for modeling the chromospheric lines of late-type stars and applied it to the K2 IIIp giant α Boo. The models which come closest to reproducing the observed Mg II k profile are not inconsistent with other evidence available concerning the mass flux and temperature of the expanding chromosphere of this star. However, additional observational evidence is still needed for complete verification.

As for future directions of research, I think that it would be fruitful to apply this technique to later type giants like α Tau (K5 III) or β And (M0 III), where there are additional lines showing evidence for expansion at chromospheric temperatures, and there will thus be much tighter constraints on any model atmosphere. I also aim to compare my best fit α Boo models with the atmospheric structure predicted by theoretical models of the winds from the stars, e.g., the Hartmann and MacGregor (1980) Alfvén-wave driven winds. Finally, it would be most valuable as a consistency check, if two independent groups were to model the same star using these techniques. Any differences between the "best-fit" model atmospheres would provide invaluable insight as to the reproducibility of these techniques.

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