Spectral Analysis of Central Stars of Planetary Nebulae

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Summary. Spectral analysis by means of NLTE model atmospheres has presently arrived at a high level of sophistication. High-resolution spectra of central stars of planetary nebulae can be reproduced in detail from the infrared to the X-ray wavelength range. In the case of LS V +46°21, the exciting star of Sh 2−216, we demonstrate the state-of-the-art in the determination of photospheric properties like, e.g., effective temperature (T_eff), surface gravity (g), and abundances of elements from hydrogen to nickel. From such detailed model atmospheres, we can reliably predict the ionizing spectrum of a central star which is a necessary input for the precise analysis of its ambient nebula.

NLTE model-atmosphere spectra, however, are not only accessible for specialists. In the framework of the *German Astrophysical Virtual Observatory* (*GAVO*), we provide pre-calculated grids of tables with synthetic spectra of hot, compact stars as well as a tool to calculate individual model-atmosphere spectra in order to make the use of synthetic stellar spectra as easy as the use of blackbody flux distributions had been in the last century.

Key words: ISM: planetary nebulae: individual: Sh 2−216 – Stars: abundances – Stars: atmospheres – Stars: evolution – Stars: individual: LS V +46°21 – Stars: AGB and post-AGB

1 Introduction

A reliable determination of properties of planetary nebulae (PNe) requires precise knowledge about their central stars (CS). A photoionization code may be perfect, yet still provide inaccurate results if the model spectrum of the exciting star does not match the actual spectrum of the star.

In the last two decades both, observational techniques as well as numerical methods in theory have been strongly improved. State-of-the-art NLTE

Fig. 1. Composite wide-field image (North is up and East is left) of Sh 2−216 (apparent diameter of 100') taken by Dean Salman (http://www.deansalman.com). The exposure time is 600 min in H α (red) and 180 min in [O III] (green). Note that Sh 2−216 has an interaction with the interstellar medium (ISM; Tweedy, Martos, & Noriega-Crespo 1995), its CS left the geometrical center about 45 000 years ago (Kerber et al. 2004) and is presently located nearly halfway towards the eastern rim (Cudworth & Reynolds 1985).

model-atmosphere codes like, e.g., *TMAP*[1], the *Tübingen NLTE Model Atmosphere Package* (Werner et al. 2003; Rauch & Deetjen 2003), calculate plane-parallel, chemically homogeneous models in hydrostatic and radiative equilibrium which consider opacities of all elements from hydrogen up to the iron-group (Rauch 1997, 2003) and thus, are well suited to provide synthetic ionizing spectra for hot, compact stars.

In this paper, we use LS V +46°21, the central star of Sh 2−216 (Fig. 1), in order to demonstrate the capabilities of *TMAP* to reproduce the UV spectra of hot stars (Sect. 2).

The perspectives of spectral analysis in the framework of the *Virtual Observatory* (*VO*) are described by the example of synthetic spectra calculated by *TMAP* (Sect. 3).

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[1] http://astro.uni-tuebingen.de/~rauch/TMAP/TMAP.html

2 Spectral analysis of hot, compact stars

Stars with high $T_{\rm eff}$ (in the case of CS up to about 200 kK) have their flux maximum in the EUV. Since precise NLTE spectral analysis needs metal lines (of highly ionized species) in order to determine $T_{\rm eff}$ (evaluation of ionisation equilibria) and elemental abundances, high signal-to-noise (S/N) and high-resolution UV spectra are necessary. These were provided by instruments aboard the HST[2], namely FOS[3] (working 1990 – 1997, wavelength range 1150 Å $<\lambda<$ 8000 Å, resolution $\approx$ 1.9 Å), GHRS[4] (1990 – 1997, 1150 Å $<\lambda<$ 3000 Å, resolving power $R \leq 80\,000$), STIS[5] (1997 – 2004, 1150 Å $<\lambda<$ 3175 Å, $R \leq 114\,000$) and by FUSE[6] (1999 – 2007, 904 Å $<\lambda<$ 1190 Å, $R \leq 20\,000$).

The photospheric spectra of CS are characterized by a few, broad and shallow, absorption lines from highly ionized species like, e.g., He II, C IV, O VI, Ne VII (Werner et al. 2004), Ne VIII (Werner et al. 2007), Si IV, Si V (Jahn et al. 2007), Si VI (Jahn et al. 2007), S VI (Miksa et al. 2002), Ar VI (Rauch et al. 2007), Ar VII (Werner et al. 2007). As an example, in Fig. 2 we show recently identified Ne VIII lines in the spectrum the PG 1159-type CS RX J2117.1+3412.

