The iron abundance in hot central stars of planetary nebulae derived from IUE spectra

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Abstract. We present the first attempt to determine the iron abundance in hot central stars of planetary nebulae. We perform an analysis with fully metal-line blanketed NLTE model atmospheres for a sample of ten stars ($T_{\text{eff}} \gtrsim 70,000$ K) for which high-resolution UV spectra are available from the IUE archive. In all cases lines of Fe vi or Fe vii can be identified. As a general trend, the iron abundance appears to be subsolar by 0.5–1 dex, however, the S/N of the IUE spectra is not sufficient to exclude a solar abundance in any specific case. Improved spectroscopy by either FUSE or HST is necessary to verify the possibility of a general iron deficiency in central stars. The suspected deficiency may be the result of gravitational settling in the case of three high-gravity objects. For the other stars with low gravity and high luminosity dust fractionation during the previous AGB phase is a conceivable origin.

Key words: stars: abundances – stars: atmospheres – stars: evolution – stars: AGB and post–AGB – white dwarfs – Ultraviolet: stars

1. Introduction

The continuing spectroscopic study of central stars of planetary nebulae (CSPN) is motivated by two observational facts which reveal our incomplete understanding of post-AGB stellar evolution. The first concerns the mere existence of hydrogen-deficient objects which comprise the spectroscopic types [WC] and PG 1159. The second concerns the apparent lack of hydrogen-rich CSPN at the hot end of the white dwarf cooling sequence, suggesting that during this stage all H-rich objects become H-deficient. The first problem initialized an almost complete analysis of all known H-deficient post-AGB stars, resulting in accurate determinations of the effective temperature ($T_{\text{eff}}$) and surface gravity ($g$), as well as the abundance of the main atmospheric constituents (He, C, O) and in some cases trace of elements (H, N, Ne). The second problem could be solved by the systematic search for (pre-) white dwarf central stars. Subsequent analyses of the H-rich objects revealed $T_{\text{eff}}$, log $g$, and H:He ratio and the results complement the analyses of other H-rich CSPN performed in numerous previous analyses (see Tab. 3).

Fig. 1. Location of the program stars in the log $T_{\text{eff}}$ – log $g$ diagram compared with post-AGB evolutionary tracks (Schönberner 1983, Blöcker & Schönberner 1990) for H-burning stars with different remnant masses (in $M_\odot$) as indicated.
Table 1. The program stars and their atmospheric parameters. Values for $T_{\text{eff}}$ [K], $\log g$ [cm s$^{-2}$], and helium abundance were taken from literature. Columns 5 and 6 list our results for the Fe abundance and the $\text{H}^+$ column density along the line of sight as derived from the Ly$\alpha$ profile; the references are listed in Tab. 2.

| PN        | $T_{\text{eff}}$ | $\log g$ | $n_{\text{He}}/n_{\text{He}^0}$ | $\log n_{\text{Fe}}/n_{\text{Fe}^0}$ | $n_{\text{H}^+}$ [cm$^{-2}$] | references | SWP numbers of co-added spectra |
|-----------|------------------|----------|----------------------------------|--------------------------------------|-------------------------------|------------|-------------------------------|
| Abell 36  | 93 000           | 5.3      | 1.5                              | $-1.3$                               | $1.9 \cdot 10^{19}$            | 4, 5, 8, 9 | 16478, 38132, 47814, 47815    |
| LSE 125   | 85 000           | 5.1      | 0.5                              | $-0.5$                               | $3.0 \cdot 10^{19}$            | 2, 5       | 30269                         |
| LSS 1362  | 100 000          | 5.5      | 1.0                              | $-0.5$                               | $1.6 \cdot 10^{19}$            | 3, 4, 5, 8 | 19830                         |
| NGC 1360  | 110 000          | 6.0      | 1.0                              | $-0.5$                               | $3.0 \cdot 10^{19}$            | 1, 2, 4, 5, 8, 10 | 55902, 56037, 56038 |
| NGC 1535  | 70 000           | 4.6      | 1.2                              | $-0.5$                               | $1.4 \cdot 10^{19}$            | 1, 2, 4, 5, 8 | 56065, 56066                  |
| NGC 4361  | 82 000           | 5.5      | 0.5                              | $-1.3$                               | $5.0 \cdot 10^{18}$            | 1, 2, 4, 5, 8, 9 | 20440                         |
| NGC 6853  | 99 000           | 6.8      | 1.0                              | $-0.5$                               | $3.0 \cdot 10^{18}$            | 5, 7, 8   | 18340                         |
| NGC 7009  | 82 000           | 4.8      | 0.5                              | $-0.5$                               | $1.5 \cdot 10^{18}$            | 2, 4, 5, 8 | 05174, 08580, 08680, 23383    |
| NGC 7293  | 107 000          | 7.0      | 0.5                              | $-0.5$                               | $5.5 \cdot 10^{18}$            | 4, 9       | 19859, 48055, 48063           |
| S 216     | 85 000           | 6.9      | 0.1                              | $-0.5$                               | $5.0 \cdot 10^{18}$            | 4, 6, 7, 8 | 56071, 56072                  |

