NLTE Model Atmospheres for Central Stars of Planetary Nebulae

Thomas Rauch, Jochen L. Deetjen, Stefan Dreizler, Klaus Werner

Institut für Astronomie und Astrophysik, Universität Tübingen, Germany

e-mail rauch@astro.uni-tuebingen.de

Abstract

Present observational techniques provide stellar spectra with high resolution at a high signal-to-noise ratio over the complete wavelength range – from the far infrared to the X-ray.

NLTE effects are particularly important for hot stars, hence the use of reliable NLTE stellar model atmosphere fluxes is required for an adequate spectral analysis.

State-of-the-art NLTE model atmospheres include the metal-line blanketing of millions of lines of all elements from hydrogen up to the iron-group elements and thus permit precise analyses of extremely hot compact stars, e.g. central stars of planetary nebulae, PG 1159 stars, white dwarfs, and neutron stars. Their careful spectroscopic study is of great interest in several branches of modern astrophysics, e.g. stellar and galactic evolution, and interstellar matter.

Introduction

During their evolution the more massive post-AGB stars can reach extremely high effective temperatures: Up to about 700 kK are predicted by Paczynski (1970) for a 1.2 $M_\odot$ star.

Due to their flux maximum in the EUV/X-ray wavelength range and depending on their photospheric composition and interstellar absorption some post-AGB stars have been detected as supersoft X-ray sources, e.g. all PG 1159 stars with $T_{\mathrm{eff}} > 140$ kK have been detected by ROSAT (Fig. 1).

Realistic modeling of the emergent fluxes of these stars requires the consideration of all elements from hydrogen up to the iron group.

NLTE Model Atmospheres

- NLTE code **PRO2** (Werner 1986, 1988)
  - plane-parallel
  - hydrostatic equilibrium
  - radiative equilibrium
- → H – Ca (Rauch 1997, Tab. 1)
  - more than 200 levels treated in NLTE
  - more than 1 000 lines
- → iron group (Dreizler & Werner 1993, Deetjen et al. 1999)
  - millions of lines Tab. 2

NLTE Model Fluxes on the WWW

A grid (T_{eff} = 50 – 1 000 kK, log g = 5 – 9 (cgs), solar and halo abundances) of H – Ca model atmosphere fluxes (Fig. 2) is available at

http://astro.uni-tuebingen.de/~ rauch/flux.html

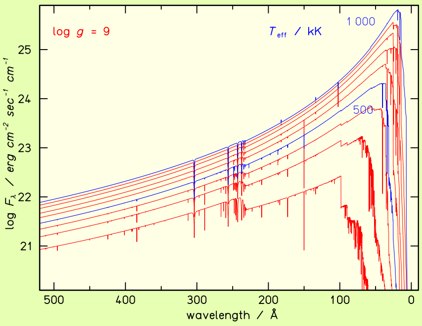

Fig. 2 Example of NLTE H – Ca model atmosphere fluxes

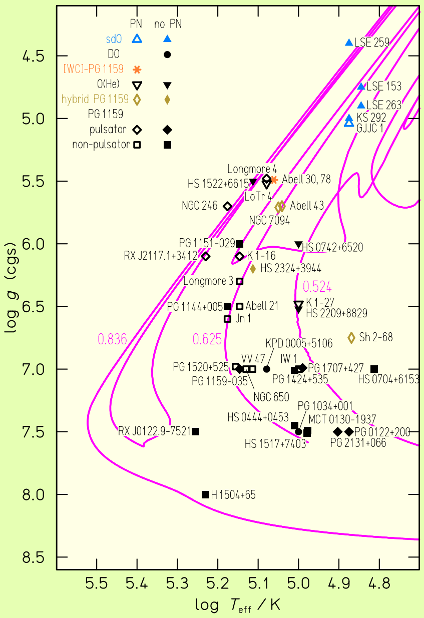

Fig. 1 Positions of post-AGB stars in the log T_{eff} – log g plane compared to theoretical evolutionary tracks for born-again post-ABG stars (Blöcker 1995). The tracks are labeled with the respective stellar masses (in $M_\odot$). Most of these objects have been analyzed by our group

Impact of light metals (F – Ca)

The drastic impact of the light metals (F – Ca) on the emergent flux in the EUV / X-ray wavelength region is shown in Fig. 3 (cf. Rauch 1997).

