THE OUTER ATMOSPHERES OF LATE-TYPE GIANT STARS

P.G. Judge

Department of Theoretical Physics, Oxford University, 1 Keble Road, Oxford, OX1 3NP.

ABSTRACT

Results of recent work with IUE on the structure of the outer atmospheres of late-type giant stars are summarized, based on empirical constraints derived from emission lines in α Boo (K2 III), α Tau (K5 III) and β Gru (M5 III), observed with deep exposures in the high resolution mode of IUE. These stars have IUE spectra typical of giant stars on the "wind" side of the "corona-wind division" in the HR diagram.

Particular attention is paid to the structure of the emitting regions, including densities, temperatures, inhomogeneities, geometric extents and velocity fields. Comparisons are made with earlier chromospheric models and with other spectroscopic work, and trends with stellar parameters are examined. Finally, the implications of this work for modelling the winds of red giants are discussed.

Keywords: Cool stars, UV spectroscopy, chromospheres, empirical constraints.

1. INTRODUCTION

Recently empirical constraints on the outer atmospheric structures of three typical late-type giant stars have been derived (Refs. 1, 2). In the present paper the major results of this work are summarized with particular emphasis on: (a) methods and some important limitations, (b) results for individual stars, (c) trends of these results with the fundamental stellar parameters, (d) comparisons with constraints from other observations, and (e) implications for theoretical and semi-empirical modelling of the outer atmospheres. For more complete details the reader is referred to Refs. 1, 2.

The stars under study and their adopted fundamental parameters are listed in Table 1. These stars have IUE spectra which are typical of the "non-coronal" stars, i.e. stars lying to the right of the well-known "corona/wind division" in the HR diagram. The division lies near KO for luminosity class III stars (see, for example Ref. 3). Typically such stars have no evidence for material at solar transition region (>2x10^8 K) or coronal (10^7 K) temperatures, and instead possess cool, relatively massive, low-velocity winds (e.g. Ref. 4).

The work reported here summarizes the most detailed and complete quantitative study of the IUE spectra of individual stars in this highly populated region of the HR diagram. Prior to this study little quantitative spectroscopic work was done (Refs. 5-8) to follow the earlier semi-empirical modelling efforts of Linsky and colleagues (Ref. 9) on these stars.

2. DATA, METHODS AND LIMITATIONS.

The basic data used to derive constraints on the atmospheric structure are fluxes and profiles of emission lines observed with IUE at high resolution. Much of the data has been obtained with

<table>
<thead>
<tr>
<th>Name</th>
<th>Sp. Type</th>
<th>Teff (K)</th>
<th>R_*/R_0</th>
<th>log g</th>
<th>[Fe/H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>α Boo^a</td>
<td>K2 III</td>
<td>4225±100</td>
<td>27±1.6</td>
<td>1.62±0.2</td>
<td>-0.56±0.07</td>
</tr>
<tr>
<td>α Tau^b</td>
<td>K5 III</td>
<td>3970±100</td>
<td>46±4</td>
<td>1.3±0.3</td>
<td>0.0±0.2</td>
</tr>
<tr>
<td>β Gru^c</td>
<td>M5 III</td>
<td>3500±200</td>
<td>180</td>
<td>0.4</td>
<td>0</td>
</tr>
</tbody>
</table>

a) For sources see ref 1.
b) For sources see ref 2.
c) Metallicity.

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deep double-shift exposures in collaboration with Linksky and colleagues at Boulder, Colorado. See Ref. 1 and 2 for lists of the images used.

The methods are based on emission-measure analyses, column density measurements from opacity-sensitive line ratios, linewidth measurements and measurements of electron densities from CII line ratios and emission measures. Details may be found in Ref. 1, and a concise description, not repeated here, is given in Ref.10. The emission lines used and the associated diagnostic information derived from them are listed in Table 2.

