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Trace Metals in PG1159 Stars and the First Identification of Metal Line Forbidden Components in Astrophysical Sources

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Abstract. We report on results of our spectroscopic analysis of five PG1159 stars. The measured abundances of trace elements are in agreement with the intershell composition of Asymptotic Giant Branch stellar models. We also report on our discovery of forbidden components of C IV lines. This is the first detection of forbidden components from elements heavier than helium in astrophysical sources.

1. Introduction

PG1159 stars are the hottest hydrogen-deficient (pre-) white dwarfs (see, e.g., the review of Werner & Herwig 2006). It is thought that their surface chemistry is identical to the composition found in the helium-buffer layer between the hydrogen- and helium-burning shells in red giants that are about to leave the Asymptotic Giant Branch (AGB) towards the white dwarf (WD) stage. As a consequence of a late helium-shell flash, intershell matter was mixed to the surface. This view is corroborated by the agreement of the observed abundances of the dominant species (He, C, O) with those encountered in the interior of stellar models. Of particular interest is the abundance determination of trace elements because they allow to check the validity of neutron-capture nucleosynthesis in AGB star models.

Quantitative spectral analyses of PG1159 stars are strongly depending on the availability of far-ultraviolet (FUV) observations. Observations with the Far-Ultraviolet Spectroscopic Explorer (FUSE) turned out to be the essential basis of respective work, because most of the metal lines are located in the FUV. Here, we report on the basic results of the analysis of five PG1159 stars. They are the only objects in the main temperature region occupied by PG1159 stars ($T_{\rm eff}$ = 75 000–150 000 K) for which observations with sufficient signal-to-noise ratio are available. The analysis of spectra of a few even hotter objects (e.g., the central star of the planetary nebula RX J2117.1+3412) is in progress. We encountered a number of unidentified lines and some of them are rather strong. They are potentially very interesting because they might stem from species hitherto undetected in the stars. In our continuing quest to identify these lines we discovered that two broad features, that are seen in essentially all PG1159 star spectra, stem from forbidden components of C IV lines.