Table 2. References in Tab. 1

1 Méndez et al. (1981) 2 Méndez et al. (1988)
3 Heber et al. (1988) 4 Feibelman & Bruhweiler (1990)
5 Méndez (1991) 6 Tweedy & Napiwotzki (1992)
7 Napiwotzki (1993) 8 Tweedy (1993)
9 Quigley et al. (1993) 10 Hoare et al. (1996)

Almost no effort has been yet made to analyze metal abundances in the H-rich CSPN. Interesting insight into AGB evolutionary phases may be gained by such analyses, because obvious abundance anomalies exist among stars with otherwise similar atmospheric parameters (Méndez 1991). Before embarking on such a project and discussing the abundance patterns it is reasonable to obtain information about the primordial metallicity of these objects by analyzing their iron abundance. The reason herefore is that iron is not affected by nuclear processes during previous evolutionary phases. Such an analysis requires UV spectroscopy. As a first step it is mandatory to check, if the IUE Final Archive contains useful data. It is the aim of this paper to exploit that archive exhaustively in order to identify and analyze quantitatively iron lines in hot central stars.

2. Sample selection and IUE data reduction

Our sample selection started from a CSPN compilation by Méndez (1991) and we complemented his list of H-rich objects by several objects dealt with in the more recent literature (e.g. see Tab. 2). For these stars we checked the IUE archive for high resolution SWP spectra and found data for 27 H-rich CSPN. From this sample those objects were excluded, which have high mass-loss rates, i.e., those showing Of-type optical spectra and those with extraordinarily strong P Cygni resonance line profiles in the UV. Thereby the final sample consisted of ten stars, which can be analyzed reliably with our static model atmospheres. All program stars have $T_{\text{eff}} \gtrsim 70 000$ K. Fig. 1 shows their position in the $\log T_{\text{eff}} - \log g$-diagram and Tab. 1 summarizes their atmospheric parameters.

Fig. 2. Calculated continuum of a typical co-added IUE spectrum

The SWP spectra were extracted from the IUE Final Archive and subject to several reduction steps before comparison with model spectra. These steps comprise the assembly of single Echelle orders in order to obtain a complete spectrum in the 1200 – 1600 Å range; elimination of the strongest interstellar absorption lines by Voigt profile fitting (Ly$\alpha$ and Si II lines); correction for radial velocity; normalization of the spectra. The last step is rather delicate. Firstly the ripple correction for the Echelle orders in the archival data is far from being perfect (see Fig. 2) and has to be corrected. Secondly, fixing the continuum is a rather subjective procedure and thus the major error source for the quantitative analysis, because of the generally high noise level in the spectra. To determine the continuum we smoothed the spectrum with a median filter of 2 Å width, followed by a convolution with a Gaussian profile of 2 Å FWHM. This method is inapplicable in regions with P Cygni profiles and the continuum has to be determined manually. Furthermore the determined continuum around deep ISM lines is too low and has to be raised manually.
Fig. 3. Distribution of the analyzed CSPN (◇) and models (□) in the $T_{\text{eff}}$ - log $g$ - plane. For each point of the grid spectra for eight different Fe and Ni abundances have been calculated.

Fig. 4. Ionization structure of iron in a model atmosphere with $T_{\text{eff}} = 110000$ K, log $g = 6.0$ and solar Fe abundance. Note particularly the relative occupation of Fe VII and Fe VIII in the deeper layers of the atmosphere where the iron lines are formed (log $m = -2...0$)

3. Model Atmospheres

We have calculated a grid of plane-parallel non-LTE model atmospheres (Fig. 3) in radiative and hydrostatic equilibrium. The computer code is based on the Accelerated Lambda Iteration method (Werner & Husfeld 1985; Werner 1986) and it can handle the line blanketing of iron group elements by a statistical approach using superlevels and superlines with an opacity sampling technique (Anderson 1985; Dreizler & Werner 1993). The latest version of the code and a detailed description of the numerical method can be found in Werner & Dreizler (1999). Our model atmospheres include the CNO elements as well as iron and nickel self-consistently, i.e. their back-reaction on the atmospheric structure is accounted for. In essence, they are very similar to the models described in detail by Haas et al. (1996).

