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Quasi-molecular satellites of Lyman β in ORFEUS observations of DA white dwarfs

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Abstract. Quasi-molecular satellite features of $Ly\,\beta$ were first observed in a HUT spectrum of the DA white dwarf Wolf 1346 and interpreted by Koester et al. (1996). In this paper we study the dependence of these features on temperature and surface gravity in 4 additional DA observed with ORFEUS-SPAS II in 1996. For the interpretation we use theoretical atmosphere models which incorporate new profiles for $Ly\,\beta$. These have been calculated by Allard et al.(1998) including the variation of the transition probability with distance between emitter and perturber. The new calculations for the general line shape, satellite positions and strengths are in very good agreement with the observations.

Key words: stars: white dwarfs – stars: atmospheres — ultraviolet: stars — line: profiles

1. Introduction

White dwarfs of spectral type DA have atmospheres consisting of extremely pure hydrogen; correspondingly, the only spectral lines visible are the Balmer lines in the optical and the Lyman lines in the ultraviolet range. Only in the very hottest objects, at very high resolution and signal-to-noise can very weak lines of C, N, Si, Fe, and Ni be detected, which are kept in the atmosphere against gravitational settling by radiative levitation. Hydrogen absorption coefficients and line broadening are generally well understood and theoretical atmosphere models for these white dwarfs have reached a level of accuracy such that they can successfully be used for the in-flight calibration of space instruments as the International Ultraviolet Explorer (IUE), the Hopkins Ultraviolet Telescope (HUT, Kruk et al. 1997), and the spectrographs onboard the Hubble Space Telescope (HST, Bohlin et al. 1995; Bohlin 1996).

In the far-UV, between the Lyman edge at 911 Å and $Ly\,\alpha$, a region which after an early start with Copernicus has only fairly recently been opened up again for spectroscopic observations with HUT and ORFEUS (Orbiting Retrievable Far and Extreme Ultraviolet Spectrograph), the DA spectra are determined by the Lyman lines and their overlapping and disappearance towards the Lyman edge. The Stark broadening is usually described with the theoretical calculations of Vidal et al. (1973), which have been extended to other transitions of HI or HeII by several authors (Schoening & Butler 1989, Lemke 1997). The dissolution of higher energy levels and the smooth transition of higher series members into the continuum can be well described with the occupation probability formalism developed by Hummer & Mihalas (1988). In our own calculations we follow a prescription by Bergeron (1993), who increased the critical ionizing field strength by a factor of 2 to achieve good agreement with laboratory measurements.

Theoretical spectra calculated with this input physics reproduce the observations of DA above $T_{\rm eff}$ = 25000 K satisfactorily all the way from the Lyman edge up to and including $Ly\,\alpha$. In cooler DA, below $T_{\rm eff}$ = 20000 K, already in the first IUE spectra additional features were noted on the red wing of $Ly\,\alpha$ (Greenstein 1980), which were interpreted as quasi-molecular satellites of $Ly\,\alpha$ by Koester et al. (1985) and Nelan & Wegner (1985). These satellites are formed — in a rather simplified picture — if the interaction between emitter and perturber occurs at a distance, where the potential difference between the upper and lower states of the transition (described by adiabatic molecular potentials) has a stationary value with respect to internuclear distance. For the absorption feature on the $Ly\,\alpha$ wing near 1400 Å the perturbers are protons, for that near 1600 Å neutral H atoms.

These satellites do not only occur in white dwarfs, they are also responsible for the famous 1600 Å feature in the λ Bootis stars (Holweger et al. 1994). In fact, these satellites are an intrinsic property of the line profile and should always be visible, if the red wing of $Ly\,\alpha$ reaches out to 1400 Å (1600 Å), and if metal lines are weak enough not to mask them, i.e. in metal poor stars. The theoretical description of this process has been improved considerably in recent years by N. Allard and coworkers (Allard & Kielkopf 1991; Allard & Koester 1992;

