Part IV

Central Stars and their Atmospheres

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Temperature Scale and Iron Abundances of Very Hot Central Stars of Planetary Nebulae

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Abstract. The determination of effective temperatures of very hot central stars ($T_{\rm eff} > 70\,000$ K) by model atmosphere analyses of optical H and He line profiles is afflicted with considerable uncertainty, primarily due to the lack of neutral helium lines. Ionization balances of metals, accessible only with UV lines, allow more precise temperature estimates. The potential of iron lines is pointed out. At the same time iron and other metal abundances, hardly investigated until today, may be derived from UV spectra. We describe recent HST spectroscopy performed for this purpose.

A search for iron lines in FUV spectra of the hottest H-deficient central stars (PG1159-type, $T_{\rm eff}$>100 000 K) taken with FUSE was unsuccessful. The derived deficiency is interpreted in terms of iron depletion due to n-capture nucleosynthesis in intershell matter, which is now exposed at the stellar surface as a consequence of a late He shell flash.

1. Introduction

In this review we choose to concentrate on very hot central stars of planetary nebulae (CSPN), whose analysis faces several difficulties. These objects generally have weak or very weak winds and can be analyzed with windless model atmospheres. Two other reviews in these proceedings concentrate on analyses of CSPN with strong winds (Hamann and Pauldrach for H-deficient and H-rich stars, respectively).

CSPN are spectroscopically assigned to one of two families: H-rich or H-deficient. The origin of H-deficiency is now regarded as the consequence of a (very) late helium shell flash occurring during post-AGB evolution (Herwig et al. 1999) and we observe a complete H-deficient post-AGB sequence. On the other hand, the apparent gap in the separate H-rich sequence has been closed by Napiwotzki (1999) who discovered numerous very hot (white dwarf) CSPN.

Several spectral sub-classes for the two sequences have been established by Méndez (1991). Most of his terms are still used in present work, some new have been added by others. To start our discussion we summarize these classification criteria.

2. H-rich and H-deficient CSPN

The H-rich CSPN can be classified by the following spectral characteristics.

hgO(H): denotes high-gravity stars with very broad Balmer absorptions. These are either hot white dwarfs or non-post-AGB stars.

O(H): stars with spectra very similar to massive, young O stars, with He II 4686Å in absorption. Spectral subtypes can be defined from the relative strengths of He I and He II absorption, but excellent spectra are needed, because He I absorptions are often masked by nebular emission. The hottest CSPN do not show He I absorptions at all.

Of(H): the stellar He II 4686Å line is a narrow emission (FWHM $>$ 4Å, sometimes with P Cyg profile). He II 4200, 4541Å are in absorption, and blueshifted by less than 50 km/s relative to the PN velocity. Hγ is in absorption.

Of-WR(H): He II 4686Å is a strong and broad emission, Hγ shows a more or less developed P Cyg profile. He II 4541Å is not in emission but, if visible in absorption, strongly blueshifted (about 100 km/s).

Spectral analysis of these stars has been pioneered by Kudritzki, Méndez and co-workers (e.g. Méndez et al. 1988), by determining basic photospheric parameters ($T_{\rm eff}$, $\log g$, He abundance). Subsequently, more analyses in this style have been published, too numerous to refer to here. Napiwotzki (1999) published new basic results on many CSPN including a very useful compilation of CSPN analyses with an extensive reference list. Mass-loss rates of O- and Of-type CSPN have been determined, too (e.g. Kudritzki et al. 1997). Metal abundance analyses of H-rich CSPN are rather scarce and mostly qualitative descriptions of spectral signatures were performed. We discuss this in more detail below. Recent and current research on H-rich CSPN concentrates on wind modeling (Pauldrach, these proceedings) for the O and Of types, and on problems with $T_{\rm eff}$ determination for the hottest O and hgO types (Napiwotzki 1999, and the present paper), and on metal abundance determinations in the latter (see below).

The H-deficient CSPN are classified as follows.

O(He), O(C): Stars showing predominantly an absorption line spectrum, dominated by He or C, respectively. O(C) stars are now more commonly called PG1159 stars (after PG1159-035) although NGC 246 is the prototype of this class (Heap 1975). The PG1159 classification has been further refined, using line-shapes of the dominant species as characteristic criteria (Werner 1992).

