(F)UV Spectroscopy of the hybrid PG 1159-type central stars of the planetary nebulae NGC 7094 and Abell 43

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Abstract. Hydrogen-deficient post-AGB stars have experienced a late helium-shell flash that mixes the hydrogen-rich envelope and the helium-rich intershell (between hydrogen- and helium-burning shell). The amount of hydrogen remaining in the stellar envelope depends on the particular moment when this late thermal pulse occurs. Previous spectral analyses of hydrogen-deficient post-AGB stars, namely PG 1159−035 and the central stars of the planetary nebulae (CSPN) K1−16, NGC 7094, and Abell 78, surprisingly revealed strong iron deficiencies of up to 1 dex. A possible explanation may be neutron captures due to an efficient s-process on the AGB that transformed iron into heavier elements. An increased abundance of these would be a strong indication for this scenario. Since reliable atomic data for highly ionized species heavier than iron is only available for cobalt and nickel, we can presently determine only the nickel abundance. We performed a detailed spectral analysis by means of NLTE model-atmosphere techniques based on high-resolution UV observations of the two PG 1159-type CSPN of NGC 7094 and Abell 43 which are spectroscopic twins, i.e., they exhibit very similar spectra. We confirmed a strong iron-deficiency of at least one dex in both stars. The search for nickel lines in their UV spectra was entirely negative. We find that both stars are even nickel deficient by about one dex.

1. Introduction

The hydrogen-deficient PG 1159 stars are the result of a late helium-shell flash (late thermal pulse, LTP; for details see Werner & Herwig 2006). The occurrence of such a flash (the reignition of helium-shell burning in a post-AGB star or white dwarf), was predicted in earlier investigations e.g. by Iben et al. (1983). For a schematic picture of the inner structure of an AGB star see Fig. 1. The time when the flash occurs determines the remaining photospheric hydrogen (Herwig 2001). Still on the AGB (AGB final thermal pulse, AFTP), flash-induced mixing of the hydrogen-rich envelope \((10^{-2} M_\odot)\) with the helium-rich intershell layer \((10^{-3} M_\odot)\) reduces the hydrogen abundance but Balmer lines remain detectable. After the departure from the AGB the hydrogen-rich envelope is less massive \((10^{-4} M_\odot)\). If the nuclear burning is still “on”, i.e. the star evolves at constant luminosity, the mixing due to a LTP reduces hydrogen below the detection limit (which is about 10 \% at the high surface gravities of \(\log g \approx 7\)). After a post-AGB star has entered the white-dwarf cooling sequence and the nuclear burning is “off”, a very late thermal pulse (VLTP) will cause convective mixing of the entire hydrogen-rich envelope.
down to the bottom of the helium-burning shell where hydrogen is completely burned. In that case, the star will become completely hydrogen free at that time. The hybrid PG 1159 stars, e.g. the CSPN of NGC 7094 and Abell 43, are AFTP stars.

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 late thermal pulse only.

Previous spectral analysis of three PG 1159 stars (NGC 7094, K 1-16, PG 1159-035) as well as one [WC]-PG 1159 transition object (Abell 78) have revealed a strong, unexpected Fe-deficiency of at least 1 dex (Miksa et al. 2002, Werner et al. 2003a). A possible explanation for the Fe-deficiency is the transformation of Fe into heavier nuclei due to s-process. Our analysis aims to determine the Ni abundance in the CSPN of NGC 7094 and Abell 43. An increased nickel abundance would be a hint for the transformation of Fe nuclei into heavier elements due to n-capture.

NGC 7094 was discovered by Lewis Swift in 1888 and it was classified as a planetary nebula (PN) in 1963 (Kohoutek 1963, PN G066.7−28.2). NGC 7094 is located at a distance of 2.2 kpc (Napiwotzki 1999) and has an apparent size of 102″5 × 99″4 (Tylenda et al. 2003). The photospheric parameters of its central star (CS) were previously determined by Dreizler et al. (1997) (T_{eff} = 110 kK, log g = 5.7 (cm/sec^2), H:He:C=0.36,0.43,0.21 in mass fractions).

Abell 43 was discovered in 1955 (Abell 1955, PN G036.0+17.6). Its apparent size is 80″×80″ (Napiwotzki & Schönberner 1995) and it is located at a distance of 2.2 kpc (Napiwotzki 1999). The CSPN of Abell 43 is a spectroscopic twin of the CSPN of NGC 7094 (Miksa et al. 2002).

