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DETECTION OF FORBIDDEN LINE COMPONENTS OF LITHIUM-LIKE CARBON IN STELLAR SPECTRA

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ABSTRACT

We report the first identification of forbidden line components from an element heavier than helium in the spectrum of astrophysical plasmas. As yet, these components were identified only in laboratory plasmas and not in astrophysical objects. Forbidden components are well known for neutral helium lines in hot stars, particularly in helium-rich post-AGB stars and white dwarfs. We discovered that two hitherto unidentified lines in the ultraviolet spectra of hot hydrogen-deficient (pre-) white dwarfs can be identified as forbidden line components of triply ionized carbon (C IV). The forbidden components (3p–4f and 3d–4d) appear in the blue and red wings of the strong, Stark broadened 3p–4d and 3d–4f lines at 1108 Å and 1169 Å, respectively. They are visible over a wide effective temperature range (60 000 − 200 000 K) in helium-rich (DO) white dwarfs and PG 1159 stars that have strongly oversolar carbon abundances.

Keywords: atomic processes — atomic data — white dwarfs — stars: atmospheres

1. INTRODUCTION

Forbidden line components are atomic transitions with $\Delta\ell \neq \pm 1$, where ℓ is the angular quantum number. They are associated with the mixing of upper states induced by the plasma electric microfield, leading to transitions that are normally disallowed by the selection rules for electric dipole transitions. This effect should not be confused with forbidden lines associated with magnetic dipole, electric quadrupole or other higher multipole transitions which are well known tools for analysing emission lines from thin astrophysical plasmas, e.g., a multitude of forbidden lines in planetary nebulae (Bowen 1927) and He-like triplets in X-ray spectra of stellar coronae (Gabriel & Jordan 1969). The forbidden line components investigated here are not restricted to low densities because they do not involve metastable states. In contrast, they appear as absorption lines at high densities when line broadening by the Stark effect is important.

The most prominent example for numerous forbidden components are neutral helium lines in optical spectra of white dwarfs (e.g., Liebert et al. 1976; Beauchamp et al. 1995), originally detected in B-type stars by Struve (1929) at He I λ4471 Å. This $2\,^3P - 4\,^3D$ transition is accompanied by the forbidden $\Delta\ell = 2$ component $2\,^3P{-}4\,^3F$. Detailed descriptions of the physical process associated with the formation of forbidden components in neutral helium can be found, e.g., in Barnard et al. (1969, 1974); Griem (1974); Adler & Piel (1991); Griem (2005).

To our best knowledge, forbidden components of elements heavier than helium have hitherto not been identified in astrophysical plasmas but in laboratory plasmas. Boettcher et al. (1987) report the detection of such components in lithium-like (i.e., one valence electron) C IV and N V. They can be used for plasma diagnostics because they are strongly density dependent. Another example is lithium itself. Li I λ4602 Å 2p–4d with its forbidden 2p–4p and 2p–4f components is used for diagnostics (e.g., Cvejić et al. 2014) in plasmas where helium with its forbidden components is not present for that purpose.

The first to investigate the presence of forbidden line components in stellar spectra was, as mentioned, Struve (1929). He wrote: "Of the various elements only helium seems to promise any results. Hydrogen shows no new lines outside the Balmer components, which are blended. All other elements are either faint in the stars or not very susceptible to Stark effect."

At last we can report here on the detection of forbidden line components of a heavier species, namely carbon in stellar spectra. They occur in hot (pre-) white dwarfs, namely, the same two C IV transitions discovered in the plasma experiment by Boettcher et al. (1987). The detection is favored by the conditions encountered in hot white dwarf atmospheres. Broad C IV lines due to