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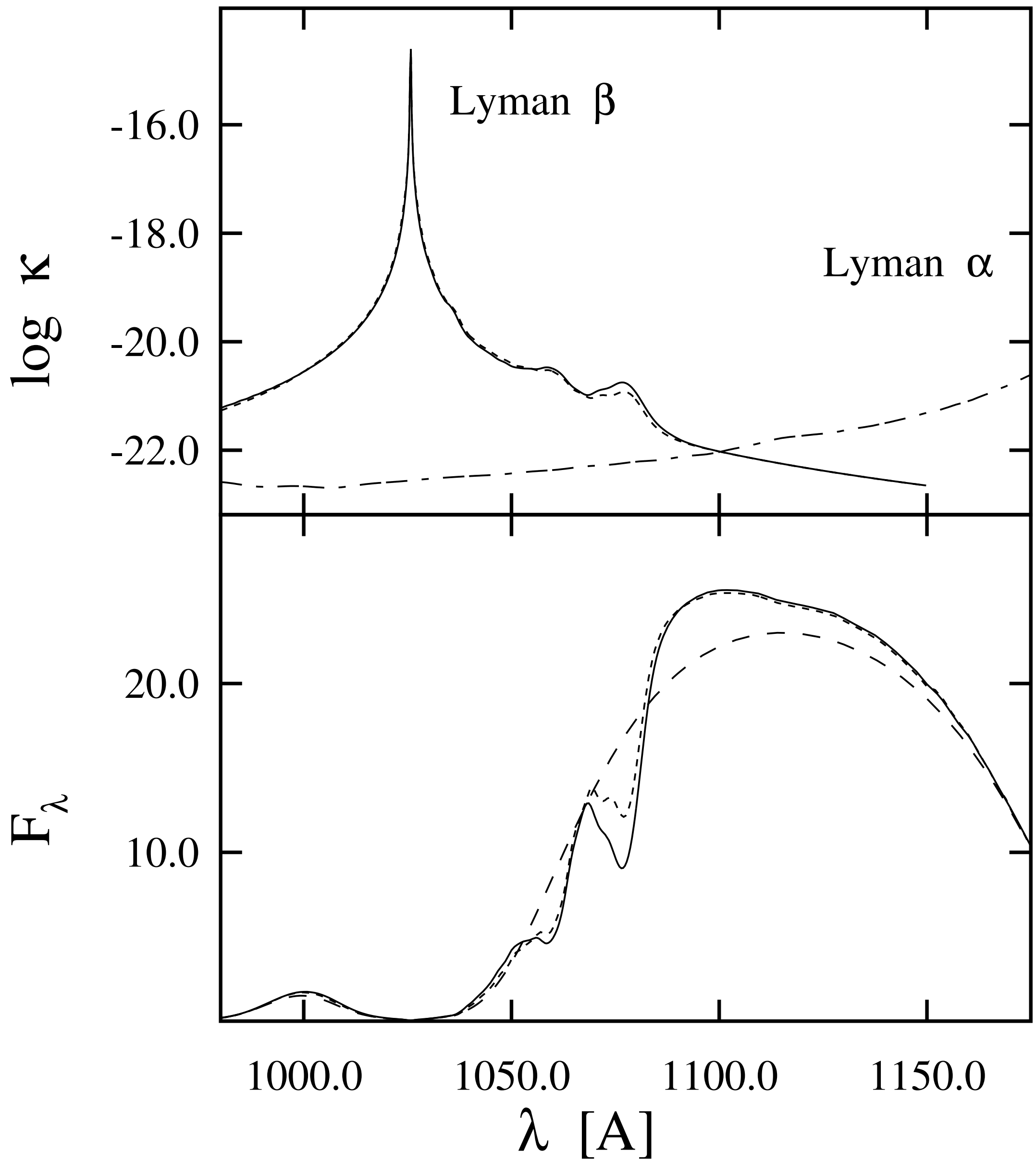

Fig. 1. Upper panel: absorption coefficient per hydrogen atom in the ground state due to $Ly\,\beta$ (left) and $Ly\,\alpha$ (right, dot-dashed line). New line profiles with variable dipole moments for $Ly\,\beta$ are drawn with a continuous line, old calculations are dotted. The density of perturbers (protons) is 10^{16} cm^{-3}. The temperature assumed for the calculation is 20000 K; the profile, however, is very insensitive to the temperature. Lower panel: theoretical synthetic spectra for a pure hydrogen white dwarf model atmosphere with $T_{\rm eff}$ = 18000, log g = 8.0. Ordinate is F_λ in units of 10^{16} erg cm^{-2} s^{-1}. The continuous line is calculated with the new profiles, the dotted lines with the old profiles with constant dipole moments, and the dashed line is a synthetic spectrum calculated with the standard VCS Stark broadening theory.

