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Discovery of two hot DO white dwarfs exhibiting ultrahigh-excitation absorption lines*

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Abstract. We report on the detection of two faint blue stars (HE 0504−2408 and HS 0713+3958) discovered by the Hamburg Schmidt surveys whose spectra are dominated by broad and shallow metal absorption lines from ultrahighly excited ionization stages (C V, C VI / N VI, N VII / O VII, O VIII, Ne IX, Ne X) with ionization energies ranging from 392eV to 1362eV. Detailed non-LTE modeling excludes a photospheric origin of these lines. Instead we propose that they are formed in a stellar wind, explaining their asymmetric shape. The underlying stellar source is probably a hot helium-rich white dwarf ($T_{\rm eff}$ about 70 000 K) causing the observed He II line spectrum with symmetric profiles. However, the He II absorptions are relatively strong and cannot simply be reproduced by a model atmosphere for a DO white dwarf.

Thus, these two stars might constitute a new spectral subclass of hot helium-rich white dwarfs exhibiting spectral signatures never observed before in any astrophysical object.

Key words: Line: identification – Stars: atmospheres – Stars: evolution – AGB and post-AGB – white dwarfs

1. Introduction

The Hamburg-Schmidt objective prism surveys, aiming at a complete coverage of the northern sky (HQS, Hagen et al. 1994) and a large fraction of the southern hemisphere (HES, Wisotzki 1994), provide a very rich source of faint ($13 \lesssim B \lesssim 17$) blue stars. Optical follow-up spectroscopy of such objects has revealed numerous interesting individual stars, for a recent review see Dreizler et al. (1994). Among these are extremely hot helium-rich (DO) white dwarfs and PG 1159 stars with effective temperatures exceeding 100 000 K. In this *Letter* we report on the discovery of two very exceptional objects (HE 0504−2408 and HS 0713+3958) whose optical spectra are dominated by absorption lines never observed before in any stellar spectrum and indicating extremely high temperatures in the line forming regions.

2. Observations and line identifications

HE 0504−2408 (α_{1950} = 05$^{\rm h}$04$^{\rm m}$14$^{\rm s}$, δ_{1950} = −24°08′14″, B=15.2±0.5) was observed in January 1992 and January 1993 at ESO. The 3.5m NTT and the EMMI spectrograph in the dichroic mode (4270–4800Å; 5680–6770Å, spectral resolution of 3.5Å) were used in 1992. In 1993, the 3.6m telescope and EFOSC 1 in Echelle mode (3800–7000Å, spectral resolution of 3.5Å) were used. HS 0713+3958 (α_{1950} = 07$^{\rm h}$13$^{\rm m}$36$^{\rm s}$, δ_{1950} = +39°58′47″, B=15.8±0.5), was observed with the Calar Alto 3.5m telescope and TWIN spectrograph (3500–8000Å) in March 1993 (spectral resolution of 6Å) and September 1994 (resolution 4Å).

The optical observations of both stars are compared in Fig. 1 to the hot DO white dwarf PG 0108+101 ($T_{\rm eff}$=90000K, $\log g$ =8.0, Dreizler et al. 1995). First of all, no He I line (e.g. 4471Å or 5876Å) is detectable, pointing at high effective temperatures. The He II Pickering series (4 → n) with a prominent 6560Å line shows a strong decrement so that the higher series members (from 4200Å) are not visible. The strong feature at 4340Å is unusually strong when compared to PG 0108+101 and we shall show below that it is strongly blended. Both stars also have a He II 4686Å line considerably stronger than in PG 0108+101. Some absorption in the blue wing of 4686Å may be attributed to C IV but all other absorption features (not present in normal DOs) remained unidentified for a while, because they were never detected before in other, even not in the hottest post-AGB stars.