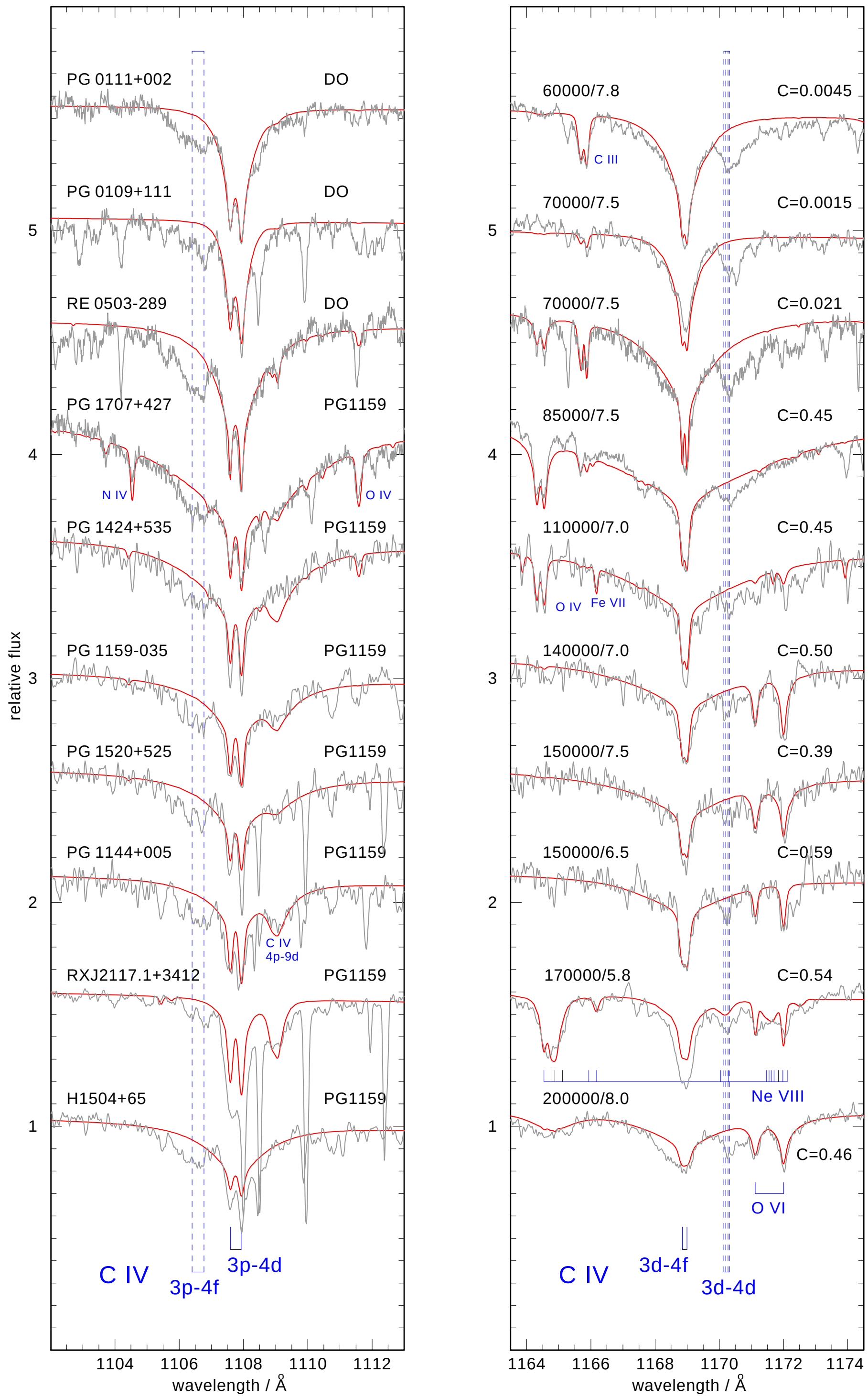

Figure 1. Observed spectra of DO white dwarfs and PG 1159 stars (grey lines) with overplotted model spectra (red lines; forbidden components not included). *Left panel:* Forbidden C IV 3p–4f multiplet (indicated by vertical, blue dashed lines) in the blue wing of the allowed 3p–4d line. Object names and spectral types are indicated. *Right panel:* For the same stars, we show the forbidden C IV 3d–4d multiplet in the red wing of the allowed 3d–4f line. $T_{\rm eff}$, $\log g$, and carbon abundance (mass fraction) of the models are indicated. Some other photospheric lines are marked in both panels.

strong Stark effect and, often, highly enriched carbon abundance. Because of the strong density dependence of the line strengths, they can potentially be used as sensitive gravity indicators in stellar spectra.

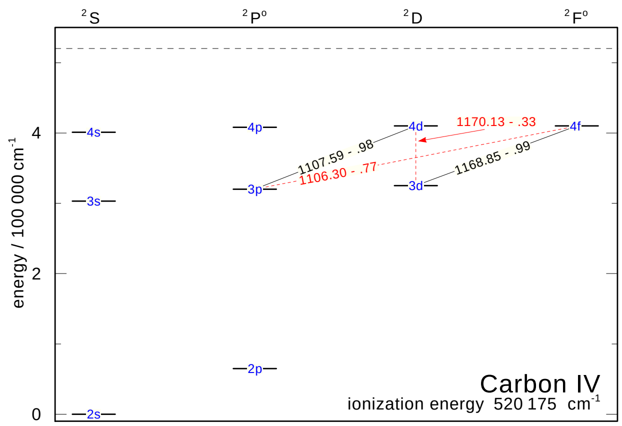

Figure 2. Grotrian diagram of the lithium-like C IV ion. Solid lines indicate the observed dipole allowed transitions, dashed lines indicate the identified forbidden components.