Allard et al. 1994; Allard et al. 1998a) and is now in very good agreement with observations (Allard et al. 1998b, 1998c).

During the Astro-2 mission in March 1995 HUT observed only one DA white dwarf cooler than 30000 K (Wolf 1346 at about $T_{\rm eff}$ = 20000 K) in the far UV range down to the Lyman limit. Whereas for all hotter DA the agreement between observations and theoretical spectra based on the VCS theory for the Stark broadening was excellent (Finley at al. 1997), Wolf 1346 showed strong deviations from the predicted shape between $Ly\,\alpha$ and $Ly\,\beta$, with two noticeable absorption features on the red wing of $Ly\,\beta$ at 1060 and 1078 Å. From a study of the potential energy curves of the H_2^+ molecule it would have been possible to predict these features; nobody had done the calculations, though, since it used to be so difficult to obtain observations in this wavelength range. After the observations were available, it was shown by Koester et al. (1996), that the same theory that had been successful for the $Ly\,\alpha$ satellites could also be used to reproduce the observed $Ly\,\beta$ profiles.

From theoretical atmosphere models incorporating the new line broadening data it could be predicted that the satellites of

Table 1. Four DA white dwarfs observed with ORFEUS. $T_{\rm eff}$ and log g are from Finley et al. (1997). The final column gives the effective temperature of the best fit to the far UV spectra, holding log g fixed at the literature value. See text for explanations. For comparison Wolf 1346 is included, which was not observed by ORFEUS but by HUT in 1995. For this object we have only used the parameters obtained from the optical fit, to demonstrate the consistency with the far UV spectra.

WD	name	Obs. Date	Expos. time	$T_{\rm eff}$	log g	$T_{\rm eff}$
WD0413-077	40 Eri B	Dec 2, 1996	1995	16490	7.77	16490
WD0644+375	He 3	Nov 22, 1996	4313	21000	8.04	21780
WD1031-114	L825-14	Nov 22-23, 1996	4133	24960	7.76	25390
WD1134+300	GD 140	Dec 3, 1996	4276	21030	8.41	22350
WD2032+248	Wolf 1346	HUT (Mar 1995)		19920	7.84	

$Ly\,\beta$ should be detectable in DA roughly between 15000 to 25000 K. In order to test this prediction, to study the dependence of line profiles on temperature and surface gravity, and to test new profile calculations with improved input physics, we have used an opportunity provided by ORFEUS to study four more DA, spanning the range of interest in $T_{\rm eff}$ and $\log\,g$.

2. New profile calculations for $Ly\,\beta$ with variable dipole moments

One of the shortcomings of the theoretical profiles as described in Allard et al. (1994) and used up to now for the interpretation of IUE, HST, and HUT spectra was the assumption of a constant electronic dipole moment during the perturbation. The transition probability was assumed to be unchanged at the asymptotic value for very large distance between emitter and perturber, i.e. at the value for the unperturbed $Ly\,\beta$ or $Ly\,\alpha$ component. This has been improved in the most recent calculations by Allard et al. (1998), which included the variation of the electronic dipole moment (and corresponding transition probability) with the distance of the perturber. The general shape of the profile is changed only insignificantly compared to the older calculations; near the satellites, however, the absorption becomes stronger and the satellites become more pronounced. The difference in the absolute magnitude of the absorption at the center of the 1078 Å satellite is about 50%. Fig.1 shows a comparison of the $Ly\,\beta$ wing in the calculations with constant versus variable dipole moment. Also shown is the effect on a synthetic spectrum at 18000 K, $\log\,g$ = 8.

Table 1 gives a list with observed objects, observing dates, integration times and stellar parameters (Finley et al. 1997).