Of(C), Of-WR(C): Defined in analogy to the H-rich counterparts (without meeting criteria for presence of H). These stars are also termed [WC]–PG1159 transition objects because of their mixed emission/absorption line spectra, bearing characteristics of both spectral classes. Examples are Abell 30 and Abell 78.

[WC]: Defined like in the case of massive Wolf-Rayet stars, with necessary extensions to earlier and later subtypes.

We remark that all of these stars are sometimes called "O VI" CSPN, because of the prominence of an O VI doublet in the optical UV. The so-called "weak emission line stars" (WELS) are sometimes equated to the [WC]–PG1159 objects (Parthasarathy et al. 1998) but better spectra and quantitative analyses may reveal that many of them are either [WC] or PG1159 stars, or even H-rich CSPN with only slightly enriched metal abundances (like discussed below).

Some PG1159 and [WC] stars do show photospheric hydrogen, which is difficult to detect because of high temperatures, blending He II photospheric or H nebular lines. H abundances in PG1159 stars can be as high as 35% (by mass), placing the respective objects somewhat between the H-rich and H-deficient CSPN, hence, they are termed hybrid-PG1159 stars. However, from an evolutionary standpoint they are to be assigned to the H-deficient sequence, because of their related origin (so-called "AGB Final Thermal Pulse" scenario, Herwig 2001). The O(He) stars (e.g. K1-27) are very rare (two CSPN and two similar objects without PN) and their status and relation to other post-AGB stars is not really understood (Rauch et al. 1998).

During the last decade, considerable effort has been put into analyses of H-deficient CSPN, see the review on [WC] stars (Hamann, these proceedings) and a recent summary on PG1159 stars (Werner 2001). It is now well established that both subclasses represent different stages of an evolutionary sequence.

Considerable progress, which can only be shortly mentioned here, has been achieved with NLTE atmospheric modeling since the last PN symposium. For models with winds we refer again to the reviews by Pauldrach and Hamann in these proceedings. Windless models are now available over a wide parameter range, including opacities of light metals and iron group elements (see contribution by Rauch, these proceedings). Results reported here were obtained with such models for both H-deficient and H-rich objects. They are calculated with an Accelerated Lambda Iteration code (Werner & Dreizler 1999).

3. Very hot H-rich CSPN

On the PN symposium in Innsbruck, Liebert (1993) pointed out that "*ironically, the temperature determinations for the H-poor sequence with their complicated and mixed atmospheric abundances of He and CNO elements may presently be more accurate than those of the H-rich sequence.*" This was certainly true for hot CSPN (say, $T_{\rm eff} > 70\,000$ K), particularly because the "Balmer line problem" came up at that time (Napiwotzki 1992). The lack of neutral helium lines in these stars prevents a reliable $T_{\rm eff}$ determination based on the He I/He II ionization balance, hence, the Balmer line spectrum alone was used for that purpose. But it turned out that no consistent fit to all lines of the Balmer series could be achieved: The higher the series member, the higher the required fit temperature. Although we have learned to circumvent this problem (the higher series member give the "correct" $T_{\rm eff}$) and partly understand its reason (neglect of metal line blanketing in the NLTE models, Werner 1996), considerable problems remain for the hottest CSPN. In contrast to cooler CSPN, line blanketed models do not resolve the Balmer line problem for these stars. The reason is still not understood, hence, other means must be used for determining their temperatures. These "other means" are the ionization balances of metals.

Metals in very hot CSPN are highly ionized and the strongest lines of these ions are found in the UV region. UV high resolution spectra usually display lines from many metals so that a number of ionization balances can be exploited simultaneously in order to fix $T_{\rm eff}$. This is highly desirable, because in principle other photospheric parameters which also affect ionization balances ($\log g$ and element abundances) must be derived from these features at the same time.