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda_{\text{approx}} [\AA] )</th>
<th>Diagnostic information</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>1657/1993</td>
<td>( N_H )</td>
</tr>
<tr>
<td>CII</td>
<td>2325</td>
<td>( n_e, E_M, \text{FWHM} )</td>
</tr>
<tr>
<td>CII</td>
<td>1335</td>
<td>( E_M )</td>
</tr>
<tr>
<td>CIII</td>
<td>1908</td>
<td>( E_H )</td>
</tr>
<tr>
<td>OI</td>
<td>1302/1641</td>
<td>( N_H )</td>
</tr>
<tr>
<td>Mg II</td>
<td>2800</td>
<td>( E_M )</td>
</tr>
<tr>
<td>Al II</td>
<td>2669</td>
<td>( E_M, \text{FWHM} )</td>
</tr>
<tr>
<td>Si II</td>
<td>1670</td>
<td>( E_H ), upper limit</td>
</tr>
<tr>
<td>Si II</td>
<td>1808,1816</td>
<td>( E_M )</td>
</tr>
<tr>
<td>Si III</td>
<td>1892</td>
<td>( E_M, \text{FWHM} )</td>
</tr>
<tr>
<td>S I</td>
<td>1900,1914</td>
<td>( N_H, \text{FWHM} )</td>
</tr>
</tbody>
</table>

Using solely UV emission lines as diagnostics of atmospheric structure necessarily limits the information which can be derived: the constraints discussed here apply only to the regions where most of the line fluxes are created. Regions with small emission measures (e.g. warm, extended but tenuous regions) or dense, cool regions (with \( T_e < T_{\text{eff}} \)) remain unconstrained by this analysis because they would not contribute substantially to the total line fluxes. (Other diagnostic techniques which have shed light on such regions are discussed below).

There are important reasons for restricting the present analysis to integrated fluxes rather than attempting to model profiles of optically thick lines: line profile modelling, although potentially a very powerful tool for diagnosing velocity fields and regions where the emission lines are scattered, requires a complete empirical analysis since one must make ab-initio assumptions about the structure of the emitting regions (e.g. spherical symmetry). The present author believes that it is important first to obtain purely empirical constraints, where possible, before proceeding with more sophisticated semi-empirical models based on possibly incorrect assumptions.

Further limitations may also be important. Since there is currently no direct way of obtaining spatial information, the constraints apply to a spatially 'averaged' emitting region spanning potentially inhomogeneous conditions. In addition the constraints apply to a 'time-averaged' region: although timescales for larger scale flows (or 'winds') are substantially longer than atomic timescales (Ref. 1), smaller timescales of flows associated with shocks, if they exist, could affect the interpretation of the emission lines (Refs. 11, 12). Such effects, ignored here, require further theoretical investigations.

3. RESULTS

Before discussing similarities and differences in the constraints for the three stars, results for a Tau are summarized (see Ref.2 for details).

3.1 Results for a Tau

Fig. 1 shows the observed CII lines in a Tau together with Gaussian fits which were used to derive linewidths and fluxes, yielding \( N_H = 10^{14.5} \text{cm}^{-2} \) from the flux ratios. Using this value of \( N_H \) and other appropriate excitation conditions, the emission measure loci in Fig.2 were derived from the observed fluxes and atomic models described in Ref.1. These are shown only

\( \text{a} \) Optical depth in the emission line

\( \text{b} \) \( N _H = N _H \) is the hydrogen column density from opacity sensitive line ratios; \( E _M = N _H \) is the emission measure, \( n _e \) the electron density, \( \text{FWHM} \) the linewidths used directly to determine non-thermal motions.

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to illustrate the procedures, limited space does not permit a fuller discussion.

By careful interpretation of the emission measure loci, column densities, electron densities and linewidths one arrives at the following conclusions for a Tau: (a) Atomic processes must be carefully examined when interpreting emission lines formed when $N_e$ is as low as $10^{-5}$ cm$^{-3}$. Radiative processes involving H Ly$\alpha$ are vitally important in determining the CI/ClI and SiII/SiIII ion balance; (b) A self-consistent set of constraints is obtained only when these processes are taken into account; (c) The self-consistency confirms the reliability of recently computed collision strengths; (d) The positively detected emission lines can be accounted for by a predominantly neutral emission region with $T_e < 10^{4}$ K. If marginal detections of Si III] and C III] lines are confirmed then material with $T_e < T < 5 \times 10^{6}$ K may exist with an emission measure relative to chromospheric material an order of magnitude smaller than that present in the quiet sun; (e) linewidths of C III] show that non-thermal pressures due to the passage of waves are less than 6 times thermal pressures (near $T_e = 7000$K); linewidths of other lines indicate non-thermal pressures $\leq$ twice thermal pressures (near $T_e = 5000$K), these values provide dynamical constraints on the geometric thickness of the emitting region (see below).