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* Based on observations collected i) at the European Southern Observatory (La Silla, Chile), ii) at the German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy, iii) with the International Ultraviolet Explorer satellite. This research has made use of the Simbad database, operated at CDS, Strasbourg, France

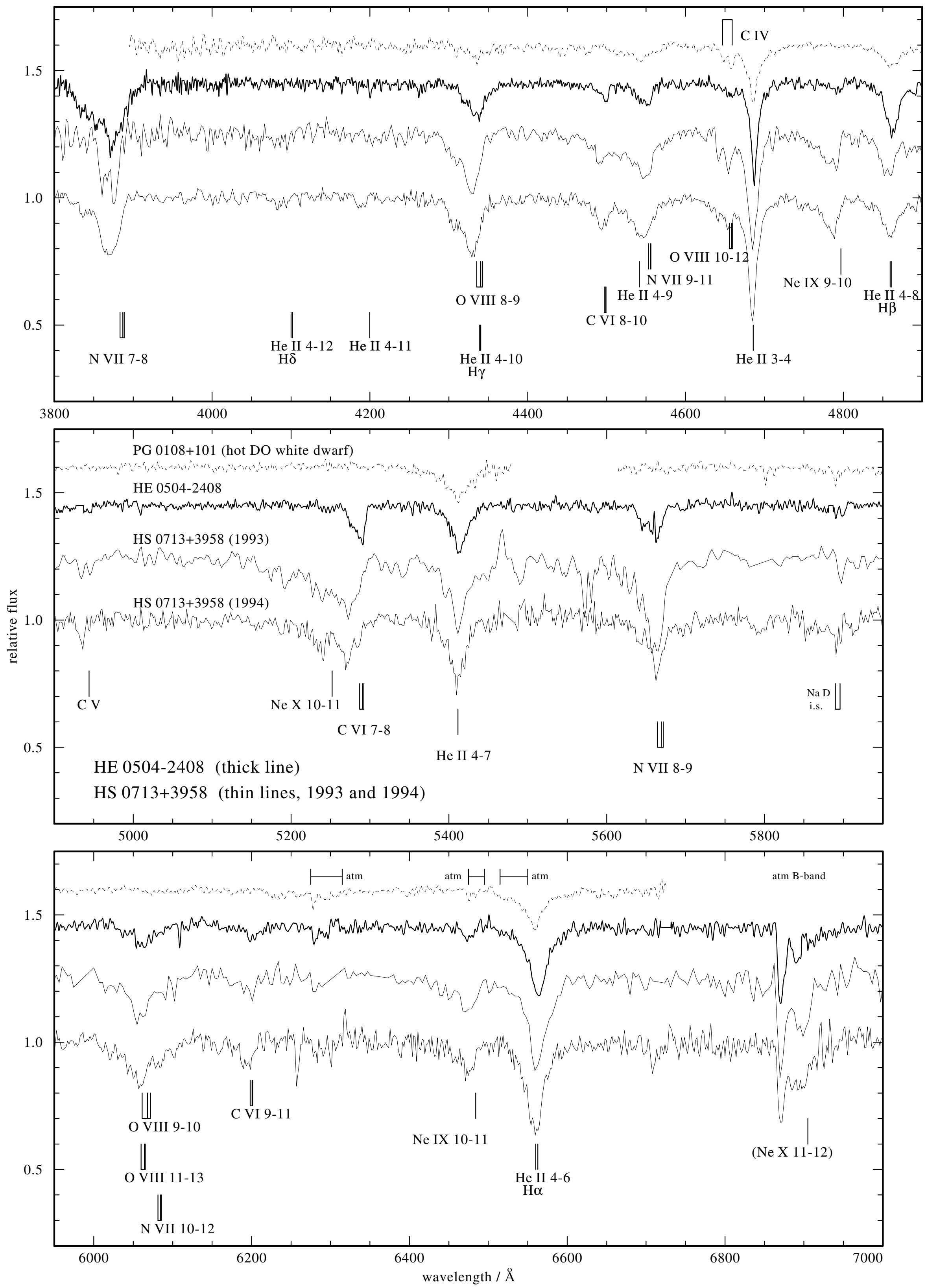

Fig. 1. Normalized optical spectra of HE 0504−2408 (1993 spectrum, resolution 3.5Å) and HS 0713+3958 (1993 and 1994 spectra, resolution 6Å and 4Å, respectively) compared to the hot DO white dwarf PG 0108+101. Note the broad absorptions from ultrahigh-excited C, N, O ions and even Ne IX and Ne X lines (HS 0713+3958, only). The width of each CNO multiplet is indicated by three vertical bars, marking the shortest and the longest wavelength as well as the statistically weighted mean of all components. Unlike the helium lines which display symmetric profiles, some of the metal lines are asymmetric (e.g. C VI 5191Å in HE 0504−2408). Telluric features are marked as "atm"

Ultraviolet spectra were taken with the IUE satellite in the low dispersion mode (HE 0504−2408: SWP 43954, LWP 22367; HS 0713+3958: SWP 49561, 49562, LWP 27020). Some other higher members of the He II Fowler series as well as the 1640Å line are detectable in the UV spectra.

A first clue as to the nature of the unknown lines comes from a comparison with the spectrum of hottest DO white dwarf known: KPD 0005+5106 ($T_{\rm eff}$=120 000 K). In this star three emission lines were identified as due to O VIII (Werner et al. 1994). The extremely high ionization potential excluded a photospheric origin and they were interpreted as emission from collisionally ionized material along shock fronts in a stellar wind from the DO star (Fleming et al. 1993). That this star might have a weak mass outflow was also argued by Sion & Downes (1992). The positions of these three O VIII emission lines coincide with three absorption features in the spectra of HE 0504−2408 and HS 0713+3958. It is then natural to look for lines that might arise from isoelectronic ions of carbon and nitrogen (C VI and N VII). In the case of KPD 0005+5106 this was unsuccessful but in the case of the two stars presented here we strikingly find that at *all* predicted positions for lines between involved levels with Δn=1 and Δn=2 we do detect an absorption feature in the observed spectra (see Tab. 1). Two additional absorptions are