2. DETECTION OF FORBIDDEN C IV COMPONENTS

We have detected two forbidden C IV components in ultraviolet spectra of three DO (i.e., He-dominated) white dwarfs and seven PG 1159 (He-C-O dominated) stars (Fig. 1). The DOs' effective temperature and surface gravity ranges are $T_{\rm eff} = 60\,000 - 70\,000$ K and $\log(g/\mathrm{cm/s}^2) = 7.5 - 7.8$, and their carbon abundances range between C = 0.0015 and 0.021 (mass fraction). The PG 1159 stars are hotter ($T_{\rm eff} = 85\,000 - 200\,000$ K) and have surface gravities between $\log g = 6.5$ and 8. Their carbon abundances are significantly higher (C = $0.39 - 0.59$). All stars have in common that the profiles of the allowed C IV transitions are very broad because of linear Stark effect in comparison to most other metal lines (e.g., from C III and O IV visible in some spectra displayed in Fig. 1).

The detected forbidden components are 3p–4f ($\Delta\ell = 2$; Fig. 2) in the blue wing of the allowed 3p–4d line at 1108 Å, and 3d–4d ($\Delta\ell = 0$) in the red wing of the allowed 3d–4f line at 1169 Å. Their profiles are asymmetric, with the broader wing pointing away from the adjacent allowed line. In some spectra, the 3p–4f transition can be resolved as two fine-structure components. The spacing between the allowed and forbidden components is about 0.5 Å. All C IV lines are multiplets with noticeable splittings because the energy levels are doublets. In Table 1, we present the wavelengths of the forbidden components as calculated from the level energies listed in the National Institute of Standards and Technology (NIST) database[1] together with new pseudo-relativistic Hartree-Fock oscillator strengths computed using the Cowan's atomic structure codes (Cowan 1981).

Table 1. Wavelengths λ and oscillator strengths f of the two forbidden C IV components' multiplets.

$n\ell - n'\ell'$	$j - j'$	f	λ/Å
3p–4f	1/2–5/2	1.199×10^{-5}	1106.40
	3/2–5/2	1.730×10^{-6}	1106.79
	–7/2	1.042×10^{-5}	1106.77
3d–4d	3/2–3/2	6.886×10^{-7}	1170.20
	–5/2	2.937×10^{-7}	1170.14
	5/2–3/2	1.958×10^{-7}	1170.32
	–5/2	7.977×10^{-7}	1170.27

We are confident that the identification of the two absorption features as forbidden C IV components is correct and that they do not stem from other elements. First, none of the ions hitherto identified in the investigated stars is visible over the entire, large $T_{\rm eff}$ range covered by the stars. Second, the observed asymmetric line profiles are neither expected nor observed from allowed transitions.

We noticed the forbidden lines during previous analyses of some of the stars presented here, however, as yet they remained unidentified. They are most prominent in the DO white dwarfs (top three spectra in Fig. 1) and generally weaker in the hottest PG 1159 stars. As can be judged from the model for RX J2117.1+3412, the 3d–4d line in this star is blended by a Ne VIII line, however, the other forbidden component 3p–4f is clearly visible.

The displayed spectra are overplotted with models whose relevant parameters ($T_{\rm eff}$, $\log g$, carbon abundance) are given in the right panel of Fig. 1. Most of them were derived in our earlier work, whilst a few are from work in progress, involving new observations (see below). For conciseness we abstain from individual references. As representative examples we mention our detailed work on the DO white dwarf RE 0503−289 (Rauch et al. 2016, and references therein) and on two PG 1159 stars (Werner et al. 2015). As to the observations, the majority of the spectra from the objects in the present study were recorded with the *Far Ultraviolet Spectroscopic Explorer* (FUSE). All were described in the publications mentioned. Spectra of PG 0111+002, PG 0109+111, and PG 1707+427, however, are from our observations recently performed with *Cosmic Origins Spectrograph* aboard the *Hubble Space Telescope* (Proposal ID 13769). Details of these observations and their

[1] http://www.nist.gov/pml/data/asd.cfm

spectral analysis will be deferred to a later paper (Hoyer et al., in prep.).

