Analysis of IUE spectra with NLTE model atmospheres

Thomas Rauch

Institut für Astronomie und Astrophysik, Astronomie, Universität Tübingen, Germany
e-mail rauch@astro.uni-tuebingen.de

Introduction

In the last twenty years, new ground-based telescopes and instruments have provided high resolution and high signal-to-noise optical spectra. Satellites like e.g. IUE, HST, EUVE, and ROSAT have opened new windows to the high energy wavelength regions in which many metal lines can be found which are very important for photospheric diagnostics.
Taking up the challenge of improved observation, spectral analysis by means of NLTE model atmosphere techniques has been developed within the last thirty years.

NLTE model atmospheres

→ low + medium resolution optical spectra
- "Classical Models" (Auer & Mihalas 1969)
  – H + He (Kudritzki 1976)
  – lowest 5 H I in NLTE + 6 line transitions, 65 frequency points

→ IUE satellite (1978 - 1996): high resolution ($\lambda/\Delta\lambda \approx 10\,000$) UV spectra
  – 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

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

→ ROSAT (since 1990): X-ray spectra 0.1 - 2.5 keV
- "Beyond Classical Models" (e.g. Werner 1986, Dreizler & Werner 1991, Rauch & Werner 1991)
  – H, He, C, N, O
  – up to 200 levels in NLTE with ≈1000 line transitions, 10 000 frequency points

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

Composite spectra - the binary problem

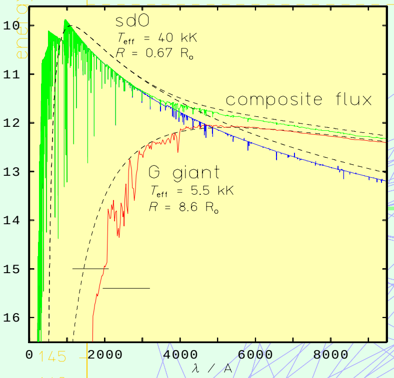

Fig. 1. Model fluxes of the binary HD 128220 at Earth. HD 128220B is represented by a LTE model (Kurucz 1979) with $T_{\rm eff} = 5\,500$ K and log g = 2.8 (Howarth & Heber 1990). The flux of HD 128220B is calculated from our NLTE model with $T_{\rm eff} = 40\,600$ K, log g = 4.5, He/H = 0.3, C/H = 0.0005, and N/H = 0.0015. The radii are adopted from Howarth & Heber (1990). Note that for wavelength ¡ 3000 Å the contribution of the cool component is negligible. The IUE SWP and LWP ranges are marked by horizontal bars. The dotted lines show the fluxes of blackbodies

- HD 128220: binary with a sdO (HD 128220B) and G0-giant (HD 128220A) component
- HD 128220A dominates optical spectrum
- HD 128220A: spectral type and radius unknown, contribution to the optical spectrum cannot be subtracted
- UV spectra uncontaminated by the cool HD 128220A → analysis of IUE spectra necessary to determine the photospheric parameters of HD 128220B (Fig. 1)
- analyses of many lines of different ionization stages (e.g. Figs. 2, 4) and different elements (Fig. 3) allow a precise determination of photospheric parameters (Rauch 1993)

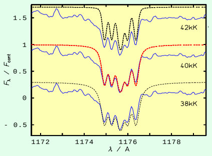

Fig. 2. Theoretical line profiles of C III 1175 Å, compared with the IUE spectrum. Model parameters are $T_{\rm eff}$ =38, 40, 42 kK, log g = 4.5, He/H = 0.5, and C/H = 0.0005

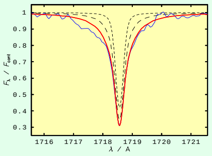

Fig. 3. Theoretical line profiles of N IV 1718 Å in comparison to the IUE spectrum. The profiles were calculated from models with N/H = 0.0001 (- - -), 0.0005 (– – –), 0.0015 (—). $T_{\rm eff}$ = 40 kK, log g = 4.5, He/H = 0.3, and C/H = 0.0005

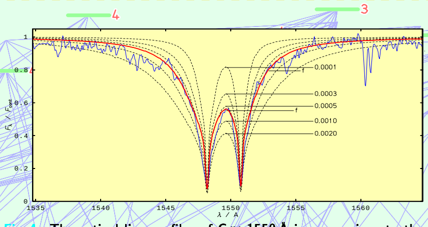

Fig. 4. Theoretical line profiles of C IV 1550 Å in comparison to the IUE spectrum. The profiles were calculated from models with $T_{\rm eff}$ = 40 kK, log g = 4.5, He/H = 0.5, and C/H = 0.0001 . . . 0.0020