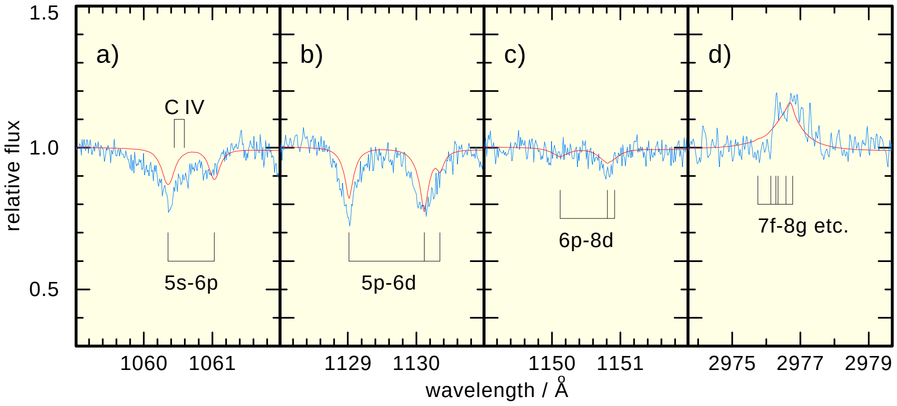

Fig. 2. Identification of Ne VIII lines in the FUSE (panels a – c) and HST/GHRS (panel d) observations of the extremely hot ($T_{\rm eff} = 170$ kK) CS of MWP 1 (PN G080.3−10.4, Motch, Werner & Pakull 1993), RX J2117.1+3412 (Werner et al. 2007). Note that the C IV doublet in panel a is not included in the model.

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[2] Hubble Space Telescope

[3] Faint Object Spectrograph

[4] Goddard High-Resolution Spectrograph

[5] Space Telescope Imaging Spectrograph

[6] Far Ultraviolet Spectroscopic Explorer

In a recent spectral analysis of LS V +46°21 by means of *TMAP* NLTE model atmospheres, Rauch et al. (2007) considered the elements H, He, C, N, O, F, Mg, Si, P, S, Ar, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, and Ni. H − Ar were represented by "classical" model atoms (Rauch 1997) partly taken from *TMAD*[7], the *Tübingen Model Atom Database*. For Ca−Ni individual model atoms are constructed by *IrOnIc* (Rauch & Deetjen 2003), using a statistical approach in order to treat the extremely large number of atomic levels and line transitions by the introduction of "super-levels" and "super-lines". In total 686 levels are treated in NLTE, combined with 2417 individual lines and about 9 million iron-group lines, taken from Kurucz (1996) as well as from the OPACITY and IRON projects (Seaton et al. 1994; Hummer et al. 1993) (see Rauch et al. 2007, and references therein for details).

More than 2000 spectral lines could be identified in the FUSE and STIS spectra of LS V +46°21. This is about 95% of all spectral features in this wavelength range. It has been possible to identify lines of, e.g., Si V (for the first time in the spectrum of this star), Mg IV (for the first time in such objects), and Ar VI (for the first time in any star). However, it is likely that the still unidentified lines simply stem from the most prominent ions as well, but their wavelengths are not precisely known because no laboratory measurements exist. E.g., Kurucz (1996) lists fewer than about one percent of his Fe VI and Fe VII lines as having measured wavelengths.

The evaluation of ionisation equilibria of different elements and ionisation stages (Fig. 3) allowed to determine $T_{\mathrm{eff}} = 95 \pm 2\,\mathrm{kK}$ (and $\log g = 6.9 \pm 0.3$) with high accuracy (cf. Rauch et al. 2007, for further details).

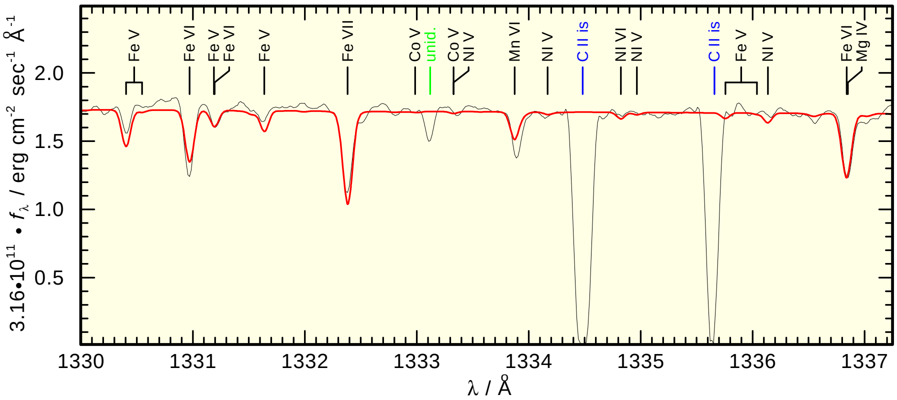

Fig. 3. Modelling the ionisation equilibrium of Fe V − Fe VII. It is well matched at $T_{\mathrm{eff}} = 95\,\mathrm{kK}$. Ionisation equilibria are sensitive indicators for T_{eff}. The marks indicate the positions of identified lines (is denotes interstellar lines, unid. is an unidentified line).

