Implications of Light Metals (Li - Ca) on NLTE Model Atmospheres for Hot Stars

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Abstract: Neither iron line-blanketed LTE model atmospheres nor "standard" NLTE models (including H, He, C, N, O, Ne) can reproduce the observed stellar EUV and X-ray fluxes of hot stars: huge differences appear at energies higher than 54 eV (He II Lyman continuum) which are a result of light metal opacities which have an strong influence on the emergent fluxes of hot stars in this energy range. These metal opacities have not been included in "standard" NLTE model atmosphere calculations so far. We present NLTE model atmospheres including all elements from hydrogen to calcium.

In order to calculate more realistic stellar fluxes, such models should preferentially be used for the EUV and X-ray analysis of very hot stars instead of black bodies which are often used in the analysis of X-ray spectra.

1 Introduction

In the last quarter of this century the numerical models for the interpretation of spectra of hot stars have been continuously improved.

In 1969 Auer & Mihalas presented the complete linearization method for the calculation of "Classical Models". These were limited due to numerical reasons and missing computational capacities — only a handful of NLTE levels and line transition could be considered.

The rapidly evolving observational techniques provided UV and X-ray spectra (e.g. IUE, EINSTEIN, and EXOSAT satellites) and high-resolution optical spectra (e.g. ESO CASPEC) and have been a challenge for theory: In 1985 Werner & Husfeld presented the newly developed accelerated lambda iteration (ALI) technique for line formation calculations. This method was later applied to the calculation of NLTE model atmospheres (Werner 1986). Presently calculated model atmospheres treat over 200 atomic levels in NLTE and consider more than 10^6 line transitions.

Further progress in observation (e.g. HST, ROSAT, EUVE, ISO, and the ESO VLT) requires adequate models, tailored for an interpretation of the complete wavelength range from the far infrared to the X-ray region.

For "cool" stars ($T_{\rm eff} < 30$ kK, spectral type B or later), the fully line blanketed LTE models (Kurucz 1979, 1991) are available, which consider all elements up to the iron group and the blanketing of millions of lines.

The present state-of-the-art NLTE models (Dreizler & Werner 1993, Rauch 1996 in prep.) include also all elements up to the iron group (including line blanketing) and permit to perform analyses of very hot stars with realistic models.

2 NLTE Model Atmospheres

Our model atmospheres are plane parallel, chemically homogeneous, and in radiative and hydrostatic equilibrium. They were calculated using the ALI method.

While the implications of H, He, C, N, and O (Rauch 1993) and of the iron group elements on NLTE model atmospheres have been studied in detail (Dreizler & Werner 1993), the light metals lithium through calcium have been regarded as trace elements and were neglected in model atmosphere calculations so far. For some of them line formation calculations (i.e. fixed atmospheric structure) had been carried out in order to determine photospheric abundances, e.g. Dreizler (1993) for Ne, Mg, Si in sdO stars. However, the “total abundance” of the light metals is comparable to that of the CNO elements and thus, not negligible.

In the construction of our model atoms we have to consider that the number of tractable NLTE levels is restricted due to numerical accuracy (< 200). Thus, we used “standard” model atoms for H and He (e.g. Rauch 1993) and small model atoms for C, N, and O. In test calculations, Li, Be, and B were found to be unimportant and neglected. F - Ca were represented by model atoms “as small as possible, as large as necessary” in order to consider all ionization stages that dominate in certain parts of the atmosphere as well as resonance lines. Their photoionization cross-sections were calculated using Opacity Project (cf. Seaton et al. 1994) data.

The changes in the temperature stratification due to the consideration of metals, especially of their resonance lines are demonstrated by Rauch (1996). The differences in the atmospheric structure have a direct influence on theoretical profiles of e.g. H I and He II lines, which are used in spectral analyses to determine $T_{\rm eff}$, $\log g$, and the photospheric He/H abundance ratio (Rauch 1996, in prep.).

3 Emergent flux

In Fig. 1 we show the emergent fluxes of models which are calculated with different $T_{\rm eff}$ and chemical compositions. Obviously, metal opacities reduce the flux in the EUV and X-ray range by orders of magnitude. A comparison to the flux of a black body (BB, at 400 kK, Fig. 1) shows that a BB is unsuitable for analyses of most stars: The BB flux maximum is at ≈ 72 Å while the NLTE flux maximum ist at ≈ 50 Å — and at a higher ($\approx 20\%$) flux level. A similar result was found by Heise et al. (1994): Their LTE model atmospheres are also more efficient soft X-ray emitters than BBs but the resulting LTE spectra are much flatter (at a lower flux level than the BBs!).