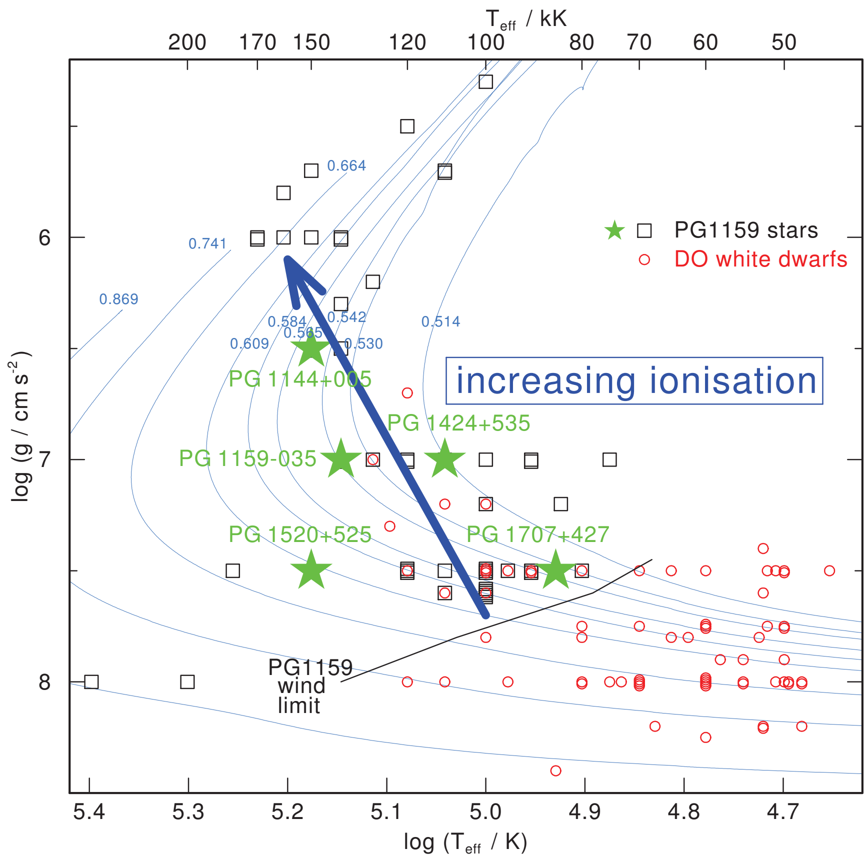

Figure 1. Location of PG1159 stars and DO white dwarfs in the effective temperature-gravity diagram. The five objects discussed in this paper are represented by the green star symbols. Evolutionary tracks from Althaus et al. (2009) are labeled with the stellar mass in $M_{\odot}$. No PG1159 star is found below the PG1159 wind limit (Unglaub & Bues 2000) because radiation-driven stellar winds become so weak that they can no longer prevent gravitational settling of heavy elements.

2. Trace Element Abundances in PG1159 Stars

In Fig. 1, we display the location of PG1159 stars and DO white dwarfs in the log T_{eff}–log g diagram. We have analysed FUSE spectra of five PG1159 stars which span a wide range of T_{eff} (75 000–150 000 K) and a gravity range of log g = 6.5–7.5. The FUV spectra are quite diverse, because the ionisation degree strongly increases towards lower gravities and higher temperatures. As an example, we show a detail from the spectra of the coolest and one of the two hottest stars of our sample in Fig. 2. With increasing T_{eff}, the dominant, broad lines of He II and C IV become weaker, while the ionisation of oxygen shifts drastically from O IV–V to O VI. In other wavelength regions, lines of O III and C III disappear while the ionisation shifts from Fe VI to Fe VIII. Even Fe X lines are visible in the hottest PG1159 stars. These objects also display lines from Ne VIII, Si VII, S VII, and Ca X.

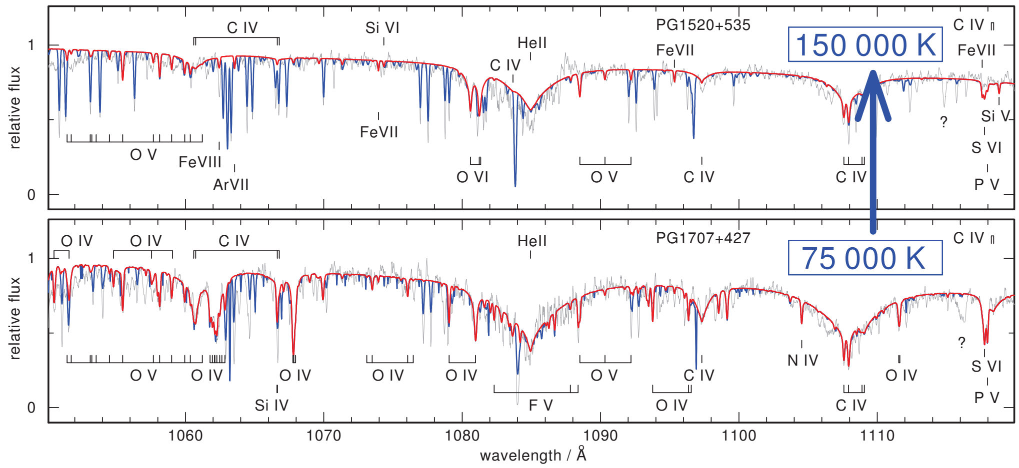

Figure 2. Details of FUSE spectra (grey) from two PG1159 stars with effective temperatures differing by a factor of two. Overplotted are photospheric models without (red) and with (blue) ISM lines. With increasing temperature, the dominant, broad lines of He II and C IV become weaker. Many lines from O IV–V are visible in the cool star while they essentially disappeared in the hotter one. At the same time, O VI lines show up.