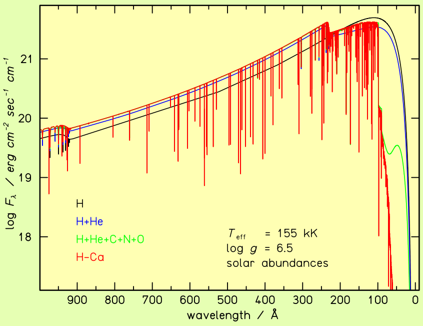

Fig. 3 Comparison of NLTE model atmosphere fluxes with different elemental composition at solar abundances

Iron-group elements (Sc – Ni)

A detailed consideration of all line transitions of the iron-group elements, like tabulated in Kurucz (1996), is impossible. Thus, we employed an opacity sampling method in order to calculate their absorption cross sections.

Tab. 1 Statistics of the model atoms used in our calculations of the NLTE model atmospheres. The notation is: NLTE = levels treated in NLTE, LTE = LTE levels, RBB = radiative bound-bound transitions

atom	ion	NLTE	LTE	RBB
H	I	10	6	45
	II	1	-	-
He	I	5	21	8
	II	10	22	45
	III	1	-	-
C	III	3	64	1
	IV	5	11	6
	V	5	28	3
	VI	1	0	0
N	III	1	44	1
	IV	3	91	1
	V	5	15	6
	VI	1	0	0
O	IV	4	7	3
	V	5	7	6
	VI	5	6	1
	VII	1	0	0
F	V	3	6	1
	VI	3	4	1
	VII	2	4	1
	VIII	1	0	0
Ne	IV	4	6	1
	V	9	4	4
	VI	8	15	9
	VII	10	35	12
	VIII	1	0	0
Na	IV	1	4	0
	V	4	4	1
	VI	5	7	1
	VII	4	7	2
	VIII	1	0	0
Mg	IV	1	13	0
	V	5	16	2
	VI	4	4	1
	VII	5	7	1
	VIII	1	0	0
Al	IV	1	16	0
	V	5	12	3
	VI	5	15	3
	VII	4	3	1
	VIII	1	0	0
Si	IV	1	6	0
	V	4	12	2
	VI	2	1	1
	VII	4	3	1
	VIII	1	0	0
P	V	3	9	2
	VI	3	2	2
	VII	2	2	1
	VIII	1	0	0
S	VI	3	9	2
	VII	6	32	4
	VIII	1	0	0
Cl	VI	3	5	1
	VII	3	5	1
	VIII	3	4	2
	IX	1	0	0
Ar	VII	3	17	1
	VIII	3	6	2
	IX	4	2	2
	X	1	0	0
K	VII	1	13	0
	VIII	4	10	1
	IX	3	4	2
	X	1	0	0
	XI	1	0	0
Ca	VII	5	12	1
	VIII	3	6	1
	IX	3	17	1
	X	3	9	2
	XI	4	28	2
	XII	1	0	0
	total	225	719	197

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NLTE Model Atmospheres for Central Stars of Planetary Nebulae

