FUV spectroscopy of DO and PG1159 stars with ORFEUS

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Abstract. We have performed FUV spectroscopy of PG 1159 type central stars of planetary nebulae and DO white dwarfs with ultrahigh ionization lines in order to study their wind properties.

For the PG 1159 stars we derive mass-loss rates of the order 10^{-7}–$10^{-8}\mathrm{M}_\odot$/yr and conclude that their winds are radiatively driven. By comparison of model atmospheres we find that the high mass-loss rates in the PG 1159 progenitors, the [WC] central stars, are possibly maintained by multi-scattering processes.

The FUV spectra of the two inspected "super-hot wind" DOs are dominated by unidentified opacity sources. UV and optical observations can be interpreted in terms of a radiation driven wind, which rapidly accelerates to a very high terminal speed (10 000 km/s) in the strong gravitational field of the DO white dwarf. The origin of super-ionization remains unknown.

1. Introduction

The UV spectral range of white dwarfs blueward of Lyα down to the Lyman limit could not be studied systematically until the advent of dedicated FUV space telescopes, like HUT and ORFEUS. A number of PG 1159 stars was observed by HUT. Except of one case, this set comprised evolved objects with high surface gravity, hence low luminosities. Instead of discussing the results of this study (Kruk & Werner 1998), we concentrate here on more recent observations of luminous PG 1159 stars with ORFEUS. From atmospheric models we expected that this low gravity objects exhibit a O VI 1035Å resonance line with a distinct P Cygni profile, provided that mass-loss occurs at a rate according to radiation driven wind theory. Knowledge of the mass-loss rate of PG 1159 stars is important to further corroborate their link to the [WC] central stars. In addition, the mass-loss rate is an essential ingredient for diffusion calculations (see e.g. Unglaub & Bues 1999). These are performed in order to explore the role of gravitational settling and radiative levitation for shaping the current chemical abundance pattern of PG 1159 stars and its temporal evolution along the WD cooling track, when the transition to a purified DO or DA atmosphere occurs.

The recent discovery that about 50% of all hot DO white dwarfs show signatures of a super-hot wind has prompted HST/UV observations (Werner et al. 1997a) and ORFEUS spectroscopy of two selected targets. The latter will be described here, and we shall summarize our knowledge of this phenomenon from observational material collected so far, which span from the X-ray to IR spectral range.

2. FUV Observations

Two PG 1159 type central stars (NGC 7094, RX J2117.1+3412) and the [WC]–PG 1159 transition object Abell 78 were observed during the ORFEUS II mission with the Berkeley spectrograph. In addition, the PG 1159 central star of NGC 246 was observed during the first ORFEUS mission with the same instrument, and another one during the HUT-Astro 2 flight (K1-16). Details concerning the calibration of HUT and the reduction of the K1-16 spectrum are found in Kruk & Werner (1998). Calibration and performance for the ORFEUS II mission are described by Hurwitz et al. (1998). For more details on these observations we refer to Koesterke & Werner (1998).

The two prototype DO white dwarfs showing the O VIII phenomenon most strongly were also observed during the ORFEUS II mission (Berkeley spectrograph). HE 0504-2408 was observed for 30 minutes (GI target) and HS 0713+3958 for 10 minutes (PI target). The spectral resolution amounts to approximately 0.5Å. The red end of the spectra of both stars overlap with HST-UV spectra taken previously (Werner et al. 1997a).