- $T_{\rm eff}$ = 40.6± 0.4 kK is precisely determined from the C III/C IV, N III/N IV, and O IV/O V ionization balances (very sensitive!)
- log g = 4.5± 0.1 dex and the photospheric composition was determined by detailed line profile fits

Hot He-rich stars – the temperature problem

For relatively cool He-rich stars, i.e. lines of both He I and He II are present in the optical spectrum, an analysis can practically follow the cookbook: $T_{\rm eff}$ from the He I/ He II ionization equilibrium; log g from the wings of the H I(/He II) Balmer lines (blends), photospheric composition from line profile fits.
In the case of hot He-rich stars (only He II lines in the spectrum) the situation is more difficult:

- elements display only lines of one ionization stage in the optical, e.g. at $T_{\rm eff}$ = 140 kK: H I, He II, C IV, N V, O VI
- flux maximum is located in the (far-)UV Fig. 1, noise in the optical hampers a precise analysis of $T_{\rm eff}$ and log g (larger error ranges)
- UV spectra complement the optical analysis: e.g. in the case of PG 1159 stars, the O V 1371 Å line is a sensitive indicator for $T_{\rm eff}$ Fig. 5

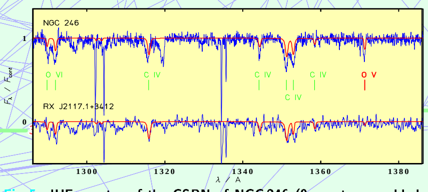

Fig. 5. IUE spectra of the CSPN of NGC 246 (9 spectra co-added, Feibelman & Johansson 1995) and of RX J2117.1+3412 (SWP 47556 + SWP 47563 taken Apr. 1993 + SWP 55411 taken Aug. 1995, co-added) compared to synthetic spectra ($T_{\rm eff}$ = 150 kK and 170 kK, log g = 5.7 and 6.0, respectively; Rauch et al. 1997). The theoretical O VI lines are too shallow for both stars. In the case of RX J2117.1+3412, a higher O abundance would result in a stronger O V 1371 Å and thus require even a higher $T_{\rm eff}$.

Hot He-rich stars – the evolutionary problem

NLTE analyses of hot stars improved our picture of post-AGB evolution. However, the evolution of hot He-rich stars is not well understood. We demonstrate this in the case of the exotic PG 1159 stars (Werner et al. 1997):

- $T_{\rm eff}$ = 65 - 180 kK
- log g = 8.0 - 5.5
- He : C : O = 33 : 50 : 17 (by mass, typical values)
- every other star has an associated planetary nebula – where are the other's nebulae?
- 7 out of 27 known PG 1159 stars shows non-radial g-mode pulsations – what is the chemical composition of the photosphere?
- standard evolutionary theory predicts observed photospheric abundances far below the stellar surface (Blöcker et al. 1997) – how do these stars loose their H-rich envelopes and most of their He-rich envelopes?
- Iben & Tutukov (1985) predict neon to be the fourth abundant element (2% by mass) in the post-AG stellar interior → Ne is a sensitive indicator for the mass-loss state
- identification of Ne VII 3643.6 Å in the spectra of the central stars of NGC 246, Lo 4, and K 1-16, and in RX J2117.1+3412 (Werner & Rauch 1994, Rauch et al. 1995)
- good agreement with abundance predictions
- confirmation by the detection of Ne VII 1982/92/97 Å in the IUE SWP spectrum of NGC 246 (Fig. 6)

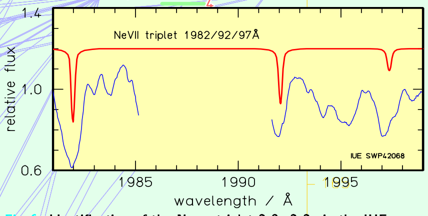

Fig. 6. Identification of the Ne VII triplet 2s3s-2s2p in the IUE spectrum of NGC 246. The theoretical profile was calculated with 2% of Ne (by mass).

Results

Significant NLTE effects can be found in any star, if one goes to short enough wavelengths any/or higher accuracy. Thus modern spectral analysis has to take into account these effects – not only for very hot stars!
NLTE spectral analysis has presently reached a high degree of sophistication: It is possible to calculate NLTE model atmospheres which consider opacities of all elements up to the iron group and to reproduce reliably stellar spectra of hot stars simultaneously from the infrared to the X-ray wavelength range.
Many elements display isolated lines of two or more ionization stages in the UV wavelength range. Since the atomic data as well as the line broadening of these lines is known sufficiently well, UV spectra play an important role in spectral analysis. Analyses of these spectra – either stand-alone or just complementing analyses of spectra of other wavelengths – have shown that, if carried out with care, theory works!

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Background: Grotrian diagram of our Ne VII model ion

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