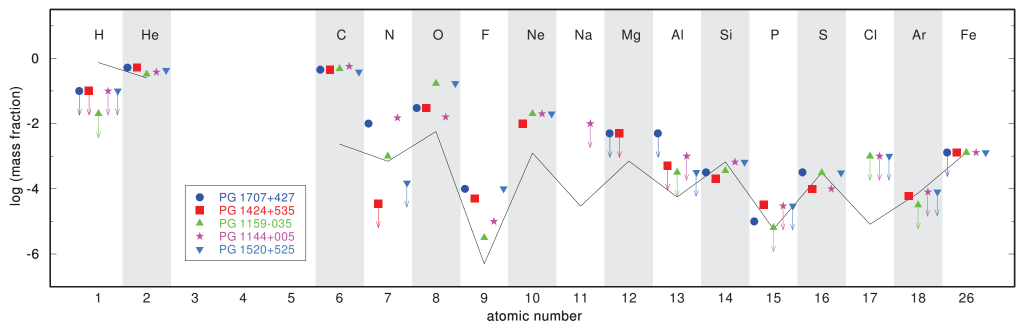

Figure 3. Elemental abundances measured in five PG1159 stars. The black line indicates solar values.

The results of our abundance analyses are summarized in Fig. 3. As was already known from optical spectroscopy, the dominant species are He, C, and O. Hydrogen cannot be detected. Because of the high temperatures and strong ionisation, the upper abundance limit is typically not stricter than H < 0.1 (mass fraction). Nitrogen displays a dichotomy, namely, its abundance is either high (of the order 0.01) or low (less than about 10^{-5}) which can be interpreted as a marker for a very late or late thermal pulse experienced by the star. As to other metals, we compare our results to the abundances found in the intershell region of AGB star models computed by Shingles & Karakas (2013). Fluorine is generally strongly enriched. The wide spread in the observed abundances is also exhibited by stellar models. They show a distinct stellar-mass dependence of the F production. We find that neon is strongly enriched to a 1–2% level

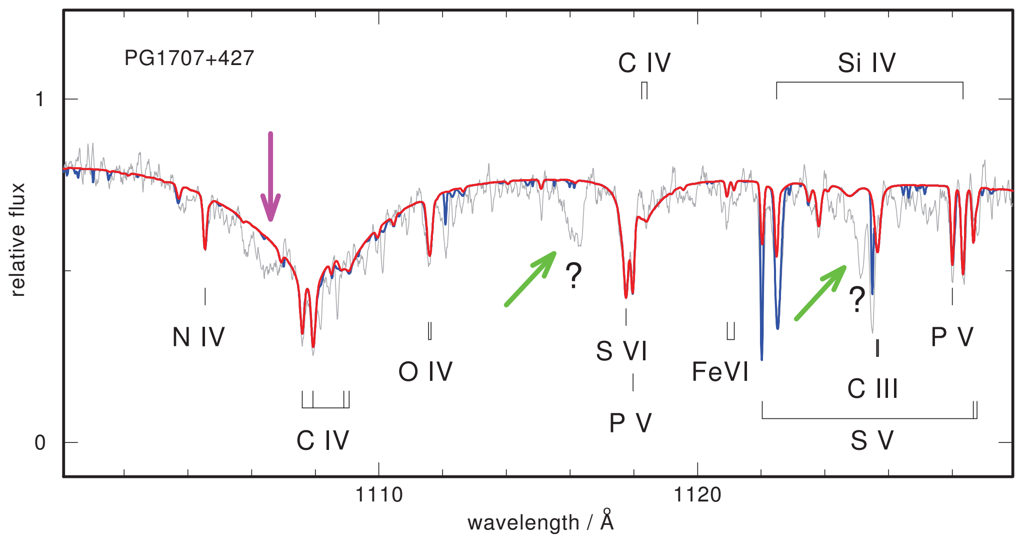

Figure 4. Two examples for strong unidentified lines (indicated by green, slanted arrows). The line indicated by the vertical (purple) arrow is one of the newly identified forbidden C IV components.