conspicuous in HS 0713+3958 which are only barely visible in HE 0504−2408, namely near 4790Å and 6480Å. Note that the 6480Å region is slightly contaminated by telluric features, but these are far too weak to explain the observed absorptions. Instead, these features may be attributed to Δn=1 transitions of helium-like Ne IX. One out of three Δn=1 lines of the hydrogen-like Ne X covered by our spectra is located near 5250Å. In HE 0504−2408 which shows only weakly Ne IX it is at best very weakly present but in HS 0713+3958 it is probably contributing to the broad absorption formed together with C VI 5291Å. The Ne X 3886Å (9→10) line is dominated by N VII and the third Δn=1 line of Ne X at 6905Å is masked by the telluric B band.

Generally the cores of the ultrahigh-ionization absorptions in HS 0713+3958 are blueshifted compared to the rest wavelength and to HE 0504−2408. The radial velocities are between 300–1400 km sec^{-1}. In contrast, the He II line centers in both objects almost coincide at their respective rest wavelength.

The occurrence of such lines *in absorption* is indeed a surprising fact and we carefully need to discuss the possibility of alternative identifications. In principle (for high principal quantum number n) each C VI line has a counterpart from the O VI ion. We can exclude the O VI identification, however, for two reasons. The fine structure splitting for O VI is larger than for C VI and should be resolvable in our spectra which is not the case (see Fig. 1). In addition, the O VI 3811/3834Å (3s→3p) doublet is not detectable. A similar situation is encountered in the case of N VI whose lines coincide with C VI lines, and N VII whose lines coincide with those of O VII. In these cases the fine structure splitting is too small to be resolvable and high resolution UV spectra are required to prove their presence if the unblended 2s→2p doublet of O VII at 1623/1640Å and of N VI at 1897/1908Å can be detected. The existing IUE spectra are of too low resolution to detect these lines. No alternative identification is found for the O VIII 6068Å line. Also, in the case of O VIII 4340Å the presence of a strong He II contribution is unlikely because of the absence resp. extreme weakness of the neighbouring series members. The third O VIII line (at 4658Å) coincides with a C IV transition as the comparison with the DO PG 0108+101 (Fig.1) demonstrates. And finally we know of no plausible other candidates for the absorptions attributed to Ne IX and Ne X.

