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Non-LTE Spectral Analysis of Extremely Hot Post-AGB Stars: Constraints for Evolutionary Theory

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Abstract. Spectral analysis by means of Non-LTE model-atmosphere techniques has arrived at a high level of sophistication: fully line-blanketed model atmospheres which consider opacities of all elements from H to Ni allow the reliable determination of photospheric parameters of hot, compact stars. Such models provide a crucial test of stellar evolutionary theory: recent abundance determinations of trace elements like, e.g., F, Ne, Mg, P, S, Ar, Fe, and Ni are suited to investigate on AGB nucleosynthesis. E.g., the strong Fe depletion found in hydrogen-deficient post-AGB stars is a clear indication of an efficient s-process on the AGB where Fe is transformed into Ni or even heavier trans iron-group elements. We present results of recent spectral analyses based on high-resolution UV observations of hot stars.

Keywords. astronomical data bases: miscellaneous, atomic data, line: identification, stars: abundances, stars: AGB and post-AGB, stars: atmospheres, stars: early-type, stars: evolution, (stars:) white dwarfs

1. Introduction

In the last decades, our picture of post-AGB stellar evolution has been greatly improved. The "standard" evolution, i.e. the hydrogen-rich sequence, has been understood in the early eighties of the last century by comparison of spectral analysis and evolutionary models. The spectral analysis of the hottest post-AGB stars with effective temperatures ($T_{\rm eff} > 100,000\,{\rm K}$) was hampered by the lack of appropriate model atmospheres which considered deviations from the local thermodynamic equilibrium (LTE) playing an important role in the photospheres of these stars. The development of such Non-LTE model atmospheres is briefly summarized in Sect. 2.

Spectral analyses of hot post-AGB stars have shown then that about a quarter of these are hydrogen-deficient (Werner & Herwig 2006). The "born-again post-AGB star" scenario by Iben et al. (1983) is – in general – able to explain the evolution of these stars. A final thermal pulse (TP, re-ignition of the helium shell) brings the star back to the AGB and it has a second, helium-burning post-AGB phase. However, the mechanism to dispose of the entire hydrogen-rich envelope was unclear. Present evolutionary calculations which consider the mixing and burning processes during the helium-shell flash in detail, are able to explain the hydrogen deficiency.

The amount of remaining hydrogen is depending on the particular time when the TP occurs. Still on the AGB (AGB Final Thermal Pulse, AFTP), the masses of the hydrogen-rich envelope and the helium-rich intershell layer (Fig. 1) are about equal, being roughly

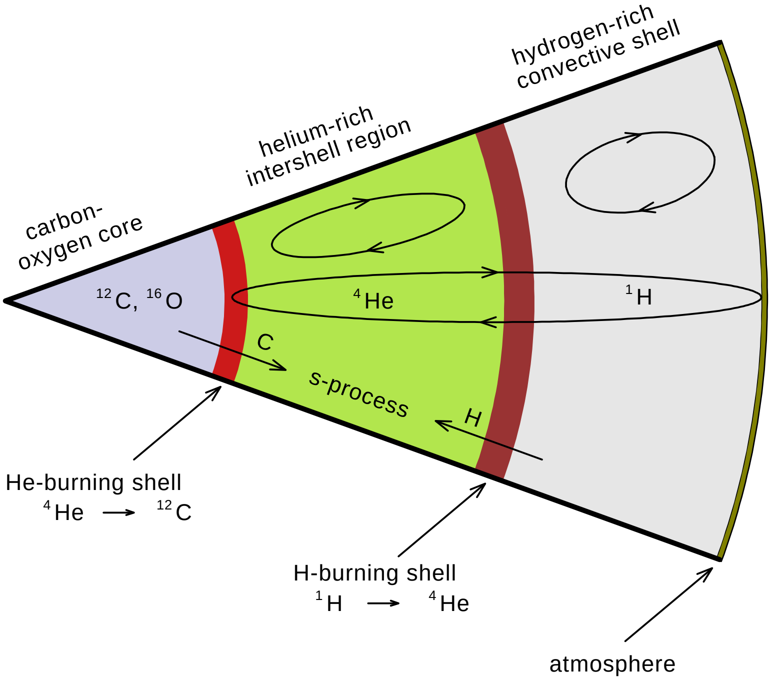

Figure 1. Inner structure of an AGB star. Note that the convection zone from the surface to the bottom of the helium-burning shell is established during a TP only.