3. Mass-loss from PG 1159 stars

The PG 1159 stars are the immediate successors of the [WC] central stars as indicated by recent results of spectral abundance analyses of [WC] stars (Hamann 1997). Unlike the PG 1159 stars, their spectra are dominated by emission lines as a consequence of high mass-loss rates, which range between 10^{-5}–$10^{-6.5}$ $M_\odot$/yr, with rates decreasing along with the post-AGB evolution. A few [WC]–PG 1159 transition objects are known. Their optical spectra show a mixed emission-absorption line spectrum as a consequence of smaller mass-loss rates, being of the order of $10^{-7.5}$ $M_\odot$/yr (Werner & Koesterke 1992, Hamann 1997). The analysis of the P Cygni profile of the O VI resonance line in our new FUV spectra confirms our earlier study on Abell 78. The results for the four PG 1159 central stars are given in Table 1. Comparison with theoretical studies (Pauldrach et al. 1988) suggests that the winds are radiation driven: The more massive objects (NGC 246, RX J2117.1+3412) have a higher $\dot{M}$. The hybrid PG 1159 star NGC 7094 (containing hydrogen) has a higher $\dot{M}$ than the H-deficient K1-16. We find $v_\infty \approx 3 \cdot v_{esc}$, and the theoretically predicted values for $\dot{M}$ agree well with the observed ones. Our results are in accordance with a contemporary analysis of the C IV 1550Å resonance line in IUE and HST spectra, which however is much weaker than the O VI line (Koesterke et al. 1998).

Table 1. Wind properties of four PG 1159 type central stars. Other stellar parameters were derived previously with static model atmospheres.

Star	$T_{\rm eff}$ kK	$\log g$ cgs	$\log L$ $L_\odot$	M $M_\odot$	$\log \dot{M}$ $M_\odot$/yr	v_∞ km/s	v_{esc} km/s
NGC 7094	110	5.7	3.6	0.63	-7.7	3500	1150
K1-16	140	6.1	3.6	0.63	-8.1	4000	1450
NGC 246	150	5.7	4.2	0.84	-6.9	3500	1200
RX J2117.1+3412	170	6.0	4.2	0.83	-7.4	3500	1350

In essence, mass-loss rates decrease with continuing evolution from the [WC] phase to the PG 1159 phase while the star shrinks and its luminosity decreases. Note that we studied here the most luminous PG 1159 stars, directly bordering the [WC] regime in the HRD. The majority of the PG 1159 group, however, is much less luminous (down to about 10 $L_\odot$) so that mass-loss is too weak to be observable. It is still debated whether the strong mass-loss from the [WC] stars can be radiatively driven. As a result of our investigation we find that in contrast to the PG 1159 stars the atmospheres of the [WC]s are strongly stratified with respect to the ionization structure. This ionization stratification might maintain the strong mass-loss by multi-scattering processes as proposed by Lucy & Abbott (1993).

4. Mass-loss from DO stars: The O VIII phenomenon in hot WD

The O VIII phenomenon describes the occurrence of high ionization absorption lines of the CNO elements (e.g. O VIII, N VII, C VI, and even Ne X) in the optical spectra of hot white dwarfs. The high excitation potentials involved require temperatures approaching almost one million K and the triangular shaped line profiles suggest their formation in a rapidly accelerating wind from the WD. Since the first discovery of such objects a few years ago (Werner et al. 1995) we now realize that 50% of all white dwarfs of spectral type "hot DO" (i.e. no He I lines detectable, only He II) are affected (Dreizler et al. 1995), hence it may be speculated that *all* DO white dwarfs experience this phenomenon at the beginning of the WD cooling sequence. The lack of proper modeling does not permit any quantitative statement about photospheric parameters at this moment. Let us summarize the characteristics of observations performed so far and draw some qualitative conclusions as far as possible.

We do not detect He I lines, therefore $T_{\rm eff}$ must exceed about 80 000 K. The He II profiles are symmetric, hence line formation occurs in hydrostatic layers.

