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

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Introduction

In the last quarter of this century enormous progress has been made in both observational technique and spectral analysis by means of model atmospheres:

→ low + medium resolution optical spectra

- "Classical Models" (Auer & Mihalas 1969)

– H + He

– lowest 5 H I in NLTE + 6 line transitions, 65 frequency points

→ IUE satellite (since 1978!): high resolution ($\lambda / \Delta\lambda \approx 10000$) UV spectra

– many important metal lines

→ EINSTEIN (1978 - 1981): X-ray spectra

→ EXOSAT (1983 - 1986): X-ray spectra

→ ESO CASPEC (since 1984): high resolution ($\lambda / \Delta\lambda \approx 25000$) optical spectra

→ HST (since 1990): high resolution optical + UV spectra

→ ROSAT (since 1990): X-ray spectra 0.1 - 2.5 keV

- "Beyond Classical Models" (e.g. Dreizler & Werner 1991, Rauch & Werner 1991)

– H, He, C, N, O

– up to 200 levels in NLTE with ≈ 1000 line transitions, 10000 frequency points

→ EUVE (since 1992): EUV spectra 70 - 800 Å

- present "state-of-the-art" Models (Dreizler & Werner 1993, Rauch 1993)

– H, He, C, N, O + iron group

- this work (Rauch 1995 in prep.)

– H, He, C, N, O + F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca + iron group

→ ISO (launch 1995): infrared spectra

→ VLT (first light 1997)

→ ...

While the implications of H, He, C, N, and O and of the iron group elements on NLTE model atmospheres have been studied in detail (see above), the "light metals" lithium through calcium have been regarded to be trace elements and were neglected in our model atmosphere calculations so far. For some of them line formation calculations (i.e. disregarding 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" (Fig. 1) of the "light metals" is comparable to that of the CNO elements and thus, not neglectable.

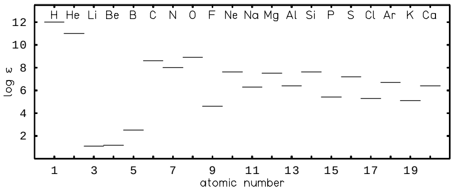

Fig. 1. Solar abundances of the elements 1 - 20 (Holweger 1979, Stürenburg & Holweger 1990)

NLTE Model Atmospheres

A newly developed numerical method based on approximated lambda iteration (ALI) techniques (Werner & Husfeld 1985, Werner 1986) allows the calculation of more realistic model atmospheres including effects of metal line blanketing (Werner 1988).

- plane parallel
- hydrostatic
- chemically homogeneous
- Accelerated Lambda Iteration Method
- different elemental composition (but always solar composition)

– pure H

– H + He

– H, He, C, N, O

– H, He, C, N, O, Ne

– H - Ca with different photoionization cross-sections for F - Ca (see below)

– H - Ca + all resonance lines for F - Ca

– H - Ca + all resonance lines for F - Ca + iron group elements

Model Atoms

In the construction of our model atoms we have to respect that the number of NLTE levels is restricted due to numerical accuracy:

- number of NLTE levels < 200 due to numerical accuracy

→ "standard" model atoms for H and He (e.g. Rauch 1993)

→ small model atoms for C, N, O

→ Li, Be, B neglected (abundances much lower than that of all other "light metals" (Fig. 1)

→ F - Ca "as small as possible, as large as necessary"

– all ionization stages that dominate parts of the atmosphere

– all resonance lines

– three different photoionization cross-sections calculations for F - Ca

σ^{H}_{bf} hydrogen-like, i.e. calculated with the Seaton formula (Seaton 1958)
$(s = 3,\ \alpha = 1)$

σ^{th}_{bf} same as σ^{H}_{bf} but the threshold cross-section is an averaged (at the threshold energy) value calculated from OPACITY PROJECT data

σ^{OP}_{bf} OPACITY PROJECT dataset

Atomic Data

- detailed model atoms (H, He, C, N, O) necessary for realistic spectra (e.g. Rauch 1993)

– atomic data from "standard sources", e.g. Bashkin & Stoner (1975), Wiese (1966)