Further results can be obtained by making comparisons with the hydrostatic, plane parallel semi-empirical model chromosphere of Kelch et al. (Ref. 13): (f) the model is consistent with the emission measure and column density constraints below 8000K. Above 8000K the sharp solar-like transition region structure adopted in Ref. 13 cannot (as expected) account for the observed emission line fluxes; (g) within the limits imposed by IUE’s resolution, non-thermal motions derived for widths of all lines except C III] are consistent with those in the model (i.e., $\leq 10$ km/s). The larger C III] widths are probably due to inhomogeneities; (h) C III] line ratios computed from the model chromosphere yield $N_e = 8.9 \times 10^{2}$ cm$^{-3}$, consistent with the observed $N_e = 9.0 \pm 0.3 \times 10^{2}$ cm$^{-3}$; (i) using constraints (e), (f) and (g) above, the geometric thickness of the CIII] emitting region must be $\leq 3$ times that of the model chromosphere, i.e., $\delta h \leq 0.3 R_e$, and not $0.4 R_e$ as suggested in Ref. 8. The assumptions made in Ref. 8 concerning the ion balance of carbon and interpretation of emission measures substantially overestimate the geometric thickness of cool giant stars.

The success of the semi-empirical model chromosphere was, initially, rather surprising given its simplicity. This is discussed further below.

3.2 Comparison of Results for a Boo, a Tau and 8 Gru.

Results (a) - (i) for a Tau apply broadly to a Boo and 8 Gru, with some important slightly different details. However, the major conclusions remain the same.

Differences and trends between the stars evident from this work are (a) Line fluxes at the stellar surface ($F_\lambda$) decrease roughly by an order of magnitude between K2 III and M5 III. Following Ref. 14, the ratio $F_\lambda$ (Mg II)/$T_{\text{eff}}^{2}$ gives a good measure of the total stellar energy used to heat the outer atmosphere via non-thermal processes. Table 3 shows the decreasing value of this fraction with later spectral type: this decrease is somewhat faster than was derived in Ref. 14. The current (uncertain) estimates of mass loss indicate that the energy in mass motions are at least an order of magnitude smaller than the radiative losses; (b) The maximum temperature of detected material decreases with later spectral type (see table 3); (c) $N_e$ decreases rapidly in a manner consistent with Ayres’ scaling law (Ref. 15) (modified to take into account the variation $F_\lambda$ (Mg II) $\propto T_{\text{eff}}^{2}$ $H^+$); (d) $N_e$ $\propto A_{\lambda \text{H}}^{1/6}$ $T_{\text{eff}}^{2}$ (see Table 3). Therefore this is consistent with Ayres’ basic assumption of hydrostatic equilibrium and constant heating (i.e., $\propto T_{\text{eff}}^{2}$) with height. Absolute values of $N_e$ are in broad agreement with hydrostatic semi-empirical model chromospheres, but the high value of $N_e$ observed in a Boo suggests that inhomogeneities may be important; (d) The “mean” optical depth at which the emission lines are formed increase slightly with later spectral type. This is also consistent with Ayres’ scaling law for the mass column density of the temperature minimum $N_a$ $\propto A_{\lambda \text{H}}^{1/6}$ $T_{\text{eff}}^{2}$, and with the underlying assumptions, however the uncertainties are quite large. (See Table 3).