Table 3. Summary of model atoms used in our model atmosphere calculations. Numbers in brackets denote individual levels and lines used in the statistical NLTE line blanketing approach for iron and nickel. The model atom for each chemical element is closed by a single level representing the highest ionization stage (not listed explicitly)

| element | ion | NLTE levels | lines |
|---------|-----|-------------|-------|
| H       | i   | 10          | 36    |
| He      | i   | 5           | 3     |
| H      | II  | 10          | 36    |
| C       | III | 6           | 4     |
|        | IV  | 4           | 1     |
| N       | IV  | 6           | 4     |
|        | V   | 4           | 1     |
| O       | IV  | 1           | 0     |
|        | V   | 6           | 4     |
|        | VI  | 4           | 1     |
| Fe      | IV  | 7           | (6472) 25 (1027793) |
|        | V   | 7           | (6179) 25 (793718)  |
|        | VI  | 8           | (3137) 33 (340132)  |
|        | VII | 9           | (1195) 39 (86504)    |
|        | VIII| 7           | (310) 27 (8724)      |
| Ni      | IV  | 7           | (5514) 25 (949506)   |
|        | V   | 7           | (5960) 22 (906189)   |
|        | VI  | 7           | (9988) 22 (1110584)  |
|        | VII | 7           | (6686) 18 (688355)   |
|        | VIII| 6           | (3600) 20 (553549)   |
| total  |   | 135         | (49041) 346 (6565054) |

Haas (1997), so we restrict ourselves here to a summary of the model atoms in Tab. 3. The main extension of that models refers to a detailed model atom for Fe VIII. This turned out to be essential in order to reliably compute Fe VII lines, because the relative occupation of both ionization stages sensitively depends on the detailed treatment of their respective level populations via ionization and recombination processes.

As an example, the iron ionization structure in a typical model atmosphere is shown in Fig. 4.

4. Results and discussion

We derived our results with two independent methods. First we compared the observed and theoretical spectra by eye (Fig. 5), second a $\chi^2$-test has been performed (Fig. 6). To get more reliable results, the $\chi^2_{\text{red}}$ has been computed only around strong iron lines excluding known ISM lines. As a general trend, the iron abundance appears to be subsolar by 0.5-1 dex with both methods (see Tab. 1). However, the S/N of the IUE spectra is not sufficient to exclude a solar abundance in any specific case.

We cannot identify nickel lines for certain, which correspond to an upper limit of a solar nickel abundance. Ni V lines have been detected in other central stars and sdO stars by...
Fig. 5. Details from fits to the iron line spectrum of two central stars. **Top:** S 216; $T_{\text{eff}} = 90\,000\,\text{K}$, $\log g = 7.0$; **Bottom:** NGC 1360; $T_{\text{eff}} = 110\,000\,\text{K}$, $\log g = 6.0$. Models (dotted): a solar Fe and Ni; b 0.5 dex subsolar Fe and Ni; c comparison of both models; d strong Fe\,VI and Fe\,VII lines are marked.
Fig. 6. Contour plot of the $\chi^2$ test for the spectrum of NGC 1360. In the left plot the $\chi^2_{red}$ values for those models with $\log g$ at 6.0 and $T_{eff}$ around 110 000 K (40 = 8 · 5 models, see Fig. 3) are shown, whereas in the right plot $T_{eff}$ remains fixed and $\log g$ varies. The high $\chi^2$ values (> 5) are due to the low S/N level and the imperfect normalization (see Fig. 3). As a general trend, the $\chi^2$ test favors models with subsolar iron abundance.

However, these stars have effective temperatures which are lower than those of our objects.

For three high-gravity objects in the sample the suspected iron deficiency may be the result of gravitational settling. For the other stars of the sample with low gravity and high luminosity another explanation must be found since mass loss efficiently suppresses gravitational settling (Unglaub & Bues 1998). Following suggestions in the literature (Lambert et al. 1988; Venn & Lambert 1991; Bond 1991; Van Winckel et al. 1992), the iron abundance in these stars might not be primordial, but the result of chemical fractionation through dust formation and subsequent loss due to stellar wind during previous AGB phases.

Therefore improved spectroscopy either by FUSE or HST is necessary to confirm or reject the possibility of a general Fe deficiency in these central stars. Furthermore, the determination of the abundance of CNO-elements is desirable in order to get a better understanding of the chemical evolution of these stars.

Our study suggests that iron is not necessarily a suitable tracer to determine the primordial metallicity. Alternatively one may use the S or Zn abundance to obtain reliable information (Van Winckel et al. 1992). The abundance of both elements is not affected by nuclear processes during previous evolutionary phases and both elements do not tend to dust formation as iron does (Habing 1996). Due to the lack of detailed atomic data for Zn, one has to concentrate on the S lines in the FUV and UV region. This emphasizes the need for improved spectroscopic data to solve these questions.

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