Light and heavy metal abundances in hot central stars of planetary nebulae

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Abstract. We present new results from our spectral analyses of very hot central stars achieved since the last IAU Symposium on planetary nebulae held in Canberra 2001. The analyses are mainly based on UV and far-UV spectroscopy performed with the Hubble Space Telescope and the Far Ultraviolet Spectroscopic Explorer but also on ground-based observations performed at the Very Large Telescope and other observatories. We report on temperature, gravity, and abundance determinations for the CNO elements of hydrogen-rich central stars. In many hydrogen-deficient central stars (spectral type PG1159) we discovered particular neon and fluorine lines, which are observed for the very first time in any astrophysical object. Their analysis strongly confirms the idea that these stars exhibit intershell matter as a consequence of a late helium-shell flash.

INTRODUCTION

The determination of photospheric parameters of very hot central stars with effective temperatures around $T_{\text{eff}}=100\,000\,\text{K}$ is most comprehensively achieved from quantitative NLTE model atmosphere analyses of optical and ultraviolet spectra. In particular, abundances of most metals can only be found from UV observations because the strongest spectral lines from the highly ionised species are located in this wavelength band. Temperature determinations from optical spectra alone suffer from the absence of neutral helium lines, preventing the use of the He I/He II ionisation balance, which is a common tool applied to cooler central stars. In addition, the Balmer line problem at these high temperatures is still unsolved, i.e., models still cannot achieve a fit to all Balmer lines of a particular object at a unique value for $T_{\text{eff}}$. However, metal lines from different ionisation stages are often detectable in UV spectra, allowing precise constraints on $T_{\text{eff}}$.

In this contribution we report on our progress in this field since our review presented on the last IAU planetary nebulae symposium [19]. We first present new results for hydrogen-rich central stars and then turn to the hydrogen-deficient PG1159 stars. These two groups represent separate post-AGB evolutionary channels, the first representing canonical post-AGB evolutionary theory, and the second probably being the outcome of a late helium-shell flash. PG1159 stars are thought to be the progeny of Wolf-Rayet type central stars ([WC]), which are dealt with in the contribution by [3] in these proceedings.

HYDROGEN-RICH CENTRAL STARS

As described in detail by [19], we have taken high-resolution UV spectra of eight very hot central stars with the STIS spectrograph aboard HST: NGC 1360, NGC 1535, NGC 4361, NGC 6853, NGC 7293, Abell 36, LSS 1362, and LS V+4621. From this sample, NGC 1535 clearly stands out because of very strong P Cygni line profiles. It was subject to a separate study because, in contrast to the other objects, expanding model atmospheres have to be used for its analysis. The results were presented by [8]. In essence, temperature, gravity, and wind parameters determined by previous analyses were confirmed and a contemporary analysis performed by [4] with a different model code arrives at similar results.

From the other objects in our sample we performed a NLTE analysis with our TMAP code which computes line blanketed models in radiative and hydrostatic equilibrium [18]. We determined temperatures and gravities as well as abundances of the CNO elements. When available, we have also utilized new far-UV spectra taken with FUSE and optical spectra taken at different observatories (Calar Alto 3.5m, Siding Spring 2.3m, Hobby-Eberly Telescope 9.2m). More details were presented by [7] and [14]. As an example for the fit procedure we
display in Fig. 1 details from the HST UV spectrum of NGC 7293, showing lines from oxygen in three ionisation stages compared to models with different Teff. It shows that temperatures can be fixed with an accuracy of the order of 5%. Our new, still preliminary results for Teff and log g as compared to previous, mostly optical, analyses, can be summarized as follows. All objects, except NGC 1360, are hotter than before, roughly by 10 000–15 000 K. The most extreme case is NGC 4361, whose Teff “increased” from 82 000 K to 126 000 K. We also correct for the gravities, on the average by 0.3 dex, in either direction depending from star to star. By comparison with theoretical evolutionary tracks we derived stellar masses. They range between 0.55 and 0.65 M⊙ and the mean mass is 0.60 M⊙, in agreement with the mean mass of white dwarfs. We find essentially solar abundances for the CNO elements in 5 of the 7 stars. This points to ineffectiveness or even lacking 2nd and 3rd dredge-up events in the preceding RG and AGB phases, which can be explained by the relatively low mass of the stars in our sample. According to the initial-final-mass relation of [15], our most massive post-AGB remnant (0.65 M⊙) had a main-sequence mass of 3 M⊙.

Two objects definitely show non-solar abundance patterns. The first is LS V +4621 (Sh2-216). It was previously known that this is a white dwarf central star with a helium-deficiency (0.1 solar) explained by gravitational settling [10]. We find T eff = 93 000 K and log g = 6.9 and, in line with the He-deficiency, a depletion of CNO elements between 1–2 dex. The second case is NGC 4361. It was realized that this is a halo-PN [13] so we expected to find subsolar metal abundances. Indeed, it is obvious already on first sight, that the iron lines are much weaker than in the other central stars and we find that N is subsolar by 1 dex. However, O is found to be solar and, even more surprising, the abundance of C is 20 times solar. This abundance pattern is similar to that found for another Pop. II object, namely K 648, the central star of the planetary nebula Ps1 in the globular cluster M15 [11]. It seems possible that carbon is enriched by 13C dredged up from the stellar C/O core.

Our analysis of iron-group lines in the HST and FUSE spectra is still on-going [7]. We often see iron lines of two ionisation stages in one object. This will serve as an additional check for T eff and we will determine abundances of these heavy metals.