$10^{-2}\,\mathrm{M}_\odot$. The TP mixing results in $\approx 40\,\%$ hydrogen content (by mass) at the stellar surface. This is detectable in the observations. After the departure from the AGB, the mass of the hydrogen-rich envelope is much lower ($M_\mathrm{H} \approx 10^{-4}\,\mathrm{M}_\odot$). If the TP occurs at still constant (high) luminosity (Late Thermal Pulse, LTP), i.e. nuclear burning is still "on", the mixing during the flash reduces the surface hydrogen to $\approx 1\,\%$ which is not detectable at the high surface gravity ($\log g \approx 5-8$ in cm/sec^2). A TP at already declining luminosity, i.e. there is no entropy barrier due to the hydrogen-burning shell, will mix down the hydrogen-rich envelope to the bottom of the now re-ignited helium shell where hydrogen is burned and the star becomes hydrogen free.

The mixing process during the TP brings intershell matter up to the stellar surface and, thus, allows a direct view on it. Spectral analysis allows then to conclude on details of both, mixing as well as nuclear processes like, e.g. the s-process, in AGB stars. This is a crucial test for stellar evolutionary models.

2. Model atmospheres and atomic data

The spectral analysis of hot stars requires suitable Non-LTE model atmospheres†. Such models are available since Werner (1986, 1989) presented the first calculation based on the accelerated lambda iteration (ALI) techniques. For more details see, e.g., Hubeny (2003); Lanz & Hubeny (2003); Rauch & Deetjen (2003). Presently, our Tübingen NLTE Model Atmosphere Package‡ (*TMAP*, Werner et al. 2003; Rauch & Deetjen 2003) is ca-

† For cool stars with spectral type B ar later LTE modeling may be adequate but there are always Non-LTE effects in any star, which are important at least if high-resolution and/or high/energy observations are analyzed.

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

pable to calculate plane-parallel and spherical, chemically homogeneous, Non-LTE model atmospheres in radiative and hydrostatic equilibrium and considers opacities of all species from hydrogen to nickel (Rauch 1997, 2003).

In the last two decades, *TMAP* has been successfully employed for the analysis of hot post-AGB stars (e.g. Jahn et al. 2007; Rauch et al. 2007). Space-based observatories like, e.g., FUSE† and HST‡, have provided high-resolution, high-S/N UV spectra which have shown that we arrived at a severe limitation due to the lack of reliable atomic and line-broadening data for highly ionized species. This is a challenge for atomic physics.

3. Selected results of spectral analyses

In this section, we will highlight some recent important results of our analyses. For a more detailed review on the spectroscopy of hydrogen-deficient post-AGB stars see Werner & Herwig (2006).

Fluorine (F VI $\lambda\,1139.50$ Å) has been identified for the first time in FUSE observations of post-AGB stars (Werner et al. 2005). F is produced during helium burning on the AGB via $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(\mathrm{p},\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$. Our spectral analysis has shown that the F abundance in hydrogen-deficient PG 1159-type stars is about 200× solar (cf. Asplund et al. 2005). This result confirms the F intershell abundances predicted by evolutionary models (Lugaro et al. 2004).

Neon (Ne VII $\lambda\,3644.6$ Å) was first identified by Werner & Rauch (1994) in optical observations of PG 1159 stars. It is worthwhile to note that this line was detected in a high-temperature discharge plasma as a weak blend on a strong Ne II line already many years ago (**?**) und is frequently used as a calibration line in the laboratory (König et al. 1993) – unfortunately this was not known in astronomy before and demonstrates the need for improvement and extension of atomic-data databases. Ne is synthesized in the helium-burning shell by the $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ chain. The determined photospheric abundance is 2% by mass (11× solar, Werner & Rauch 1994), well in agreement with early evolutionary models of Iben & Tutukov (1985).

In FUSE observations of PG 1159 stars, we could firstly identify Ne VII $\lambda\,973.3$ Å (Werner et al. 2004) – a stellar wind can form a strong Ne VII P Cygni profile (Herald et al. 2005) – the closely located C III $\lambda\,977.3$ Å line is much too weak at the relevant temperature regime (Fig. 2).

Recently, Kramida & Buchet-Poulizac (2006) presented reliable atomic data of Ne VIII. This enables us to calculate the Ne VIII spectrum of hot post-AGB stars and we could identify Ne VIII absorption lines in FUSE observations (Werner et al. 2007b).