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[7] http://astro.uni-tuebingen.de/~rauch/TMAD/TMAD.html

The abundance pattern found in LS V +46°21 (Fig. 4) is the result of the interplay of gravitational settling (in the case of lighter elements, like He and C) and radiative levitation (for the iron-group elements). The results of Rauch et al. (2007) are mostly in good agreement with diffusion models for DA white dwarfs (Chayer et al. 1995, Fig. 4). Unfortunately, it is not possible to compare the results for all elements from H − Ni. One reason for this is the lack of reliable atomic data for all the species and especially their higher ionisation stages. Every endeavor should be made to improve the atomic data, as the gaps in our knowledge in this area hamper reliable modeling in many fields of astronomy, not only in stellar spectral analysis.

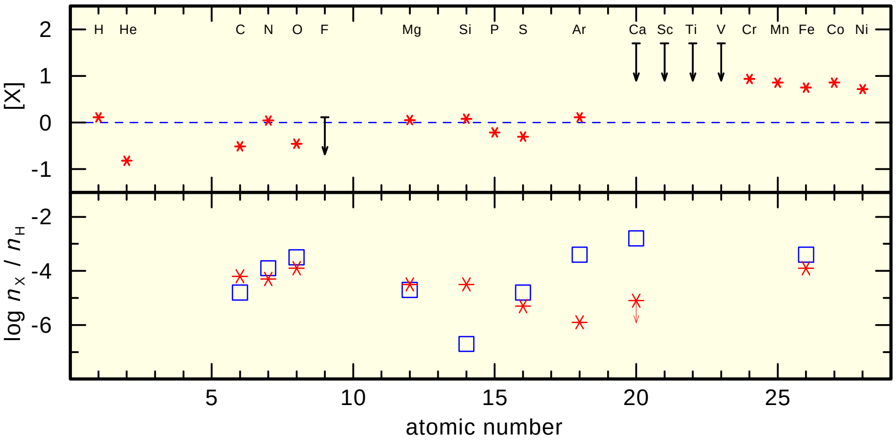

Fig. 4. Top: Photospheric element abundances of LS V +46°21 determined from detailed line profile fits. [x] denotes log (mass fraction / solar mass fraction) of species x. The dashed, horizontal line indicates the solar abundance values (Asplund, Grevesse & Sauval 2005). For F, Ca, Sc, Ti, and V upper limits can be found only. Bottom: Comparison of the elemental number ratios found in our spectral analysis (red stars) compared to predictions (blue squares) of diffusion calculations for DA models (Chayer et al. 1995) with $T_{\mathrm{eff}} = 95$ kK and $\log g = 7$.

Another problem for the precise analysis of UV spectra of hot stars is the contamination by interstellar absorption. Rauch et al. (2007) have used the *OWENS* program in order to model simultaneously both, the stellar as well as the interstellar absorption lines (cf. Oliveira et al. 2007, for more details).

The spectral analysis of LS V +46°21 (Rauch et al. 2007) has made use of the most detailed model atmospheres which were calculated with *TMAP* so far. The interested reader may have a look at the large online plots[8] which are provided by Rauch et al. (2007) in order to convince oneself that the agreement between observation and theory is impressive.

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[8] http://vizier.cfa.harvard.edu/viz-bin/ftp-index?J/A%2BA/470/317