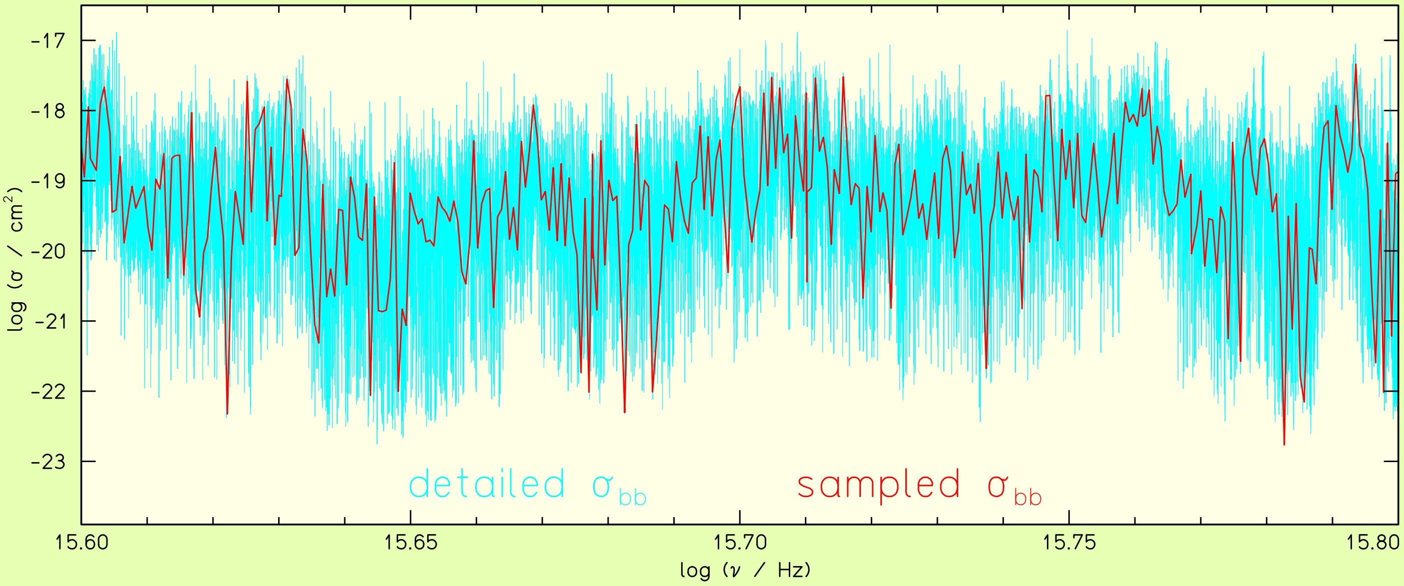

Fig. 3 Radiative bound-bound cross-section $\sigma_{4,6}$ (band 6 to band 4) of Fe IV at $n_e = 10^{16}\,\mathrm{cm}^{-3}$, considered in detail (blue, more than 1 000 000 frequency points within $10^{12}\,\mathrm{Hz} \le \nu \le 10^{17}\,\mathrm{Hz}$) and with our opacity sampling method (red, about 10 000 frequency points)

Cross-sections of iron-group elements

- Cross-Section Creation Package **CSC** (Deetjen 1999)

→ http://astro.uni-tuebingen.de/~ deetjen/csc.html

→ line cross-sections
  - radiative und collisional bound-bound
  - Kurucz's line lists (1996)
  - opacity sampling method

→ photoionization cross-sections
  - radiative und collisional bound-free
  - Opacity Project (Seaton 1994) for Fe

The term scheme of the model atom is typically divided into seven energy bands (Haas 1997, Fig. 4)

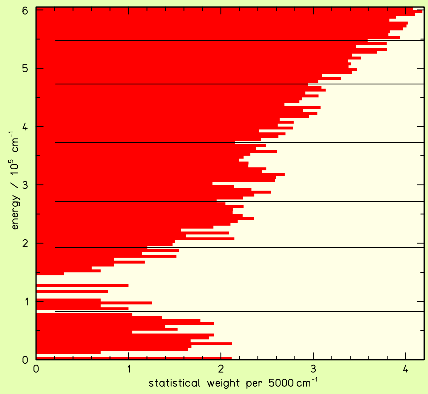

Fig. 4 Energy band structure of an iron-group model atom

A sample of iron-group elements can be combined in one generic model atom. The statistics of a typical generic model atom are summarized in Tab. 2