3. Observations

Observations of four DA white dwarfs were obtained in a guest observer project during November and December 1996 with the ORFEUS-SPAS II (Shuttle Pallet Satellite) platform. This platform was launched and recaptured at the end of the mission by the space shuttle Columbia during flight STS-80. We used the Tübingen Echelle spectrograph, which provides a range of $\approx 900 - 1400$ Å with a resolution of $\Delta\lambda/\lambda \approx 10000$ and a total effective area (1m telescope + instrument) of about 1.3 cm^2. A detailed description of the ORFEUS instruments has been presented by Grewing et al. (1991) and Hurwitz & Bowyer (1991). The reduction of the data to one-dimensional flux- and wavelength-calibrated spectra was done by the ORFEUS team in Tübingen. This reduction consists of the following steps:

- Extraction of Echelle orders from the two-dimensional image. The data were summed over a fixed number (depending on the order) of pixels perpendicular to the dispersion direction. The extraction "slit" followed the order, but always centered on integer pixels.
- Subtraction of the background, which was extracted with 3 pixels width between the orders and smoothed
- Correction of the blaze function. The position of the maximum efficiency was found to change with order number; corrections to the standard blaze function were obtained individually for each spectrum either using the whole object spectrum, or only the overlapping regions of adjacent orders, depending on the S/N of the observation.
- Wavelength calibration, with an accuracy of 0.1 Å
- Corrections for a decrease in sensitivity at the corners and and edges of the detector

4. Comparison with theoretical spectra

We have calculated a grid of model spectra between $T_{\rm eff}$ = 15000 and 30000 K, with a step width of 250 K below 20000 K and 500 K above, $\log\,g$ = 7.50 to 8.50 in steps of 0.25 using the latest line profiles. Interpolating within this grid for $T_{\rm eff}$ and $\log\,g$, using the literature values of Table 1, resulted in all cases in satisfactory fits of the $Ly\,\beta$ to $Ly\,\alpha$ region, when the flux level was fitted at the maximum between the lines near 1100 - 1120 Å. The relatively small wavelength region covered by ORFEUS, which is essentially dominated by the two Lyman lines, is not suited for an independent determination of the two atmospheric parameters. A change in temperature can always almost exactly be compensated by a change in surface gravity, as far as the line profiles are concerned. The far UV spectrum therefore only defines a relation between the parameters. We have therefore not used the spectra for an independent least square analysis, but instead relied on the parameters from the optical analysis. However, in order to find the best possible fit for the $Ly\,\beta$ satellite region, we have allowed the fitting