which can be explained by the production of Ne by α captures on nitrogen. Silicon is found to be solar which is in accordance with stellar models because they predict just a slight depletion to 0.8 solar. Similarly, phosphorus is found to be slightly enriched, which agrees with stellar models because they predict 2–4 times solar P abundances, depending on stellar mass. For S, Ar, and Fe we find (roughly) solar abundances which is also in agreement with stellar models. We searched for lines from Na, Mg, Al, Cl, and trans-iron elements, but to no avail. This excludes at least strong overabundances that would contradict nucleosynthesis models. To conclude, we find metal abundances that agree well with stellar evolution models.

Details of this analysis were published in Werner et al. (2015) and Werner et al. (2016b).

Many photospheric lines in the FUSE spectra remain unidentified. Two examples for particularly strong features are marked in Fig. 4. Also indicated in this figure is an absorption feature that has been identified to stem from C IV, namely, a so-called forbidden component.

3. Identification of Forbidden Components of C IV Lines

Forbidden components of spectral lines are well known from neutral helium. They are lines that do not obey the quantum mechanical selection rule for electric dipole transitions, $\Delta\ell = \pm 1$, where ℓ is the angular quantum number. A forbidden component of the He I 4471.48 Å line has already been noted by Struve (1929) in B star spectra, namely a $\Delta\ell = 2$ transition at 4470.04 Å. The detection of the respective $\Delta\ell = 0$ transition at 4517 Å by Liebert et al. (1976) represents the first identification of a forbidden He I