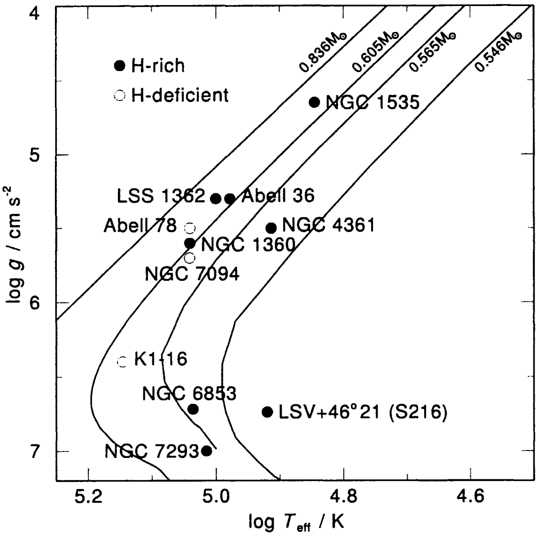

Figure 1. Location of the very hot CSPN in the g–$T_{\rm eff}$ plane subject to HST and FUSE spectroscopy as described in the text. Evolutionary tracks for H-burning post-AGB stars with different remnant masses are from Schönberner (1983) and Blöcker & Schönberner (1990).

Iron promised to be exceptionally useful, because iron lines in IUE spectra of hot CSPN and related subdwarfs were reported earlier (Schönberner & Drilling 1985). In order to proof the viability of such an analysis we proposed HST UV spectroscopy of eight H-rich CSPN. Their location in the g–$T_{\rm eff}$ diagram (mainly derived from optical analyses and, hence, possibly uncertain) is displayed in Fig. 1. Another immediate motivation for these observations came from an analysis of archival IUE spectra, which indicated a possible general iron deficiency in many hot H-rich CSPN (Deetjen et al. 1999). Furthermore, Méndez (1991) emphasized that the optical spectra of many hot H-rich CSPN indicate a variety of carbon abundances which promise insight into previous (post-) AGB evolutionary processes. Our HST observations were performed in 2001/2002 with the STIS spectrograph and cover the wavelength range 1150-1730Å with a resolution of better than 0.1Å and S/N≈50. The data are currently analyzed. Only NGC 1535 exhibits wind signatures in the strongest CNO lines. Sample spectra shown in Fig. 2 give an impression of the data quality. We discuss some qualitative results on individual objects in some detail.

NGC 4361 was highlighted by Méndez (1991), because it shows very strong C IV lines in the optical, as compared to NGC 1360 which has otherwise similar $T_{\rm eff}$ and $\log g$ thus, NGC 4361 is apparently strongly overabundant in C. In the meantime, we have presented evidence from extended optical and EUV observations (Hoare et al. 1996) that NGC 1360 is about 20 000 K hotter than previously thought, which possibly explains the relative weakness of C IV in this star. But still, the strong C IV lines in NGC 4361 are even more remarkable since Torres-Peimbert et al. (1990) found that it must be a metal-poor halo ob-

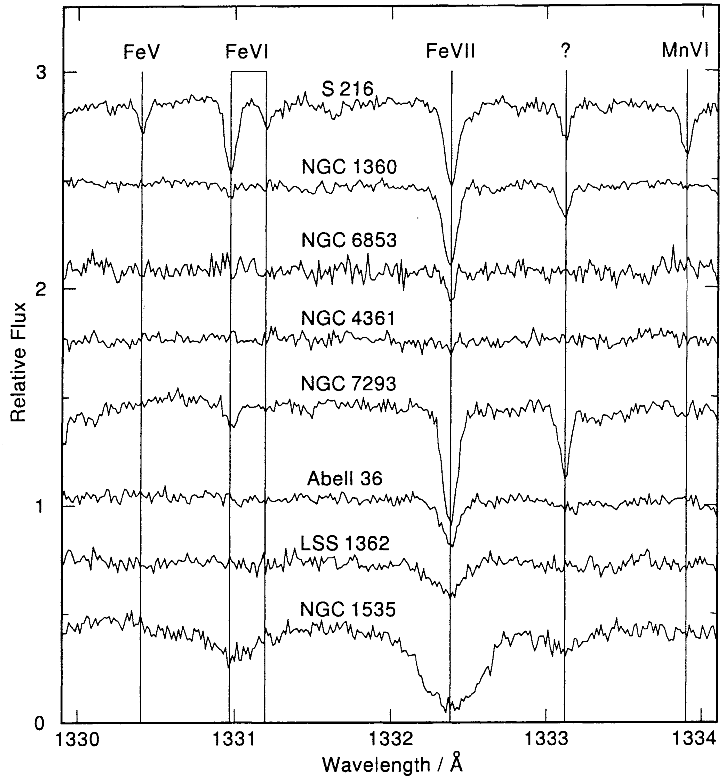

Figure 2. Detail from HST spectra of very hot CSPN, displaying lines from Fe V-VII. Their relative strength is an indicator for T_{eff}. Also seen are a Mn VI line in S 216 and an unidentified absorption that possibly stems from an as yet unknown Fe VII line.