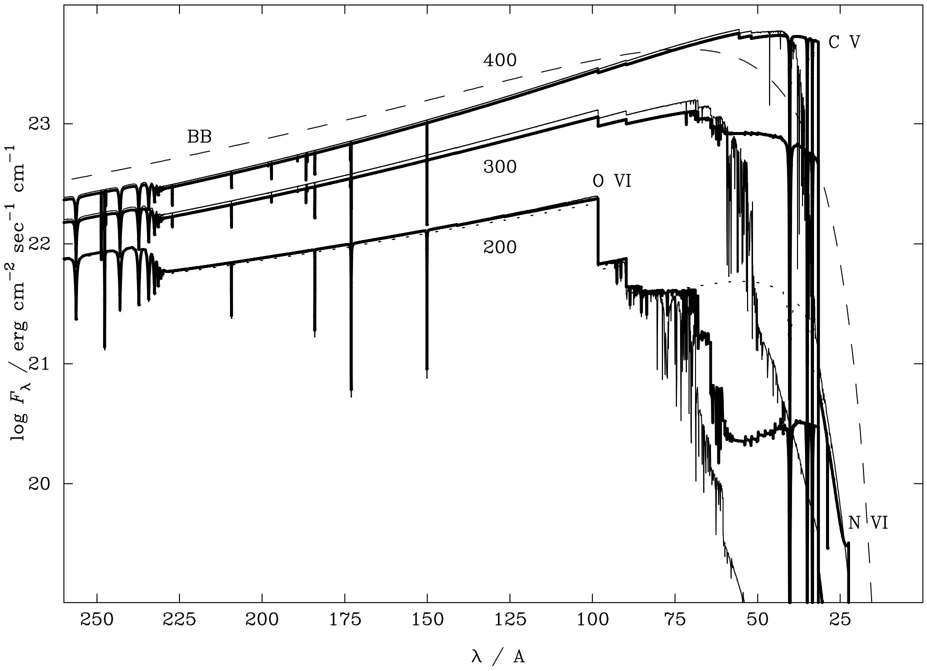

Fig. 1. Emergent fluxes of NLTE model atmospheres with $\log g = 8$, $T_{\rm eff}$= 200, 300, 400 kK, and solar abundances calculated with H+He+C+N+O (200 kK only, dotted line) and H+He+C+N+O+Ne (——) compared to those of H - Ca (——) models. The dashed line is the flux of a black body (BB) with 400 kK. Note the strong absorption edges of O VI 2p at 98 Å and 2s at 89 Å which almost disappear at $T_{\rm eff}$= 400kK due to the changing ionization equilibrium, and the much stronger ground state absorption edge of C V at 31.6 Å which will also disappear towards higher $T_{\rm eff}$ (Fig.2).

4 Summary

Emergent fluxes calculated from NLTE model atmospheres which include the "light metals" F - Ca show a drastic decrease of the flux level at energies higher than 126 eV (= O VI 2p continuum) compared to that of "standard" (H+He+C+N+O+Ne) models.

However, at a given $T_{\rm eff}$, NLTE and LTE model atmospheres have their flux maxima at higher energies than a BB. The flux level of a NLTE model is higher than that of a LTE model (this will be investigated in a forthcoming paper).

For a realistic X-ray analysis of very hot stars the use of NLTE model atmospheres which consider metal opacities is highly recommended.

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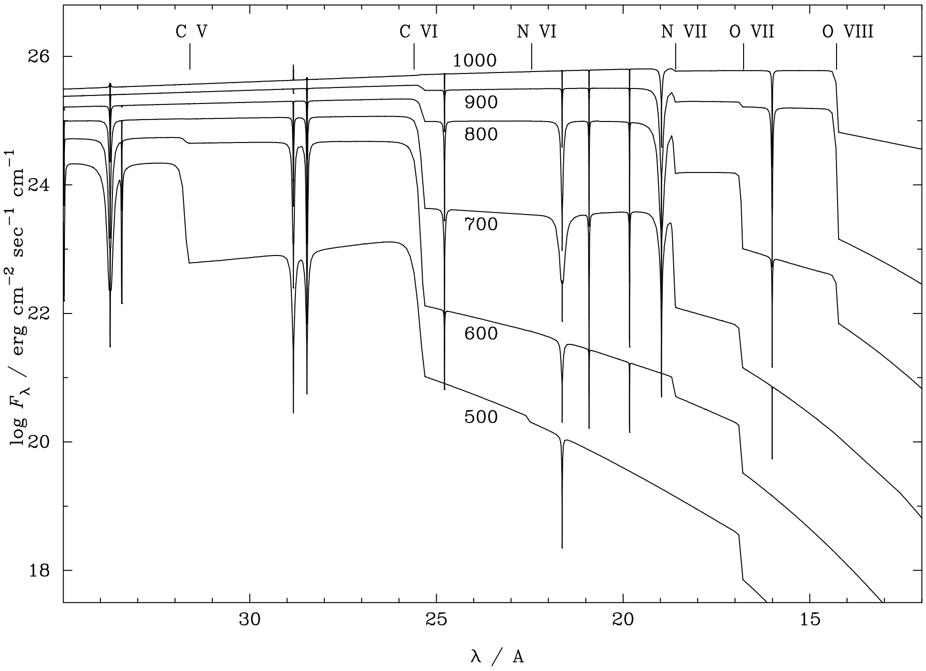

Fig. 2. Emergent fluxes of H+He+C+N+O NLTE model atmospheres (including lines) with $\log g = 9$, $T_{\rm eff}=$ $500, \ldots, 1000$ kK, and solar abundances. The wavelengths of the ground state thresholds of C V, C VI, N VI, N VII, O VII, and O VIII are marked. Note that their edges appear always in absorption, and have a maximum at that $T_{\rm eff}$, where the respective ion dominates in the atmosphere due to the ionization equilibrium (e.g. N VII at ≈ 700 kK, O VIII at ≈ 900 kK).

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