We note that the CSPN of Abell 43 as well as of NGC 7094 are non-radial g-mode pulsators (Vauclair et al. 2005, Solheim et al. 2007). According to Solheim et al. (2007), the pulsation periods of Abell 43 lie in a range between 2.380 and 6.075 sec, which agrees reasonably well with the predicted theoretical periods (2.604 − 5.529 sec, Quirion et al. 2005). The theoretical pulsation periods of NGC 7094 (2.550 − 5.413 sec, Quirion et al. 2005) are also in good agreement with the observed periods (2.040 − 4.980 sec, Solheim et al. 2007).

In this analysis, we determine the photospheric parameters of the CSPN of NGC 7094 and Abell 43 precisely. In Sect. 2 we briefly describe the observations. Then, in a first step, we scrutinize the photospheric parameters determined by Dreizler et al. (1997) (Sect. 3). A detailed spectral analysis based of models that consider opacities of all elements from H to Ni is presented in Sect. 4.
2. **Observations**

A precise spectral analysis of hot stars requires high-resolution and high-S/N UV observations because most of the strategic lines of highly ionized metals are located in this wavelength range. E.g. in the Far Ultraviolet Spectroscopic Explorer (*FUSE*) spectra (905 $-$ 1187 Å, resolving power $R \approx 20\,000$), strong Fe$^{vii}$ and Ni$^{vi}$ lines might be found.

For our analysis, we performed *HST/STIS* observations of the CSPN of NGC 7094 (Table 1). They cover the range between 1150 $-$ 1730 Å with $R \approx 45\,800$. The spectra were retrieved from the MAST archive (standard pipeline reduction in version of 2006) and then co-added and subsequently smoothed with a Savitzky-Golay filter (Savitzky & Golay 1964). The achieved S/N is $> 50$. For Abell 43 no *HST/STIS* observation is available. *FUSE* observations were performed for both objects (Table 1), and processed in the standard pipeline with CalFUSE v3.1.

| Object       | Instrument | Dataset       | Start time (UT) | Aperture | Exp. time / sec |
|--------------|------------|---------------|-----------------|----------|-----------------|
| NGC 7094     | HST/STIS   | O8MU02010     | 2004-06-24 20:43:30 | E140M    | 650             |
| NGC 7094     | HST/STIS   | O8MU02020     | 2004-06-24 22:19:29 | E140M    | 656             |
| NGC 7094     | HST/STIS   | O8MU02030     | 2004-06-24 23:55:29 | E140M    | 655             |
| NGC 7094     | FUSE       | P1043701000   | 2000-11-13 08:53:28 | LWRS     | 22754           |
| Abell 43     | FUSE       | B0520202000   | 2001-08-03 22:18:20 | LWRS     | 9528            |
| Abell 43     | FUSE       | B0520201000   | 2001-07-29 20:41:47 | LWRS     | 11438

**Table 1.** *HST/STIS* and *FUSE* observation log for the CSPN of NGC 7094 and Abell 43.

![Figure 2](image_url)

*Figure 2.* Comparison of the *FUSE* spectra of the CSPN of NGC 7094 (top) and Abell 43 with synthetic spectra of our final model.

The *FUSE* observations of the CSPN of NGC 7094 and Abell 43 are strongly contaminated by interstellar line absorption (Fig. 2). We determine a reddening of $E_{B-V} = 0.15$ and $E_{B-V} = 0.25$ for the CSPN of NGC 7094 and Abell 43, respectively. A prominent P Cygni profile of O$^{vi}$ λλ 1031.9, 1037.6 Å is visible in the *FUSE* spectra of both stars. Ne$^{vii}$ λ 973.3 Å shows a weaker P Cygni profile (Fig. 5).
3. Model Atmospheres and Preliminary Analysis

Dreizler et al. (1997) used medium-resolution optical spectra of the CSPN of NGC 7094 for their analysis. Since then, our model atmospheres improved and high-resolution, high-S/N (R = 18 000) spectra were obtained during the SPY campaign (Napiwotzki et al. 2001) with VLT/UVES. Before we started to calculate detailed model atmospheres with all elements from H to Ni, we wanted to check the previously determined parameters.