Interestingly, HS 0713+3958 shows a weak line of the helium-like C V (6→7 at 4945Å). Unfortunately, this is the only Δn=1 transition of this ion covered by our spectra. But it shows that we have to account for lines from helium-like N and O, which are N VI and O VII as discussed above.

Table 1. Line identifications in HE 0504−2408 and HS 0713+3958. Wavelengths are from theoretical predictions (Garcia & Mack 1965) except for the C V (Moore 1970), N VI, O VII and Ne (hydrogenic). C VI / N VI and N VII / O VII blends are unresolved.

ion	ionization energy (eV)	Δn=1 transitions		Δn=2 transitions	
		λ/Å	n→n'	λ/Å	n→n'
C V	392	4945	6→7		
C VI	490	5291	7→8	4499	8→10
				6201	9→11
N VI	552	5293	7→8	4501	8→10
				6204	9→11
N VII	667	3887	7→8	4550	9→11[a]
		5669	8→9	6085	10→12
O VII	739	3889	7→8	4558	9→11[a]
		5673	8→9	6088	10→12
O VIII	871	4340	8→9[a]	4658	10→12
		6068	9→10	6064	11→13
Ne IX	1196	4797	9→10		
		6484	10→11		
Ne X	1362	5252	10→11		

[a] unresolved blend with He II

3. Origin of ultrahigh-excitation lines

An attempt was made to explain the exceptional absorption line spectrum by an extremely hot, static, plane-parallel non-LTE model atmosphere. A photospheric origin of the lines from highly ionized C, N, O and Ne with ionization energies ranging from 392eV to 1362eV (see Tab. 1) cannot be excluded from the outset. Theoretical evolutionary tracks of post-AGB remnants predict that massive objects may reach very high effective temperatures, although for a very short temporary phase. A 1.2 $M_\odot$ post-AGB star reaches a maximum $T_{\rm eff}$ of 700 000 K (Paczynski 1970). We have for the first time computed NLTE line blanketed model atmospheres in this temperature range with various surface gravities and chemical compositions. Much effort has been made to calculate opacities as detailed as possible. Due to the high temperatures and high ionization stages completely new model atoms had to be designed. Atomic data for that were almost exclusively obtained from the Opacity Project (Seaton et al. 1994) data base. In total, 45 ions of 13 species were included (H I-II, He I-III, C V-VII, O VI-IX, Ne VIII-IX, Na IX-X, Mg IX-XI, Al X-XII, Si X-XIII, P XI-XIV, S XII-XV, Ar XII-XVI,