– lack of precise collisional and photoionization cross-sections, oscillator strengths

– line broadening theory available only for H I, He II, and partly for He I, C IV, N V

- OPACITY PROJECT (1987 - 1994, cf. Seaton et al. 1994)

→ TOPBASE operated at CDS, Strasbourg

– level energies

– photoionization cross-sections

– oscillator strengths

– no collisional cross-sections

- IRON PROJECT (since 1993, Hummer et al. 1993)

→ collisional cross-sections

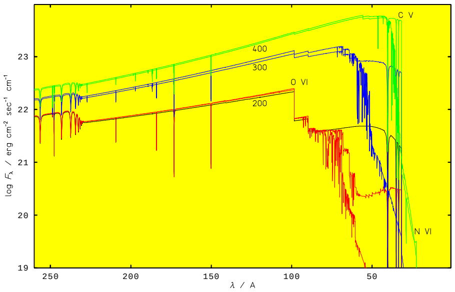

Fig. 2. Emergent flux of the models with $\log g = 8$ and $T_{\rm eff}$ = 200 kK (red and black), 300 kK (blue), and 400 kK (green), calculated with H, He, C, N, O, Ne compared to those of H - Ca models. The black line is calculated from a model with a H, He, C, N, O composition. Note the strong absorption edge of the C V ground state continuum at 31.6 Å

Results

- emergent flux

→ enormous decrease in the EUV / X-ray range → Fig. 2

→ effect of additional iron group elements on the flux of a H - Ca model only marginal

- atmospheric structure

→ drastic temperature drop in the outer atmosphere due to desaturating resonance lines (mainly Ne VII) → Fig. 3

→ changes in the ionization equilibria

- theoretical H + He line profiles

→ change strongly depending on formation depths (Fig. 4)

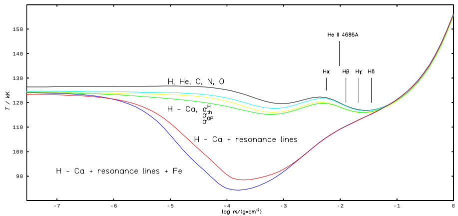

Fig. 3. Temperature structure of the models ($T_{\rm eff} = 155$kK, $\log g = 6.5$, solar abundances) including H, He, C, N, O, H - Ca (with different calculation of the photoionization cross-sections, see text), H - Ca with all resonance lines of F - Ca, and H - Ca + iron group elements. The formation depth of the line cores of Hα - Hδ and of He II $\lambda 4686$Å are marked. Note the drastic temperature drop in the outer atmosphere due to the included resonance lines of the metals (red line)

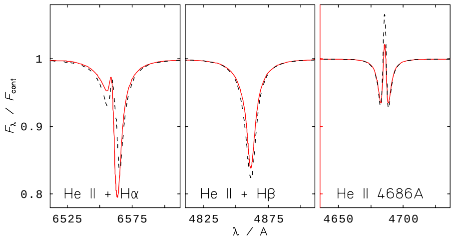

Fig. 4. Theoretical line profiles (convoluted by a Gaussian with FWHM=3Å) calculated from our models: —: H+He; -- --: H-Ca with $\sigma^{OP}_{bf}$and additional all resonance lines of F-Ca. Note that the "H-Ca" Hα component in the H II / Hα appears shallower due to a much stronger emission reversal which is not visible in the convolved profile

Conclusions

- inclusion of "light metals" F - Ca in model atmosphere calculations

→ necessary to calculate realistic EUV / X-ray fluxes

– prediction of count rates

– ionizing spectra e.g. for central stars of planetary nebulae

→ abundance determination ?

→ changes in theoretical line profiles due to their formation depths (→ Fig. 1)

– solution of the Balmer Line Problem (Werner 1995)

Problems and Future Work

- abundance determination for F - Ca (here: solar abundances)

→ detailed model atoms necessary → new method which allows to use about 200 level per chemical species

→ atomic data

→ line broadening theory ?

- line blanketing of F - Ca neglected so far (only resonance lines are considered)
- excessive computational time

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