Improved NLTE Model Atmospheres for the Analysis of Hot Compact Stars

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Introduction

- flux maximum of hot stars in the UV/EUV (Fig. 1)
- → reliable models are required to reproduce the emergent flux at the complete wavelength range from the IR to the X-ray simultaneously
- observational improvements in the last thirty years (see below)
- → challenge for theorists
- fully line-blanketed LTE models (Kurucz 1979)
- metal-line blanketed NLTE models (Werner 1986)

LTE model atmospheres

- cool stars with spectral type B or later
- → in many cases LTE model atmospheres (Kurucz 1979, 1991) are an adequate tool to determine photospheric parameters
- there are always NLTE effects in any star!
- → use of NLTE model atmospheres is recommended – not only for hot stars!
  - e.g. sun: NLTE calculations of the radiative transfer show 20-40% deviation from LTE in the case of O I equivalent widths (Sedlmayr 1973)

Development of NLTE model atmospheres and Observational techniques

- → low + medium resolution optical spectra
- "Classical Models"
- H models, complete linearization ("CL", Auer & Mihalas 1969)
- Copernicus (1972 – 1982): high resolution ($\lambda/\Delta\lambda \approx 20\,000$) UV (710 – 3185 Å) spectra
- H + He models (Auer & Mihalas 1972, Kudritzki 1976)
- H + He + "average light element" models (Mihalas 1972)
  - lowest 5 H I in NLTE + 6 line transitions, 65 frequency points
- IUE (1978 – 1996): high resolution ($\lambda/\Delta\lambda \approx 10\,000$) UV (1150 - 3200 Å) spectra
- → absolute fluxes
- → many important metal lines (of different ionization stages)
- EINSTEIN (1978 - 1981): X-ray spectra
- EXOSAT (1983 - 1986): X-ray spectra
- ESO CASPEC (since 1984): high resolution ($\lambda/\Delta\lambda \approx 25\,000$) optical spectra
- H + He + C + N + O, ground states of CNO treated in NLTE (Husfeld et al. 1984)
- Accelerated Lambda Iteration ("ALI") introduced for the calculation of NLTE models (Werner 1986)
- HUT (1990) medium resolution UV spectra
- HST (since 1990): high resolution optical + UV spectra
- ROSAT (since 1990): X-ray spectra 0.1 - 2.5 keV
- Multi-Frequency/Multi-Gray ("MF/MG") algorithm (Anderson 1990): NLTE calculations with millions of lines of elements H – Fe
- "Beyond Classical Models" (Dreizler & Werner 1991, Rauch & Werner 1991)
- H + He + C + N + O models
  - up to a total of 200 levels treated in NLTE with ≈1 000 line transitions, 10 000 frequency points
- EUVE (since 1992): EUV spectra 70 - 800 Å
- hybrid CL/ALI method (Hubeny & Lanz 1993, 1995): Detailed studies on the impact of iron group elements
- ORFEUS (1993, 1996) high resolution FUV + EUV spectra
- present "state-of-the-art" models (Dreizler & Werner 1993, Rauch 1993, 1997)
- H, He, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca + iron group
  - millions of metal lines

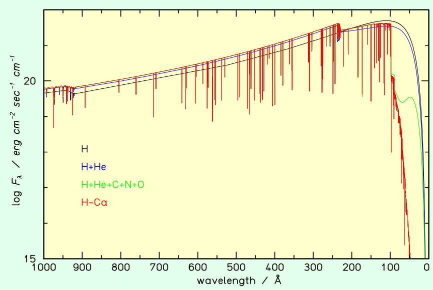

Fig. 1. Comparison of NLTE model atmosphere fluxes with different chemical composition ($T_{\rm eff} = 150$ kK, $\log g = 6.5$, solar abundances).

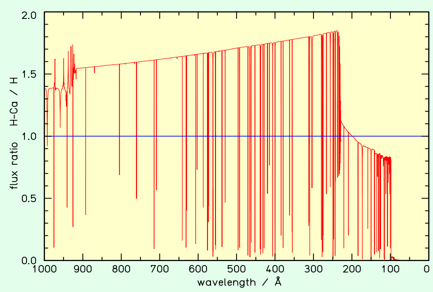

Fig. 2. Flux ratio of models with all elements from H to Ca and a pure H model (from Fig. 1). Note that the flux which is blocked by the He and metal opacities at high energies is redistributed at lower energies. This increases the flux level between the H I (13.6 eV, 911 Å) and the He II (54 eV, 228 Å) ground state edges by almost a factor of two!

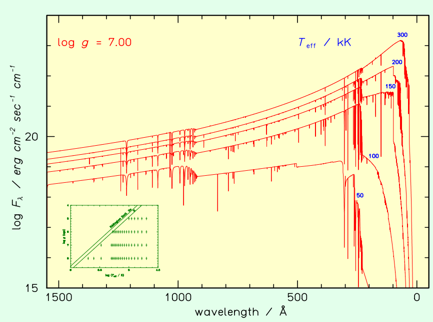

Fig. 3. Example of NLTE model atmosphere fluxes with different $T_{\rm eff}$ (50 – 300 kK). An overview of the available models is given in the lower left corner.

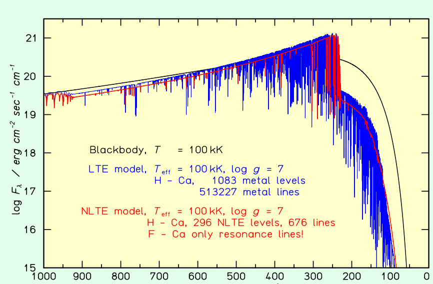

Fig. 4. Impact of metal line blanketing. The LTE flux (blue) was calculated from a model ($T_{\rm eff} = 100$ kK, $\log g = 7$) which considered all elements from H to Ca and about half a million of metal lines. The NLTE flux (red) was calculated from a model with the same elements but only the resonance lines for F – Ca were included. Note that NLTE effects cannot be studied from this comparison because different model atoms were used! This will be presented in detail elsewhere. The blackbody flux (black), however, is only a coarse estimate for the stellar flux.

Ongoing Work

- calculation of a model atmosphere grid which includes extensive metal-line blanketing
- "light metals" F – Ca (Rauch 1997)
- → up to 200 levels per element treated in NLTE
- → elaborated model ions for F – Ca, lines: Opacity Project (Seaton et al. 1994)
- → Ar + Ca lines: Kurucz's line lists
- iron group (Dreizler & Werner 1993) Kurucz's lists

Applications of NLTE Models

- spectral analysis of hot compact stars (e.g. Werner & Rauch 1994, Rauch & Werner 1995)
- → stellar parameters
- → check against evolutionary theory of post-AGB stars (e.g. Werner et al. 1997)
- properties of planetary nebulae (Rauch et al. 1994, 1996)
- → realistic emergent model atmosphere fluxes
- → ionizing spectra for planetary nebula
- → consistent models of planetary nebula and exciting star
- **grid of H-Ca model fluxes (Fig. 3) is available at http://astro.uni-tuebingen.de/~rauch/flux.html $T_{\rm eff} = 50 - 500$ kK, $\log g = 5 - 8$, solar abundances**

Conclusions

- taking up the challenge of improved observation, spectral analysis by means of NLTE model atmosphere techniques has been developed within the last thirty years
- LTE and NLTE models have their flux maximum at higher energies and higher peak intensities than blackbodies (Fig. 4)
- the consideration of C, N, O, light metals F – Ca, and iron group elements is essential for a reliable emergent model flux (Fig. 2)
- metal line blanketing has a strong influence on the emergent flux (Fig. 4)

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