Tab. 2 Summary of a generic Sc-Ni model atom used in our model atmosphere calculations. Numbers in brackets denote individual levels and lines used in the statistical NLTE line-blanketing approach

element	ion	NLTE levels	line transitions
generic	V	7 (20 437)	26 (6 042 725)
	VI	7 (16 062)	26 (4 784 314)
	VII	7 (12 870)	26 (2 573 617)
	VIII	7 (9 144)	28 (3 229 141)
total		28 (58 513)	106 (16 656 797)

Impact of iron-group elements

- H-Ca + iron-group model
- H-Ca trunk model atom (Tab. 1)
- Sc – Ni in addition, generic model atom (Tab. 2)
  - all available (experimental + theoretical) levels + lines

The impact of the iron-group elements (Sc - Ni) on the model flux is shown in Fig. 5.

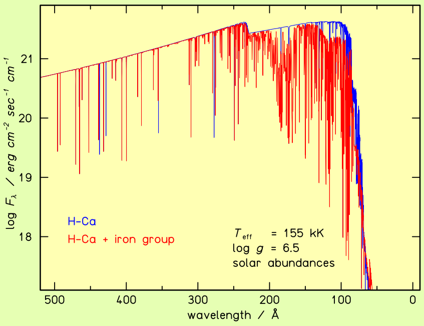

Fig. 5 Comparison of two NLTE model atmosphere fluxes without and with (cf. Fig. 3) consideration of iron-grup elements at solar abundances

In order to estimate the influence of an improved metal-line blanketing of Ca, we calculated a H-Ca model where we used the opacity sampling method analogously for Ca. The changes are significant and are shown in Fig. 6.

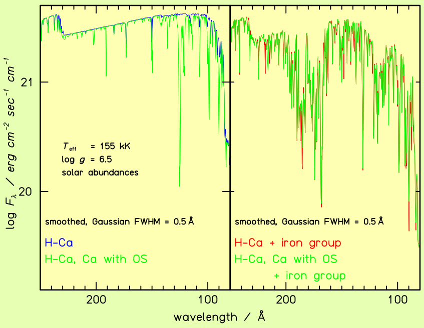

Fig. 6 Comparison of NLTE model atmosphere fluxes. Left: a H-Ca model with and without opacity sampling (OS) for Ca, right: H-Ca + iron group model from Fig. 5 with and without OS for Ca

Conclusions

- Emergent fluxes calculated from NLTE model atmospheres which include iron-group line blanketing show a drastic decrease of the flux level at high energies.
- For a reliable analysis of extremely hot stars, or the calculation of ionizing spectra from these (e.g. used as input for photoionization models) the consideration of all elements from hydrogen up to the iron group is mandatory.
- In the case of H – Ca models, a detailed consideration of the metal-line blanketing with all available lines of the light metals has an important influence on the spectrum.

Ongoing and future work

PRO2 is permanently updated in order to calculate state-of-the-art models for the analysis of the available spectra. This includes in the near future

- sphericity
- diffusion
- polarized radiation transfer

A new grid of models (cf. Fig. 2) which includes a detailed line blanketing by Ca and by the iron group (cf. Figs. 5, 6) is presently calculated and will be available on the WWW at the end of this year.

References

Blöcker T. 1995, A&A 299, 755
Deetjen J.L. 1999, diploma thesis, University Tübingen
Deetjen J.L., Dreizler S., Rauch T., Werner K. 1999, in: White Dwarfs, ed. J.-E.Solheim, The ASP Conference Series, in press
Dreizler S., Werner K. 1993, A&A 278, 199
Haas S. 1997, PhD thesis, University Erlangen-Nürnberg
Kurucz R.L. 1996, IAU Symp. 176, Kluwer, Dordrecht, p. 52
Paczynski B. 1970, Acta Astr. 20, 47
Rauch T. 1997, A&A 320, 237
Seaton M.J., Yu Yan, Mihalas D., Pradhan A.K. 1994, MNRAS 266, 805
Werner K. 1986 A&A 161, 177
Werner K. 1988, A&A 204, 159

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