ject. Our HST spectrum confirms both, the halo nature of NGC 4361 because of the almost complete absence of iron lines, and the high C abundance: NGC 4361 reveals the strongest C IV lines in our sample of stars. The probably high C overabundance is reminiscent of the same situation in K 648, the central star of the PN Ps 1 in the globular cluster M15 (Rauch et al. 2002). NGC 1360 on the other hand shows a rich spectrum of Fe VI/Fe VII lines. They are weaker than expected, which either indicates an even higher T_{eff} or a subsolar Fe abundance.

LSS 1362 and Abell 36 show only Fe VII but no Fe VI lines. This might indicate that these stars are hotter than NGC 1360, as opposed to their currently known position in Fig. 1. This is supported by the fact that all three stars display O V and O VI lines while only NGC 1360 displays O IV, too.

NGC 6853 and NGC 7293 both have high gravities and do show iron lines. NGC 7293 has Fe VI and Fe VII lines, NGC 6853 only Fe VII. The higher T_{eff} and the lower gravity of NGC 6853 explains this qualitative difference. The helium abundance in NGC 6853 is solar, while it is subsolar in NGC 7293, indicating that the photospheric abundances are influenced by gravitational settling

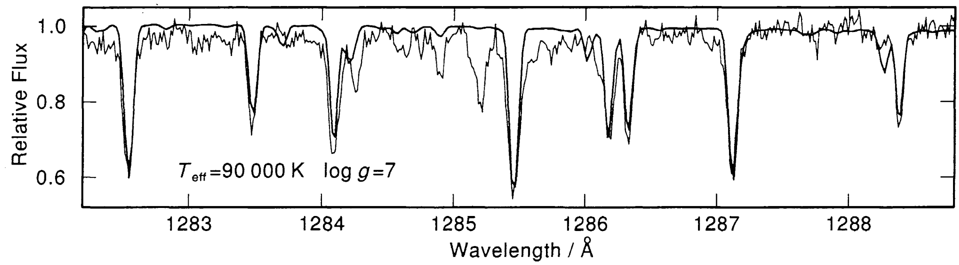

Figure 3. Preliminary fit to the Fe VI line spectrum of S 216 with a solar iron abundance model. The unmatched absorptions at 1284.14Å 1284.79Å, and 1285.10Å are two Ni VI lines and a Mn VI line, respectively, which are not included in the model.

in the latter. Detailed analyses are needed to see if metal abundances comprise the signature of diffusion and radiative levitation. The white dwarf central star of S 216 has a spectrum which is very rich in iron (Fe V-VII) and nickel (Ni V-VI) lines (see Fig. 3), the strongest of them were detected earlier in IUE spectra (Tweedy & Napiwotzki 1992). In our HST spectra we also find lines of other iron group elements: chromium, cobalt, and manganese (ionization stages V and VI). Their line strengths as well of Ni clearly points at an overabundance with respect to Fe, which is a result of radiative levitation. Many absorptions in the UV remain unidentified, most of them are probably unknown iron lines, as can be concluded by comparison with known line features in the different stars.

From the FWHM of the iron lines in NGC 1360 and NGC 7293 we find that the projected equatorial rotation velocity or any turbulent atmospheric motion does not exceed about 20 km/s. This is in contrast to Méndez et al. (1988) who deduced 100 km/s and 50 km/s, respectively, from weak metallic absorption lines in their optical spectra, and who attributed this to some kind of "macroturbulence". Similar iron line widths are found in S 216 and NGC 6853. For Abell 36 and LSS 1362 we find larger values, namely 30 km/s and 50 km/s.