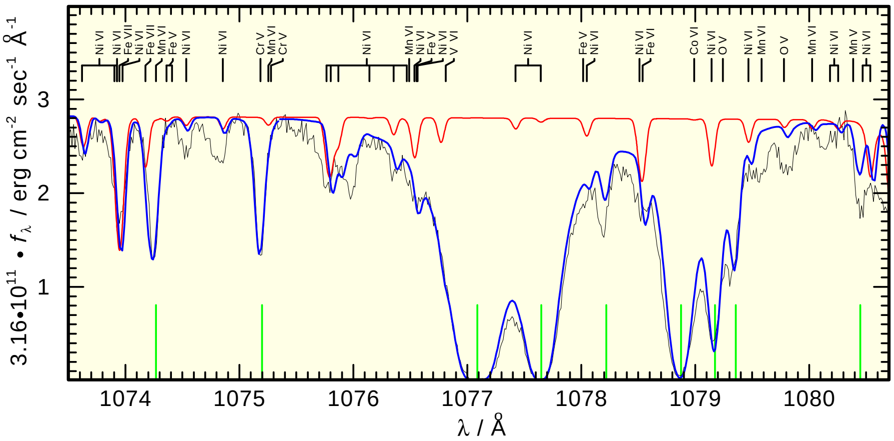

Fig. 5. Modelling of the ISM absorption lines with *OWENS*. Section of the FUSE spectrum of LS V +46°21 compared with the final model of Rauch et al. (2007, thin line) and with the combined ISM + model-atmosphere spectrum (thick line). Identified lines are marked at top. Most of the interstellar absorption is due to H_2 (the line positions are marked by vertical bars at the bottom). The synthetic spectra are normalized to match the local continuum. Note that it is possible to unambiguously identify a few isolated photospheric lines, e.g. Fe VII λ 1073.9 Å, which are suitable for spectral analysis.

3 TMAP and the Virtual Observatory

In the framework of the *German Astrophysical Virtual Observatory* project (*GAVO*, please note that the URLs given below will change to the *GAVO* portal[9] later), we use *TMAP* to provide synthetic model-atmosphere spectra. For the *VO* user, there are three access levels:

- The most easy way is to use pre-calculated grids of model-atmosphere flux tables (*TMAF*[10]).
- A WWW interface allows to calculate simple (H+He+C+N+O) model atmospheres based on pre-defined model atoms for an individual object without profound experience with *TMAP* (*TMAW*[11]).
- For a more detailed analysis, the *VO* user may use atomic data which are provided within the *Tübingen Model-Atom Database TMAD*[12] in order to construct a custom model atom (H − Ni) which is suited for the investigation on a particular star.

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[9] http://www.g-vo.org/portal/

[10] http://astro.uni-tuebingen.de/~rauch/TMAF/TMAF.html

[11] http://astro.uni-tuebingen.de/~rauch/TMAW/TMAW.html

[12] http://astro.uni-tuebingen.de/~rauch/TMAD/TMAD.html

With this approach, a *VO* user may compare observation and synthetic spectra at three stages: The easiest and fastest way is the inter- or extrapolation within the flux-table grids. For a more detailed analysis, the *VO* user may improve the fit to the observation by the calculation of adjusted model atmospheres with individual stellar photospheric parameters via *TMAW*. A more experienced *VO* user may tailor own atomic-data files for an individual analysis and then calculate model atmospheres and flux tables with these.

TMAP flux tables are already incorporated into the photoionization codes *CLOUDY* (Ferland et al. 1998) and *MOCASSIN* (e.g. Ercolano et al. 2003, 2005). We will create a WWW interface for the control of the 3D-code *MOCASSIN* which makes then directly use of model-atmosphere fluxes within the *GAVO* database. However, any photoionization code may benefit from the synthetic spectra provided by the *VO*.

4 Conclusions

NLTE model atmospheres which are calculated with state-of-the-art codes like, e.g., *TMAP* have presently arrived at a high level of sophistication and are successfully employed for the analysis of, e.g., central stars of planetary nebulae.

The spectral analysis of high-resolution and high-S/N UV spectra has shown that the available atomic data is not complete and partly not accurate enough even for the most abundant species (cf. Rauch et al. 2007)

Atomic physicists are therefore challenged to measure atomic data precisely for many elements and for higher ionization stages. Better atomic and, e.g., line-broadening data will then strongly improve future spectral analyses and thus, make determinations of photospheric properties more reliable.

NLTE model-atmosphere fluxes are now easy to access and it is recommended to use them instead of blackbody flux distributions which are only a bad approximation of a real star.

The *VO* has become an invaluable source for the future spectral analysis. Any astronomer who has data, either observations or models, should be aware of this and contribute to the improvement of databases and tools within the *VO*.

Acknowledgement. T.R. is supported by the *German Astrophysical Virtual Observatory* project of the German Federal Ministry of Education and Research under grant 05 AC6VTB. J.W.K. is supported by the FUSE project, funded by NASA contract NAS532985. This research has made use of the SIMBAD Astronomical Database, operated at CDS, Strasbourg, France. This work has been done using the profile-fitting procedure *OWENS* developed by M. Lemoine and the FUSE French Team.

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