The identification of Ne VII and Ne VIII lines provides a new sensitive tool for very hot stars to determine T_{eff} by an evaluation of the Ne VII/VIII ionization equilibrium. It is worthwhile to note, that T_{eff} of the hottest known helium-rich DO white dwarf, KPD 0005+5106, had to be revised to $T_{\mathrm{eff}} \approx 200\,000$ K (previously 120 000 K) by the identification and modelling of Ne VIII emission lines in its spectrum. These lines were previously thought to be O VIII lines which however could not be of photospheric origin (Werner et al. 2007b).

Argon also provides an ionization equilibrium (Ar VI/VII) for the determination of T_{eff} in very hot stars. Werner et al. (2007a) identified Ar VII $\lambda\,1063.55$ Å in FUSE observations

† Far Ultraviolet Spectroscopic Explorer
‡ Hubble Space Telescope

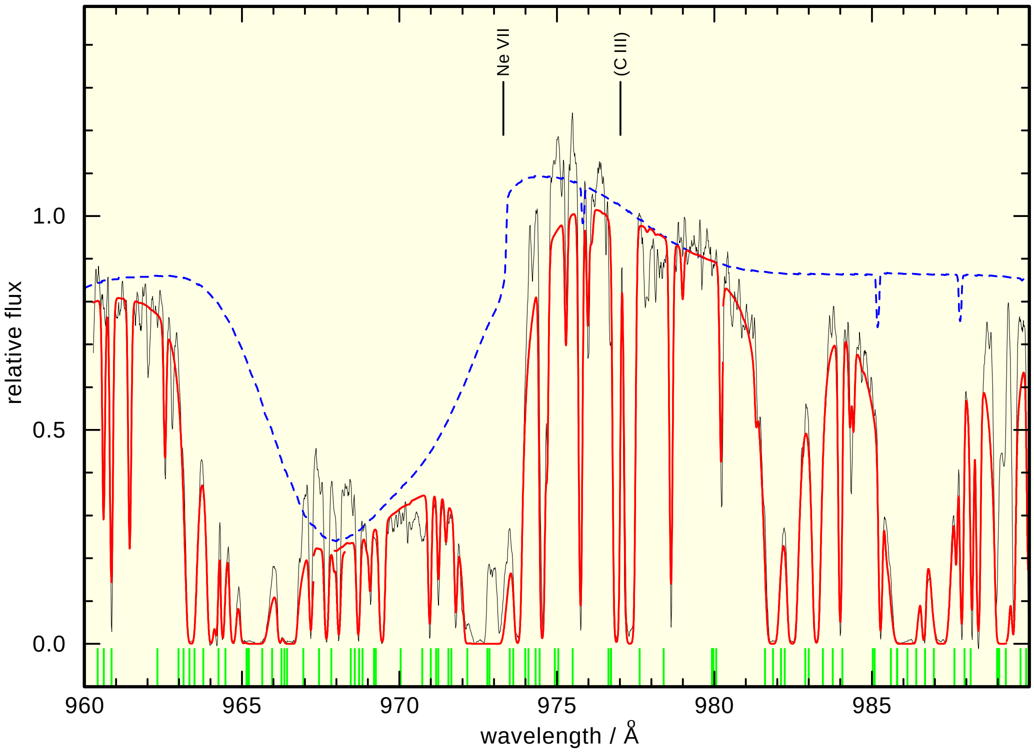

Figure 2. Comparison of the synthetic stellar spectrum (dashed, calculated with the *HotBlast* wind code) and the combined synthetic stellar and interstellar line spectrum around Ne VII λ 973.3 Å with the FUSE observation of the CSPN NGC 7094. Note that C III λ 977.3 Å is much too weak at $T_{\rm eff} = 110\,000$ K to explain the observed (Ne VII) profile. The vertical bars at the bottom mark the positions of H_2 lines in the interstellar spectrum.

of hot central stars of planetary nebulae (CSPNe) and in white dwarfs. Rauch et al. (2007) identified Ar VI lines in a HST/STIS¶ observations of the CSPN LSV 46°21.

Iron is not affected by nuclear burning but its abundance may be reduced due to n-captures in the s-process. Evolutionary calculations predict only a very weak extent of its depletion. In contrast, spectral analyses of FUSE observations with sufficiently high S/N of four hydrogen-deficient post-AGB stars have shown that no iron lines are detectable. Thus, a very strong Fe depletion (at least $1-2$ dex) takes place in the intershell (Miksa et al. 2002).