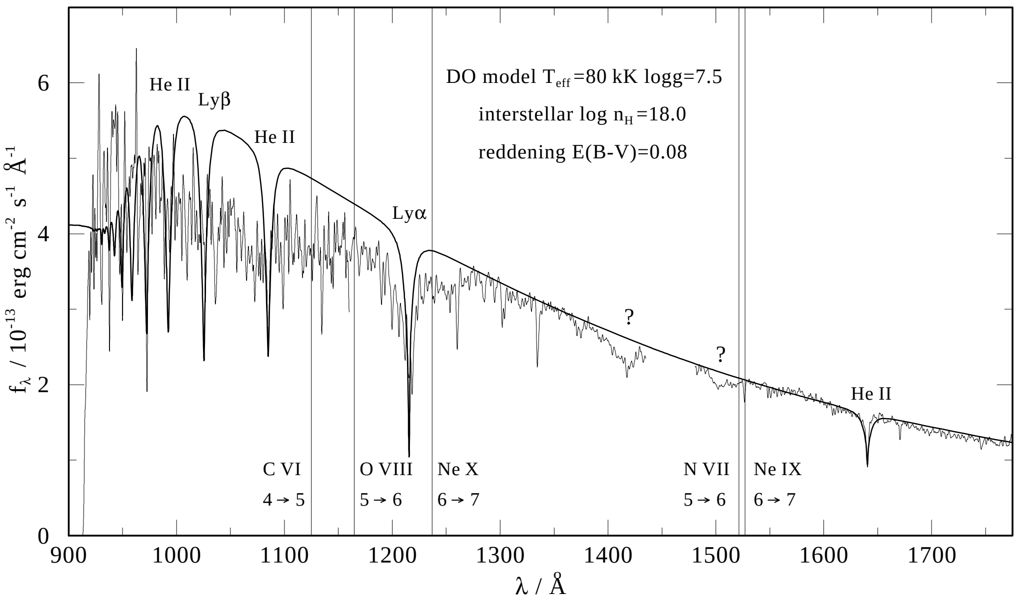

Figure 1. Combined HST and ORFEUS spectra of HE 0504-2408 (joined at λ=1160Å). Overplotted is a DO model. All spectra are smoothed with 1Å FWHM Gaussian. Vertical bars represent expected - but not observed - positions of high ionization metal lines. A possible broad P Cygni profile of C IV 1550Å indicates a wind speed of the order of 10 000 km/s. The flux deficit in the FUV range points at additional opacity sources either of interstellar or stellar origin.

Disturbingly, we cannot fit the unusually strong profiles with any model atmosphere. This prevents a surface gravity determination and further constraining $T_{\rm eff}$. IR photometry revealed that HS 0713+3958 has a cool companion (spectral type K7) separated about 1" from the primary (Napiwotzki 1998). Future IR spectroscopy might reveal the distance to this system and eventually enables a more definite statement about $T_{\rm eff}$ of the primary.

The optical high ionization CNO lines have pronounced blue wings, corresponding to outflow velocities of up to several thousand km/s. We are not able to give any abundance estimate. Preliminary calculations of wind models suggest mass-loss rates between 10^{-7} and 10^{-10}M$_\odot$/yr. However, at present these radiative equilibrium models are crude at best, as they simply assume a very high $T_{\rm eff}$ in order to produce the high ionization stages. Since the post-AGB age is of the order of 10^5-10^6 yr, consequences of the stellar wind on evolutionary times scales and chemical surface composition are possible, if the mass-loss rates are in fact as high as estimated above.

In the UV range (IUE, HST) no high ionization CNO line is detectable, except possibly O VIII 2978Å. This negative result is not at all understood and must be explained by any modeling attempt. Strictly speaking, the only clearly identified photospheric line is He II 1640Å. The detection of O V 1371Å is doubtful. On the other hand we detect two unidentified broad absorption features