NGC 1535 is the lowest gravity CSPN in our sample. It has a most remarkable UV spectrum. The strongest CNO lines have P Cygni profiles which has been know long before (Heap 1983). What is new, however, is the detection of prominently strong and broad Fe VI and Fe VII lines (Fig. 2). We think that this is no indication for an iron overabundance. Rather, the broad lines indicate some macroturbulent motions with a speed of the order of 100 km/s. Clearly, this object requires an analysis with atmosphere models including a wind.

4. Very hot hydrogen-deficient CSPN

The first attempt to determine the iron abundance in H-deficient CSPN arrived at a surprising result. Since PG1159 stars belong to the disk population and since diffusion effects can be excluded due to ongoing mass-loss, one expects a solar iron abundance in these stars. However, Miksa et al. (2001) report an underabundance of at least one dex as derived from the absence of Fe VII lines in FUSE spectra of the extremely hot CSPN K1-16. Subsequent analyses of FUSE spectra from other PG1159 stars confirmed that such an Fe underabundance is possibly the rule rather than the exception among these objects: Miksa et al. (2002) and Werner et al. (these proceedings) failed to detect Fe VII lines in NGC 7094 and Abell 78, respectively.

As already mentioned, the high C and O abundances in H-deficient CSPN results from envelope mixing caused by a late He-shell flash, hence, this event also dredges up matter where s-process elements were built up by n-capture on ^{56}Fe seeds during the AGB phase. In principle, this scenario can be tested by analyzing the resulting Fe/Ni abundance ratio, because it is significantly changed in favor of Ni by the conversion of ^{56}Fe into ^{60}Ni. The Fe depletion by n-captures typically amounts to a factor of 10 (Busso et al. 1999). In order to roughly estimate the Ni/Fe ratio one can assume nuclear statistical equilibrium. The two most abundant Ni isotopes are ^{60}Ni (26%) and ^{58}Ni (68%). During s-process ^{58}Ni is destroyed (and not synthesized), by conversion into ^{60}Ni. ^{60}Ni is converted to heavier elements 4 times faster than it is produced from ^{56}Fe. Consequently, a ratio Fe/Ni$\approx$4 results, which is a factor of five below the solar value. This could be detected by high resolution HST and FUSE UV spectroscopy. Interestingly, Asplund et al. (1999) have indeed found that in Sakurai's object, which is thought to undergo a late He-shell flash, Fe is reduced to 0.1 solar and Fe/Ni$\approx$3. This and other s-process signatures might also be exhibited by Wolf-Rayet central stars and PG1159 stars. More quantitative results from nucleosynthesis calculations in appropriate stellar models have been presented at this conference by Herwig et al. and inclusion of nuclear networks in evolutionary model sequences will become available in the near future.

Other results presented at this conference confirm that Fe deficiency among H-deficient post-AGB stars is not restricted to PG1159 stars, as can be expected from evolutionary considerations. Three Wolf-Rayet central stars are iron deficient, too. Gräfener et al. report a low Fe abundance in SMP 61, an early type [WC5] central star in the LMC. Its abundance is at least 0.7 dex below the LMC metallicity. Crowther et al. find evidence for an iron underabundance of 0.3–0.7 dex in the Galactic [WC] stars NGC 40 ([WC8]) and BD+30 3639 ([WC9]).

5. Conclusion

We have discussed the potential of high-resolution UV spectroscopy for the determination of photospheric parameters of the hottest CSPN. Ionization equilibria of metals, particularly of iron, are the only means for precise temperature determinations. NLTE model atmospheres have been developed to fully exploit this technique. HST and FUSE are essential instruments and have been successfully used to obtain F(UV) spectra of the necessary high quality.

Metal abundance determinations from UV data are necessary to understand mixing processes in the interior of the precursor AGB stars. In the case of hydrogen-deficient CSPN the surface abundances reflect the intershell abundances of the former AGB star with some superimposed modification due to the mixing and nucleosynthesis processes as a consequence of a late thermal pulse. This can also explain their Fe deficiency, as due to n-capture nucleosynthesis on Fe seeds during the AGB evolution and/or the neutron burst which occurs during rapid burning of protons initiated by the late He shell flash.

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