4. One example of spectral analysis: The exciting star of the planetary nebula NGC 7094

The CSPN NGC 7094 is a so-called hybrid PG 1159 star, i.e. it exhibits hydrogen lines in its spectrum. In a Non-LTE spectral analysis Dreizler et al. (1995) determined $T_{\rm eff} = 110\,000$ K, $\log g = 5.7$, and H:He:C:N:O = 0.42:0.51:0.05:(< 0.01):(< 0.01) in mass fractions. The CSPN NGC 7094 may thus be an AFTP star. Miksa et al. (2002) discovered a strong iron deficiency of about two dex. In an on-going analysis of FUSE and HST/STIS observations (Ziegler et al. in prep.), we aim to identify nickel lines in order to determine

¶ Space Telescope Imaging Spectrograph

the Fe/Ni abundance ratio which is a indicator for the efficiency of the s-process. We did not succeed in this attempt. It is possible that the s-process has transferred iron into nickel and then into more heavy species. Unfortunately, we cannot search for lines of trans iron-group elements because no atomic data are available.

We used the newly developed *HotBlast* Non-LTE code for spherically expanding atmospheres in order to calculate the P Cygni profile of Ne VII $\lambda\,973.3$ Å. *HotBlast* uses as an input the atmospheric structure of our static *TMAP* model to simulate the atmosphere below the "wind region". In the course of our analysis, it turned out that the FUSE observation is strongly contaminated by interstellar line absorption (Fig. 2). Therefore, we employed the programme *OWENS* (cf. Lemoine et al. 2002; Hébrard et al. 2002) which can simulate interstellar clouds with individual parameters like, e.g., radial velocity, column density in the line of sight, temperature of the gas, and microturbulence velocity. Although we show in Fig. 2 only a qualitative fit of the ISM line absorption, it is obvious that simultaneous modeling of both, the stellar and interstellar line spectrum, is necessary in order to search and identify weak metal lines.

5. Spectral analysis in the 21$^{\rm st}$ century

Spectral analysis by means of Non-LTE model-atmosphere techniques has for a long time been regarded as a domain of specialists. Within the *German Astrophysical Virtual Observatory* (*GAVO*†) project, we have created the VO service *TheoSSA*‡. A VO user may use pre-calculated grids of spectral energy distributions (SEDs, in a pilot phase calculated by *TMAP* for hot, compact stars only) which are ready to use and it may be interpolated between them to match the user-required parameters. This is the easiest way to use synthetic SEDs calculated from Non-LTE model atmospheres. They represent stars much better than still oftenly used blackbody flux distributions for PNe analyses.

If individual parameters are requested which do not fit to an already existing SED in the database, the VO user is guided to *TMAW*¶. With this WWW interface, the VO user may calculate an individual model atmosphere, requesting $T_{\rm eff}$, $\log g$, and mass fractions $\{X_{\rm i}\}$, i $\in$ [H, He, C, N, O] (more species will be included in the future). For this calculation, standard model atoms are used which are provided within the Tübingen Model-Atom Database (*TMAD*‖). Since the VO user can do this without detailed knowledge of the programme code working in the background, the access to individually calculated SEDs is as simple as the use of pre-calculated SEDs – however, the calculation needs some time (depending on the number of species considered, the wall-clock time is ranging from hours to a few days). Standard SEDs of all calculated model atmospheres are automatically ingested into the *GAVO* data base and, thus, it is growing in time.

In case that a detailed spectral analysis is performed, an experienced VO user may create an own atomic data file tailored for a specific purpose considering all necessary species (i $\in$ [H − Ni]) and calculate own model atmospheres and SEDs.

In close collaboration of *GAVO* with the *German Astronomy Community Grid* (*AstroGrid-D*††), the calculations of *TMAW* will be performed on GRID computers in the future. This will allow to calculate small grids of model atmospheres and SEDs on a reasonable timescale.

† http://www.g-vo.org
‡ Theoretical Simple Spectra Access, http://vo.ari.uni-heidelberg.de/ssatr-0.01/TrSpectra.jsp
¶ http://astro.uni-tuebingen.de/~rauch/TMAW/TMAW.shtml
‖ http://astro.uni-tuebingen.de/~rauch/TMAD/TMAD.html
†† http://www.gac-grid.de

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