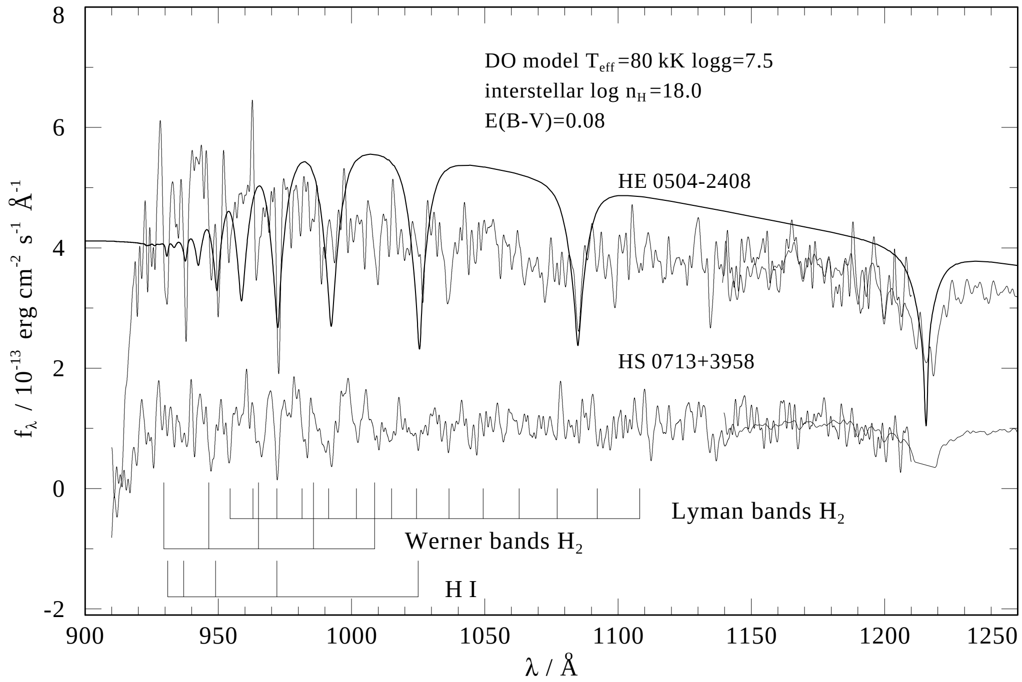

Figure 2. Overlapping ORFEUS II spectra ($\lambda < 1210$Å) and HST spectra ($\lambda > 1140$Å) of HE 0504-2408 and HS 0713+3958.

($\lambda\lambda$ 1420, 1500Å, see Fig. 1). In addition clusters of weak absorption lines near 1560Å and near 1610Å are possibly present, which are perhaps linked to circum-/interstellar molecules (Werner et al. 1997a). This is supported by the detection of H_2 features in our new FUV spectra. The 1500Å feature represents possibly the blue shifted absorption component from a P Cygni profile of C IV 1550Å. This is corroborated by a very weak and broad emission bump near the rest wavelength. We note that such shallow P Cygni profiles are observed in PG 1159 type central stars (e.g. Feibelman 1995). If this interpretation is correct here, then the terminal wind speed is about 10 000 km/s. If we assume $T_{\rm eff}$=80 000 K, M=0.6 M$_\odot$, then R=0.02 R$_\odot$ and the escape velocity from the surface amounts to $v_{\rm esc}$=3400 km/s. Extrapolation of results from radiation driven wind theory for central stars (Pauldrach et al. 1988) predicts that the terminal velocity $v_\infty \approx 4.2 \cdot v_{\rm esc} \approx 14\,000$ km/s. This compares reasonably with the observed wind speed, hence, we conclude that we may witness radiation driven winds from DO stars.

The ORFEUS observations reveal that the FUV spectral shape is surprisingly flat (Figs. 1 and 2). Strong reddening by interstellar dust alone is unlikely, because the interstellar hydrogen column density is not much larger than 10^{19}/cm^2, as judged from the Lyα profile in the HST and ORFEUS spectra. We can identify molecular hydrogen in HS 0713+3958, but additional opacity sources are probably present. There are hints for CO in the HST spectra (see above), and this molecule might be the origin of additional FUV opacity, but for definite statements we wait for results of granted FUSE observations which will have a better spectral resolution. In this context we remark, that no PN was found around HS 0713+3958 (Werner et al. 1997b), in which circumstellar molecules could reside. As it is the case in the HST/UV spectra, we do not see any high-ionization metal line from the wind (a C VI line near 1120Å was a possible candidate). No photospheric feature is identified in the HS 0713+3958 FUV spectrum, even no He II line (Fig. 2). In HE 0504-2408 we see He II 1085Å, but no other line of the corresponding series. An absorption near 1036Å could stem from the O VI resonance line, but we do not identify the other component of the doublet.

None of the objects was detected in the X-ray region (ROSAT survey and pointed observation of HE 0504-2408). The inferred low X-ray luminosity confirms that we do not see absorption lines from super-hot photospheres, but that the high temperatures are possibly localized along shock fronts in the wind.

Finally we emphasize that the O VIII phenomenon is not restricted to DO white dwarfs. We have also detected one DAO with similar high ionization features (Dreizler et al. 1995). This is the only case discovered among DA/DAO white dwarfs so far, and it is not understood why there is such a strong preference among DOs to show this phenomenon.

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