Spectral energy distributions (SEDs) from TheoSSA\textsuperscript{1}, a service provided by the German Astrophysical Virtual Observatory (GA VO\textsuperscript{2}), showed that $T_{\text{eff}} = 100$ kK and log $g = 5.5$ with a H/He abundance ratio of H:He=0.17:0.69 gives a much better fit (Fig. 3) compared to the “old” parameters given by Dreizler et al. (1997). Especially the hydrogen abundance is much less than previously thought. We adopt $T_{\text{eff}} = 100$ kK, log $g = 5.5$, and H:He=0.17:0.69 for our further analysis. The abundances of the other metals that are considered in our models are adjusted to fit the observation (Sect. 4).

![Figure 3. Synthetic line profiles of He II $\lambda$4860.7 Å / H β (left) and He II $\lambda$5411.5 Å (right) calculated from two H+He+C+N+O model atmospheres (thick: $T_{\text{eff}} = 100$ kK, log $g = 5.5$, H:He=0.17:0.69; thin: $T_{\text{eff}} = 110$ kK, log $g = 5.7$, H:He=0.36:0.43, Dreizler et al. 1997) compared with the VLT/UVES observation of the CSPN of NGC 7094.](image)

4. Metal Abundances

We employed TMAP, the Tübingen NLTE Model Atmosphere Package (Rauch & Deetjen 2003, Werner et al. 2003b) for the calculation of plane-parallel, hydrostatic atmospheres in radiative equilibrium (for details on atomic data etc., see Rauch et al. 2007). Because the photospheric spectra of the two stars are so similar, we used a single set of models for both stars in our initial analysis. The calculated model atmospheres considered the opacities of 23 elements, including the iron-group (Ca–Ni). We calculated a small grid of model atmospheres with all elements and adjusted their abundances (Table 2).

The comparison of synthetic spectra calculated with different iron abundances shows that an upper limit of 0.1 times solar can be determined ([Fe] = −1, Fig. 4). This confirms a similar result by Miksa et al. (2002). The strongest nickel lines are not visible in the FUSE spectra.

\textsuperscript{1} http://vo.ari.uni-heidelberg.de/ssatr-0.01/TrSpectra.jsp
\textsuperscript{2} http://www.g-vo.org/
Table 2. Photospheric abundances of the CSPN of NGC 7094 and Abell 43. [X] denotes log (mass fraction / solar mass fraction) of element X. Solar abundances are adopted from Asplund et al. (2005). The other iron-group elements are not detected but considered with solar abundance (observational upper limit).

| X  | H  | He | C  | N  | O  | F  | Ne | Si | P  | S  | Fe | Ni |
|----|----|----|----|----|----|----|----|----|----|----|----|----|
| [X]| -0.62 | 0.45 | 1.76 | -0.85 | -1.81 | 0.34 | 0.00 | -0.21 | -1.15 | 0.16 | < -1 | < -1 |

The comparison with synthetic spectra gives an upper limit of the Ni abundance of 0.1 times solar ([Ni] = -1, Fig. 4).

Due to the similarity of their spectra, we used the same synthetic UV and FUV spectra for NGC 7094 and Abell 43. Despite a difference in the reddening, observation and model fit equally well in the UV wavelength range (Fig. 2). This is confirmed by comparison to optical spectra as well. We therefore adopt the same parameters for both stars.

The FUSE observations of the CSPN of NGC 7094 and Abell 43 are strongly contaminated by interstellar line absorption. To identify weak photospheric lines that are possibly hidden in this ISM absorption, it is necessary to model the ISM spectrum as well. This was done using OWENS, a code that considers a number of ISM clouds with different parameters such as radial and turbulent velocity, chemical composition, column densities of the included elements and the cloud temperature. We calculated a normalized ISM absorption spectrum which is then multiplied with the stellar model-atmosphere spectrum. An example of the quality of our fit to the FUSE observation of NGC 7094 can be seen in Fig. 5. However, we were not able to identify weak photospheric line hidden between ISM lines.