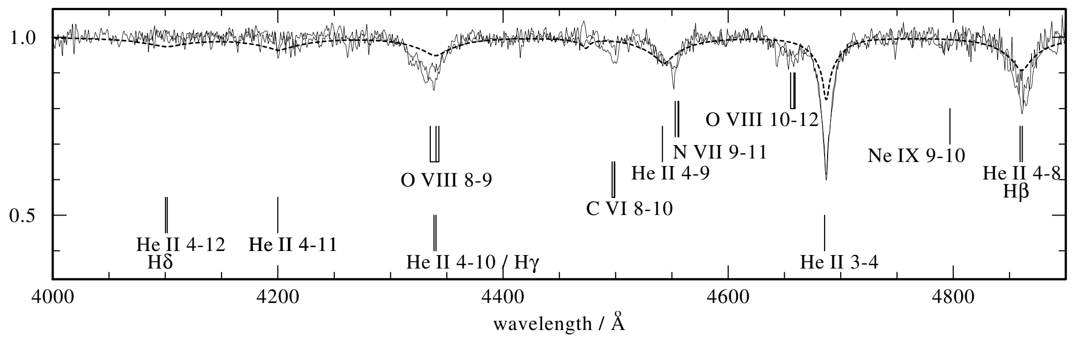

Fig. 2. Comparison of the blue spectra of HE 0504−2408 taken in 1992 and 1993. No significant line profile changes are detected, the He II 4686Å line profiles coincide perfectly. The dashed line shows the synthetic He II line spectrum from a DO model ($T_{\rm eff}$=70 000 K, log g =7.5, convoluted with a 3.5Å Gaussian). Note that the predicted 4686Å and 4860Å profiles are too shallow (see text)

Ca XI-XVI). However, the results of our calculations show that the observed spectra cannot be of photospheric origin assuming extreme $T_{\rm eff}$. While some models do show absorption lines of highly ionized C, N, O, and while He II 4686Å is still showing up as an absorption line in models which are close enough to the Eddington limit, the other He II lines like 5410Å have completely disappeared.

Rejecting the photospheric hypothesis it becomes very difficult to explain the presence of the metal line absorptions. One possibility is that they are originating from a hot stellar wind which is optically thick in these transitions along the line of sight towards the stellar disk. This could explain the triangular shape of the line profiles, which are reminiscent of theoretical considerations of the influence of velocity fields on the formation of weak metal lines in a simplified plane-parallel model (Kudritzki 1992). The absence of any emission components would require that the line forming regions are very close to the stellar surface ($<$ 1 R_*). The width of the profiles may then be used as a measure for the velocity involved: it is about 1500 km sec^{-1}, (following e.g. from the 30Å wide C VI 5291Å line in HE 0504−2408), which is of the order of the stellar surface escape velocity. We have already mentioned the blueshift of metal lines in HS 0713+3958 which corresponds up to a similar velocity. The cause for the necessarily high temperatures might be the same as that invoked for the emission lines of KPD 0005+5106, namely shock fronts in the winds. Detailed modelling must be awaited to decide if this hypothesis for the origin of the strange absorption lines is correct. Both stars were not detected by the ROSAT survey (PSPC and WFC), which is not surprising if they were normal DOs, since no DO white dwarf with $T_{\rm eff}$<100 000 K has been detected by ROSAT so far. The implications of these non-detections for the shocked-wind or any other scenario for the origin of the ultrahigh-excitation features remain to be worked out.

4. The helium line spectrum

The symmetry of the helium line profiles is a hint that they are at least partly formed in the static stellar atmosphere so that we may confine its parameters. As already mentioned, the He II Pickering series shows a very strong decrement. Along with the absence of neutral helium lines this points at a very hot, high gravity atmosphere.

Inspecting the profiles of a grid of DO model atmospheres immediately reveals the problem that the He II lines of the low Pickering series members (4860Å, 5410Å, 6560Å) are much too shallow in the models. The same holds for the first line of the Fowler series (4686Å), see Fig. 2 which shows the profiles of a $T_{\rm eff}$=70 000 K, log g =7.5 model. The higher Fowler series lines and 1640Å in the UV are inconclusive due to the noise level of the IUE data. Reducing $T_{\rm eff}$ below 70 000 K results in the occurrence of He I lines which are not observed. In order to deepen the He II profiles one can alternatively reduce the gravity, but then higher Pickering series members (4200Å, 4100Å) appear which are also not observed. Similarly, the addition of hydrogen yields no solution. We are therefore left with the problem that we cannot consistently explain the He II line spectrum. In view of a possible contamination by the stellar wind this might not be too surprising, but Dreizler et al. (1995) report similar problems in a case where no wind signatures are noticeable in the optical spectrum. Therefore this He II line problem is probably of a more general nature and comparable to the Balmer line problem (Napiwotzki & Rauch 1994) for DA white dwarfs.

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