NLTE Model Atmospheres
for Central Stars of Planetary Nebulae

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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.

1. 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 star with a remnant mass of 1.2 M⊙. Realistic modeling of the emergent fluxes of these stars requires the consideration of all elements from hydrogen up to the iron group under NLTE conditions.

2. NLTE Model Atmospheres

The model atmospheres (plane-parallel, hydrostatic and radiative equilibrium) are calculated using the code PRO2 (Werner 1986). All elements from hydrogen to the iron group are considered (Rauch 1997, Dreizler & Werner 1993, Deetjen et al. 1999). A grid of model atmosphere fluxes (T_{eff} = 50 – 1000 kK, log g = 5 – 9 (cgs), H – Ca, solar and halo abundances) is available at the WWW [http://astro.uni-tuebingen.de/~rauch/flux.html].

3. Impact of light metals (F – Ca)

The high-energy model atmosphere fluxes strongly depend on the metal-line blanketing. The impact of H – Ca is shown in Fig. 1 (cf. Rauch 1997).
Figure 1. Comparison of NLTE model atmosphere fluxes with different elemental composition at solar abundances ($T_{\text{eff}} = 155$ kK, $\log g = 6.5$). Note the drastic decrease of the flux level at wavelengths shorter than 100 Å if the metal-line blanketing of the light metals H-Ca is considered.

4. Impact of 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 account for their absorption cross-sections. Their cross-sections are calculated with the newly developed Cross-Section Creation Package CSC (http://astro.uni-tuebingen.de/~deetjen/csc.html). Radiative und collisional bound-bound line cross-sections are calculated from Kurucz’s line lists (1996; Fig. 2). Radiative und collisional bound-free photoionization cross-sections of Fe are calculated from Opacity Project data (Seaton et al. 1994).

Figure 2. Part of the radiative bound-bound cross-section $\sigma_{4,6}$ (band 6 to band 4) of Fe V at $n_e = 10^{16}$ cm$^{-3}$, considered in detail (520 360 frequency points within $2.0 \cdot 10^{15}$ Hz $\leq \nu \leq 6.8 \cdot 10^{15}$ Hz) and with our opacity sampling grid (973 frequency points)
All iron-group elements can be combined in one generic model atom. Its term scheme is typically divided into seven energy bands (Fig. 3, Dreizler & Werner 1993). The statistics of a typical generic model atom are summarized in Tab. 1.

![Figure 3. Energy band structure of an iron-group model atom](image)

Table 1. 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

| ion | NLTE levels | line transitions |
|-----|-------------|------------------|
| 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) |

In order to investigate the impact of the iron-group elements on the emergent flux, we used a H-Ca trunk model atom (Rauch 1997) and added Sc – Ni in form of a generic model atom (Tab. 1), including all available (experimental + theoretical) levels and lines from Kurucz’s list (1996). In Fig. 4 we show the additional impact of the iron group elements.
5. Conclusions and future work

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 UV/EUV and X-ray spectra of central stars of planetary nebulae, 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. A detailed consideration of the metal-line blanketing with all available lines has an important influence on the spectrum.

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 spherical geometry, element diffusion, and polarized radiation transfer.

A new grid of model fluxes which includes a detailed line blanketing by Ca and by the iron group will be soon available on the WWW.

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