The FUSE observations of NGC 7094 and Abell 43 exhibit strong P Cygni profiles (Fig. 2, indicating ongoing mass loss driven by radiation pressure of the hot CS. The P Cygni profiles of Ne vii λ973.3 Å, the O vii λ1031.9, 1037.6 Å resonance doublet, F vii λ1139.5 Å, and the C iv λλ1548.2, 1550.8 Å resonance doublet are shown in Fig. 5. Previous analyses of P Cygni profiles of NGC 7094 determined a terminal wind velocity of $v_\infty = 3900$ km/sec (Kaler & Feibelman 1985). Koesterke et al. (1998) determined a mass-loss rate of $\log M/M_\odot/yr = -7.3$ from C iv λλ1548.2, 1550.8 Å using HST/GHRS and IUE observations. Koesterke & Werner (1998) used ORFEUS observations and analyzed O vii λ1031.9, 1037.6 Å. They derived a slightly different value of $\log M/M_\odot/yr = -7.7$.

For the calculation of the wind profiles (Fig. 5), we employed HotBlast, a newly developed NLTE code for spherically expanding model-atmospheres. It utilizes the static model-atmosphere structure provided by TMAP and calculates the expanding part of the atmosphere. A combination of a modeled ISM and wind spectrum agrees well with the observation. We can confirm the previously determined mass-loss rate for the CSPN of NGC 7094. Fig. 2 shows that the CSPN of Abell 43 has a significantly weaker wind. A detailed analysis of its properties is in progress.

5. Results and Conclusions

Our re-analysis of the basic photospheric parameters of NGC 7094 based on better observations and improved NLTE model-atmospheres revealed slightly different $T_{\text{eff}} = 100 \pm 15$ kK and $\log g = 5.5 \pm 0.2$ (previous values were 110 and 5.7, respectively). The H:He=0.17:0.69 ratio is much lower than previously determined (0.36:0.43, Dreizler et al. 1997). Fine-tuning of the metal abundances (Table 2) yields a good agreement with the observation. We note that the CSPN of NGC 7094 and Abell 43 have a subsolar oxygen abundance. If they are AFTP stars, carbon and oxygen should be dredged up during the thermal pulse and therefore be enhanced.
Figure 4. Comparison of the strongest Fe\textsc{vii} (top panels) and Ni\textsc{vi} (bottom panels) lines (wavelengths are given in the middle) in the \textit{FUSE} spectra of NGC 7094 (left) and Abell 43 (right) with synthetic spectra ($T_{\text{eff}} = 100$ kK, $\log g = 5.5$, abundances in Table 2) and different Fe and Ni abundances (thick: [Fe] = [Ni] = 0, dashed: [Fe] = [Ni] = −1, and thin: [Fe] = [Ni] = −2). 10\% of the continuum-flux level are indicated by a vertical bar.
Figure 5. Sections of the FUSE and HST/STIS observations of NGC 7094 around the strongest P Cygni profiles compared with combined synthetic stellar and interstellar spectra. For Ne\textsuperscript{vii} $\lambda$973.3\,Å (top left) the pure synthetic stellar spectrum (dashed) is shown, too. Marks at the bottom (left panels only) denote interstellar H\textsubscript{2} lines.

This discrepancy poses a problem to AGB nucleosynthesis that is to be solved.

For the CSPN of Abell 43, a detailed spectral analysis based on individual model-atmospheres is ongoing. This will show whether it is still a spectroscopic twin of the CSPN of NGC 7094. The FUSE observations showed that at least their wind properties (Fig. 2) are different.

Our analysis of the two hybrid PG 1159 stars NGC 7094 and Abell 43 confirmed the previously found Fe-deficiency. Although we have derived new parameter values which improved the agreement between model and observation, we were not able to find any Ni enhancement. Instead, we found Ni to be deficient by at least one dex for a model atmosphere with $T_{\text{eff}} = 100$\,kK and $\log g = 5.5$. It is therefore possible that s-process also converted Ni into even heavier trans-iron group elements. Unfortunately, we are presently not able to search for these elements...
because of the lack of reliable atomic data of the expected high ionization stages.

Modelling of the interstellar line absorptions improves the agreement with the observation. In the case of the CSPN of NGC 7094 and Abell 43, this did not help to identify weak photospheric lines. Prominent P Cygni profiles that are heavily blended by interstellar line absorption, show a good fit only if the ISM is properly modelled (Fig. 5). We conclude that without ISM modelling, the wind properties cannot be derived precisely.

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