<table>
<thead>
<tr>
<th>Star</th>
<th>$F_\lambda$ (Mg II)/$T_{\text{eff}}^{2}$</th>
<th>$T_{\text{max}}$/K</th>
<th>$\log N_e$ (cm$^{-3}$)</th>
<th>$T_{\text{eff}}$/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>a Boo</td>
<td>9.4(6) $\times 10^{4}$</td>
<td>$&gt;1.5 \times 10^{4}$</td>
<td>9.7</td>
<td>5.6(3)</td>
</tr>
<tr>
<td>a Tau</td>
<td>4.9(6) $\times 10^{4}$</td>
<td>$&gt;1.5 \times 10^{4}$</td>
<td>9.0(3)</td>
<td>7.4(3)</td>
</tr>
<tr>
<td>8 Gru</td>
<td>2.2(6) $\times 10^{4}$</td>
<td>$&lt;1.5 \times 10^{4}$</td>
<td>8.5(3)</td>
<td>1.4(4)</td>
</tr>
</tbody>
</table>

In summary, all the empirical constraints imply that the bulk of UV emission line fluxes is formed in predominantly neutral regions below $10^{4}$K, with structures (densities, linewidths) consistent with semi-empirical models which are supported by non-thermal motions. Large mass flows implied by asymmetric profiles (discussed below) are therefore probably not important in the moment and energy balance of the emitting regions, but become more important in the less dense scattering or “wind” regions (see below).

4. OTHER CONSTRAINTS.

Given the above constraints on the emission regions one can try to build a more complete picture of the whole outer atmosphere by considering other observational constraints.

Empirical evidence of inhomogeneous chromospheric structure in a Boo was presented in Ref. 16, where strong CO infrared absorption bands were found to be inconsistent with a temperature structure increasing outward from the temperature minimum region. The inferred multi-component temperature structures are consistent with the density inhomogeneities inferred from the analysis of CIII] lines in a Boo, since the confinement of the emission region to a smaller area.
requires larger densities (for a given geometric extent) to account for the observed flux. Further work with CO and more reliable measurements of $N_e$ are required before quantitative estimates of surface coverage and degrees of inhomogeneity can be made. Other spectral diagnostics of the cooler material would be most valuable.

Recently, pioneering work has been done in the radio (Ref. 17) and on asymmetric MgII profiles (Ref.18) to derive temperature, density and velocity constraints on the tenuous, warm regions referred to as 'extended chromospheres' or winds around cool giants. The radio observations, which provide useful information on material with considerably lower emission measures than those where the UV fluxes are created, have been shown to be consistent with extended ($\Delta N_e$) tenuous regions probably associated with spherically symmetric outflowing winds (Ref. 17). Assuming spherical symmetry, the asymmetric profiles automatically imply that the star is losing mass, but the author of Ref. 18 acknowledges that there are problems concerning the uniqueness of the derived semi-empirical models. In addition, Judge (Ref. 19) has pointed out potential problems with these spherically symmetric wind models in the regions close to the sun where the bulk of the Mg line fluxes are created. The reliability of the models' wind and extended regions where the MgII asymmetry is produced is therefore also questionable. Further work is under progress to assess the information from the radio fluxes and line asymmetries and their relation to the empirical constraints described here.

5. IMPLICATIONS FOR FURTHER MODELLING.

There is now firm empirical evidence for temperature and density inhomogeneities in the outer atmosphere of a Boo: one-component semi-empirical or theoretical models of this star therefore must be treated with care. With this in mind, the constraints derived are sufficiently stringent to provide useful constraints on semi-empirical modelling efforts, such as those described in Ref.18. In addition, theoretical work (such as that of Ref.12) can also be usefully comparing to the constraints. Higher resolution observations with the HRS on Space Telescope will enable much more stringent constraints to be derived from lines previously unresolved with IUE.

6. CONCLUSIONS

Useful empirical constraints on the outer atmospheric structures of three typical late-type giant stars have been obtained using emission lines observed with IUE. Results show that the emission regions are near hydrostatic equilibrium where the emission line fluxes are created in all three stars. Evidence exists for temperature and density inhomogeneities which may affect one-component semi-empirical modelling efforts. However, the present constraints may usefully be applied to constrain theoretical or semi-empirical models which are currently being considered.

REFERENCES