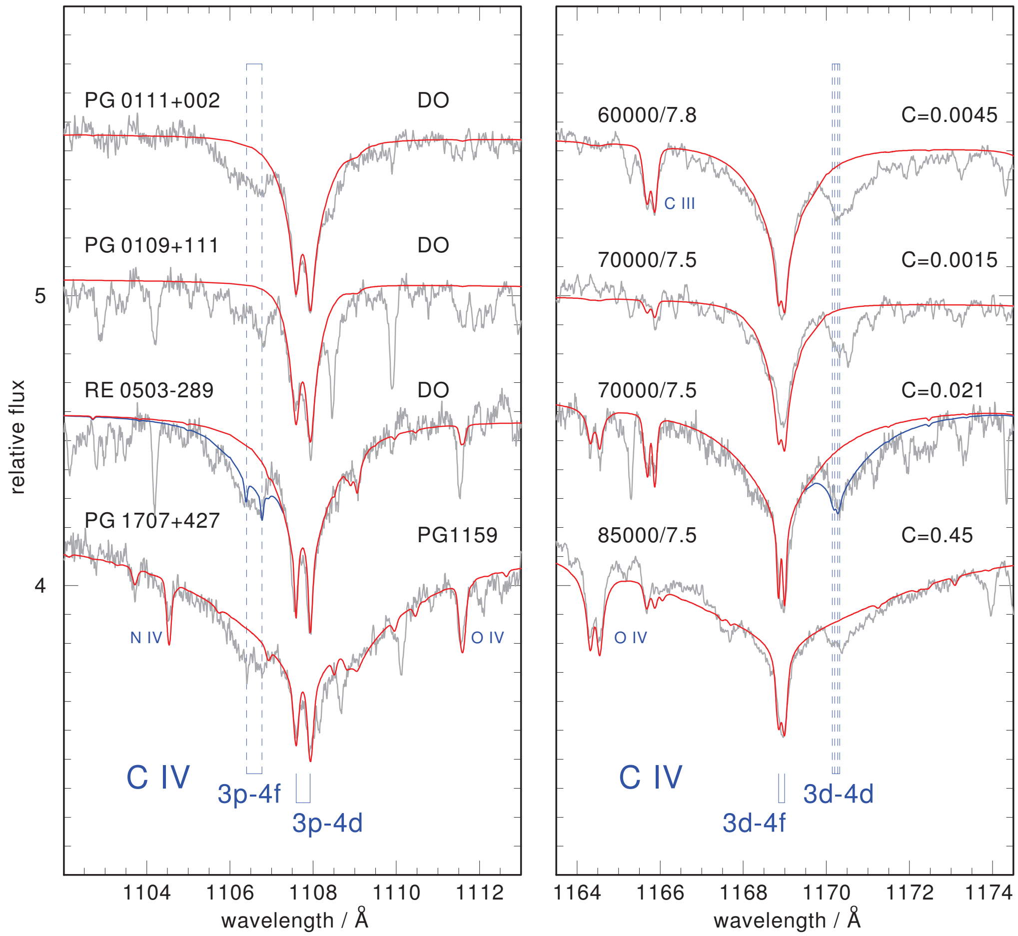

Figure 5. The two forbidden C IV components (left panel: 3p–4f transition; right: 3d–4d transition) in three DO white dwarfs and a PG1159 star. Overplotted are models without the forbidden components (red graphs). An additional model including the forbidden components (blue graph) is shown for the DO RE 0503−289.

component in WDs. Many more forbidden components of He I are known today, see, e.g., Beauchamp et al. (1995).

Forbidden components are associated with the mixing of upper states induced by the plasma electric microfield. They must not be confused with forbidden lines that are associated with magnetic dipole, electric quadrupole or higher multipole transitions, which are well known tools to analyse emission lines from thin plasmas, e.g., the multitude of forbidden lines in planetary nebulae or H II regions, and the He-like triplets used in X-ray spectroscopy of, for instance, stellar coronae. The appearance of forbidden components is not restricted to low gas densities because they do not involve metastable states. In contrast, they appear as absorption lines at high densities when Stark effect is important. It is worthwhile to note that, up to now, no forbidden line components from elements heavier than helium were detected in astrophysical sources.

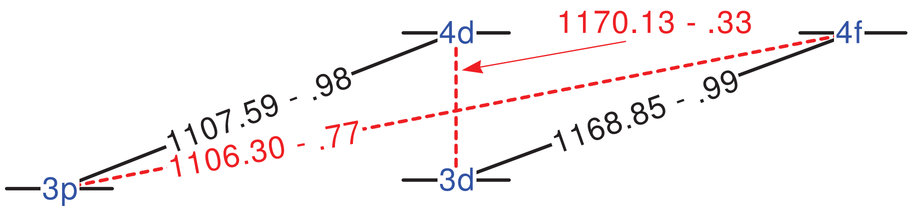

Figure 6. Partial Grotrian diagram of C IV with the discussed two allowed transitions (full lines) and related forbidden components (dashed lines).

Forbidden components are frequently used in laboratory plasma spectroscopy to measure electron densities, for example using neutral helium or lithium. What is relevant for our work is the fact that forbidden components of C IV lines were discovered in experiments conducted by Boettcher et al. (1987). They discovered exactly those two components that we now identified in the spectra of PG1159 stars and DO white dwarfs. These are the 3p–4f and 3d–4d transitions (i.e., $\Delta\ell = 2$ and 0) located at 1106 Å and 1170 Å in the blue and red wing of the respective allowed lines 3p–4d and 3d–4f (Figs. 5 and 6). All transitions (allowed and forbidden) are multiplets and some of them can be resolved.

The observed profiles of the two forbidden C IV components are asymmetric. The steep wing is pointed towards the allowed transition. This is reminiscent of the same behaviour of He I forbidden components that was explained by detailed investigations of line formation depths and Stark widths (Beauchamp & Wesemael 1998).

For the case of the DO white dwarf RE 0503−289, we computed C IV line profiles including the forbidden components by artificially increased oscillator strengths and Stark broadening parameters for the latter. Accurate line broadening data are not available. Respective quantum mechanical calculations would be very useful because the forbidden line components could be sensitive gravity indicators.

Details on our identification of the C IV forbidden components can be found in Werner et al. (2016a).

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