HYDROGEN-DEFICIENT CENTRAL STARS

It now seems well established that the H-deficient central stars of spectral type [WC] and PG1159 form an evolutionary sequence, although there still exists an embar-

![Figure 1](image.png)

**FIGURE 1.** Details from a high-resolution spectrum of NGC 7293 (thin line) taken with HST/STIS showing absorption lines from three ionisation stages of oxygen, allowing to constrain T eff. Overplotted are three models with different T eff as given in the left panel. **Left:** The O iv line is not observed in the spectrum, excluding a temperature as low as 115 000 K. Only the high T eff models produce weak, undetectable profiles. **Middle:** The core of the observed O v line is bracketed by the models with 115 000 K and 120 000 K, excluding a temperature as high as 125 000 K. **Right:** The O vi lines are matched satisfactorily, however, they are insensitive against changes in T eff in this parameter range.

rassing systematic difference in the He/C ratios between early and late type [WC] stars [3]. There is mounting evidence that the surface composition of [WC] and PG1159 stars is identical to that of the interstellar matter in the progenitor AGB stars. The observed relative abundances of He, C, and O are consistent with this picture. It is further confirmed by the iron-deficiency found in a number of [WC] and PG1159 stars [19] which can be explained by neutron captures of iron in the 13C pocket where s-processing occurs. To us it seems most likely that the H-deficiency of these stars is the result of a late He-shell flash which caused ingestion and burning of the H-rich envelope [6]. But in this case one would expect to observe systematic differences in the nebula properties of H-rich and H-deficient central stars which, however, are not evident [2]. Another problem with the late He-shell flash scenario is the simultaneous occurrence of C- and O-rich circumstellar dust about [WC] central stars, which is difficult to understand. An alternative scenario to explain the origin of [WC] stars with this double-dust chemistry is a merging event of the AGB progenitor with a planet or low-mass star, causing extra envelope mixing [1].

Whatever the cause of hydrogen-envelope mixing is (late helium-shell flash or merging event), results of new spectral analyses further corroborate the picture that such mixing results in the exposure of intershell matter on the surface. These are the detection of a high abundance of neon in fluorine in a large number of PG1159 stars.
For a few of the brightest PG1159 stars a neon abundance of 2% (by mass) could be derived from the Ne VII 3644 Å line [17]. We have extended these analyses to fainter objects using one of the VLT 8m telescopes [20]. In addition, we identified a hitherto unknown strong neon line in FUSE spectra, Ne VII 973 Å, which allows to determine the neon abundance in PG1159 stars in a wider $T_{\text{eff}}$-$\log g$ range than before. We also identified a new Ne VII multiplet in the optical wavelength range (3850–3910 Å). In all cases we find Ne=2%, in full agreement with the neon intershell abundance in AGB stars [6]. In the upper left panel of Fig. 2 we show as an example the Ne VII 973 Å line in the FUSE spectrum of the PG1159-type central star PG1520+525. The line is so strong that it is still easily seen in hydrogen-rich central stars with a solar neon abundance level, which is 20 times lower. This is presented in the lower left panel of Fig. 2 which displays the FUSE spectrum of NGC 1360. In early [WC] stars and in the most luminous PG1159 stars this neon line exhibits a strong P Cygni profile. Formerly this line has been erroneously interpreted as the C III 977 Å resonance line but it could not be matched by models because they showed too weak profiles due to high ionisation [5].

FUSE spectroscopy also allowed for the first time to identify fluorine in post-AGB stars [21]. In the right panels of Fig. 2 we show the identification of the F VI 1139.5 Å line in the two central stars just discussed. We find a solar F abundance in all five analysed H-rich central stars but a wide abundance spread in the eight PG1159 stars: from solar up to 250 times solar. The F enrichment can be explained by efficient F production in the intershell of AGB stars, being in quantitative agreement with nucleosynthesis calculations [9]. The F production efficiency is strongly mass-dependent and this might be the reason for the large abundance spread observed.

We have continued to investigate the iron-deficiency in PG1159 stars. We planned to obtain high-resolution HST/STIS spectra of the prototype PG1159+035 and the central stars of NGC 7094 and Abell 78 to possibly detect a nickel enrichment caused by the transformation of
iron to nickel during the s-process. The observing programme was performed, except for the Abell 78 observation because of the fatal STIS failure in 2004. The spectra are still being analyzed. As an example of the quality of these spectra, we display in Fig. 3 the O\textsc{v} 1371 Å line profile for PG1159-035; this illustrates that we can fix $T_{\text{eff}}$ on a few-percent accuracy level.

We will also work on other trace elements in PG1159 stars to see if their abundances are compatible with stellar evolution models. In this respect, the FUSE spectra are, again, a rich source of information. For instance, in Fig. 4 we display a detail from the spectrum of PG1424+535, a relatively cool and high-gravity PG1159 star ($T_{\text{eff}}=110{,}000$ K, $\log g=7$). It is located on the WD cooling sequence and its nebula has probably long being dispersed. We identify lines from silicon, sulfur, and phosphorus; however, their abundances still remain to be determined [12].

As a final remark, we note that the high-resolution spectroscopy performed with the hot central stars reveals problems with the available atomic data. Many of the O\textsc{vi} lines and the newly identified optical Ne\textsc{vii} multiplet appear at wavelength positions clearly deviating from atomic line lists. In a positive sense, these spectra can be used to improve our knowledge about the term structure of highly ionised metals. On the other hand, many lines detected in the UV spectra remain unidentified even today.

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