3. DISCUSSION AND CONCLUSIONS

Appropriate quantum-mechanical calculations for the Stark line broadening of forbidden C IV components are not available. Godbert et al. (1994a) performed such calculations for the interpretation of laboratory spectra with a computer code presented by Calisti et al. (1990) but, to our best knowledge, they were not published. For the 3p–4f transition, broadening data were published by Dimitrijević et al. (1991), however, they are useless in our context because it was assumed an isolated line. At the moment, we are only able to include the lines by assuming linear Stark effect (as for the allowed components) in the approximation presented by Werner et al. (1991) and guessing their strength by arbitrarily upscaling theoretical f-values computed by us. As an example we show in Fig. 3 (black line) the result of this procedure in the case of the DO white dwarf RE 0503−289. The f-values required scaling by factors of 400 and 10 000 for the 3p–4f and 3d–4d transitions, such that they amount to about $f = 0.004 - 0.008$. The line positions are matched while the asymmetries are not because, obviously, our assumption for broadening is poor. The extended wings that point away from the allowed line component are not broad enough in the model. An arbitrary increase of the Stark damping constant by a factor of six and a further increase of the f-values by a factor of two results in a better fit, but then the steep wings pointing towards the allowed line components are too broad (Fig. 3, dashed blue line).

The asymmetric line shape of the forbidden components (with their steep wing always towards the adjacent allowed line) is identical to the behaviour of such lines of neutral helium in stellar atmospheres. Under certain circumstances, the asymmetry can be very pronounced as was demonstrated by Beauchamp & Wesemael (1998, their Fig. 2) and was explained by the effect of varying ratios of line widths to the separation of forbidden and allowed components as a function of formation depths of line cores and wings.

The detection of the C IV 3d–4d forbidden component at 1171 Å in the experiment by Boettcher et al. (1987) (observed in second order) was subsequently questioned by Godbert et al. (1994b) who argued that the respective spectral feature is an impurity line, namely the λ585 Å C III 2p 3s–2p^2 line (at 1171 Å in fourth order). In light of our observations in white dwarfs we conclude that Boettcher et al. (1987) indeed saw the C IV 3d–4d component, at least contributing to the impurity line.

The forbidden components of C IV originally identified in laboratory plasmas (Boettcher et al. 1987) and now in stellar spectra are $n = 3 - 4$ transitions, where n is the principal quantum number. The 3d–4d forbidden component of lithium-like N V was also detected by Boettcher et al. (1987). It is located at 749 Å and therefore not accessible in stellar spectra because of extinction by interstellar neutral hydrogen. The respective $n = 3 - 4$ lines of lithium-like O VI have even shorter wavelengths. O VI has strong and broad lines, comparable to the C IV lines, in the ultraviolet spectra of the PG 1159 stars presented here. Candidates for forbidden components are $n = 4 - 5$ transitions, but we could not identify any.

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Facilities: HST(STIS,COS), FUSE

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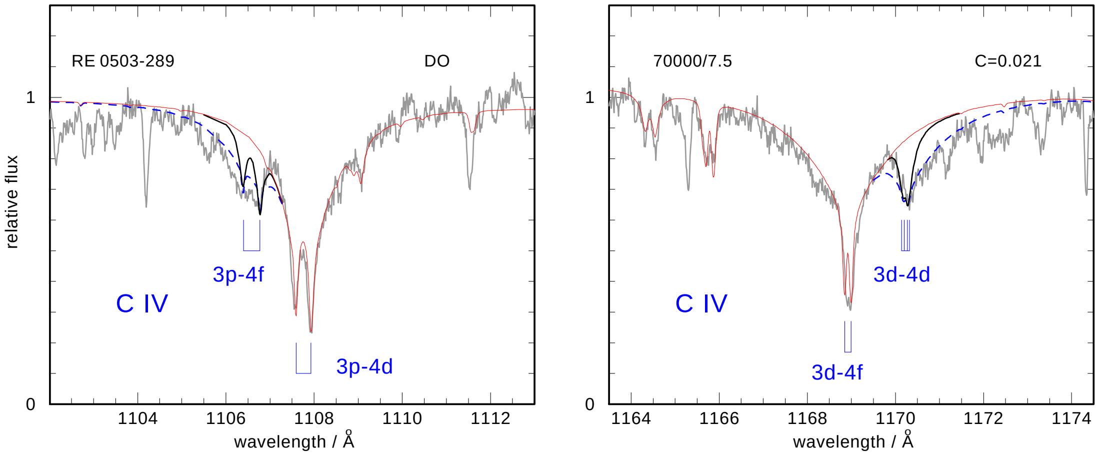

Figure 3. Details from Fig. 1 showing the DO white dwarf RE 0503−289 and a model without the forbidden components (thin, red line). In addition, two more models that include the C IV forbidden components in an approximate manner (see text) are overplotted. Thick, black line: f-values artificially increased. Thick, blue dashed line: Stark broadening parameter increased.

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