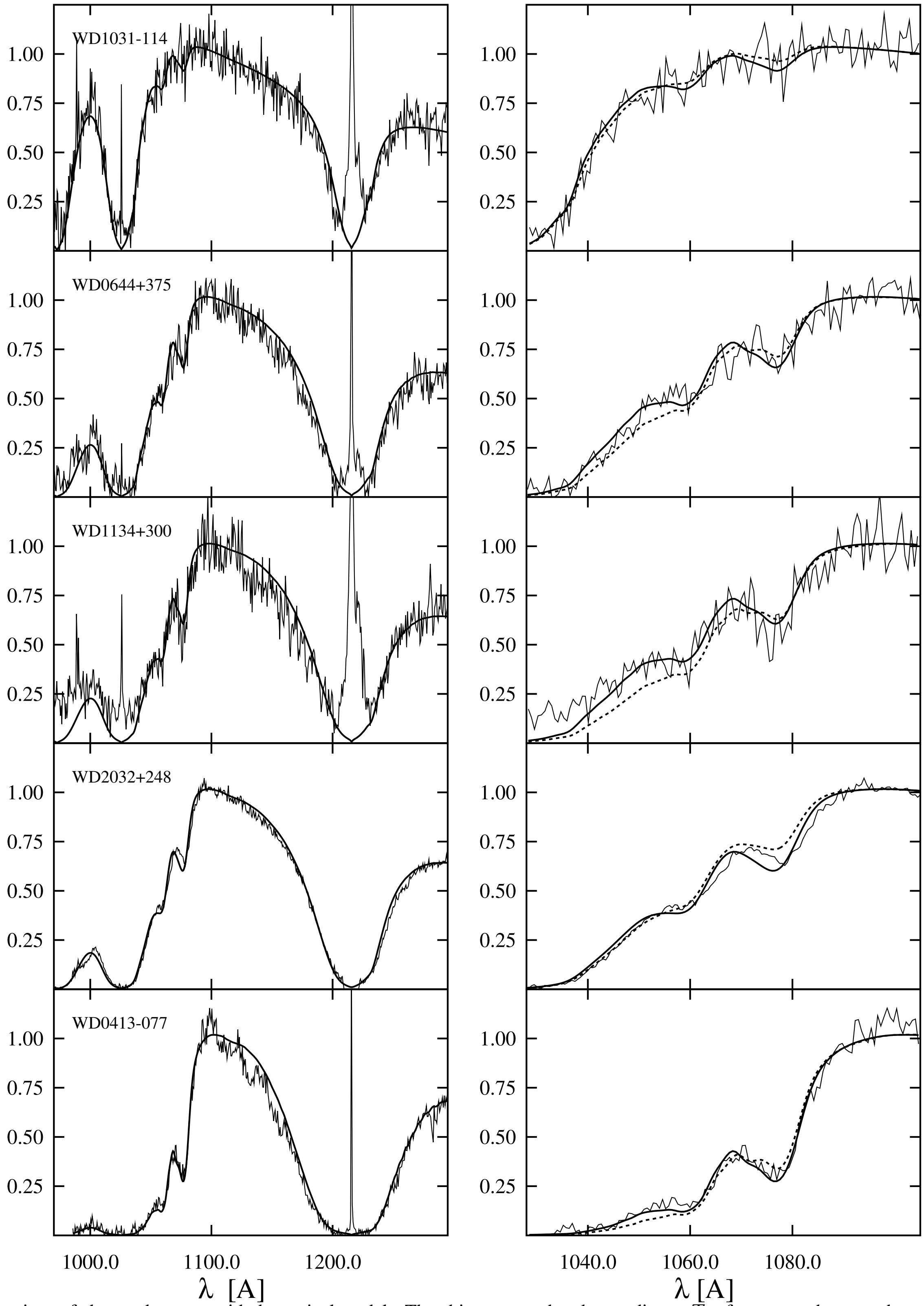

Fig. 2. Comparison of observed spectra with theoretical models. The objects are ordered according to $T_{\rm eff}$ from top to bottom; the second object from the bottom is the HUT spectrum of Wolf 1346, where the airglow emission has been artificially removed. The dotted lines in the right column are the best fits using the older profiles calculated with constant dipole moment. The features between 1100 and 1160 Å in several ORFEUS spectra but not visible in the HUT spectrum are very likely artefacts of the reduction process in the overlapping range of Echelle orders. On the other hand, a feature near 995 Å in WD1031-114 and WD0644+375 is also visible in the HUT spectrum and may be a new satellite in the wing of $Ly\,\gamma$.

routine to vary the temperature for the ORFEUS objects, with $\log g$ fixed at the value of Table 1. The last column in that table lists the resulting effective temperatures. For Wolf 1346, observed with HUT at high S/N, but lower resolution of about 4 Å, we have used only model spectra at exactly the parameters obtained from the fit to optical spectra (Finley et al. 1997), in order to demonstrate the consistency of the models from the optical to the far UV.

In Fig. 2, where we compare the observations with theoretical models, the left column shows the model corresponding to this best-fit temperature. The right panel shows an enlargement of the satellite region, including also a theoretical model using the older line profiles calculated with constant dipole moments. The spectra are contaminated with airglow emission lines in the centers of $Ly\,\beta$, $Ly\,\alpha$, and the O I lines around 989 and 1304 Å.

5. Results and discussion

As can be seen from the comparison in Fig. 2, the general agreement between the overall line shapes in the region between the centers of $Ly\,\alpha$ and $Ly\,\beta$ is excellent, proving the validity of the theoretical assumptions underlying the work of Allard and co-workers. The two prominent satellites at 1060 and 1078 Å are exactly at the predicted position. The dependence on temperature and surface gravity agrees with that predicted by the theoretical models: in the hottest object (WD1031-114) at about 25000 K, the satellites are not visible anymore at this S/N, in agreement with theory. In the next two objects with similar temperature, the higher surface gravity of WD1134+300 causes broader wings of both $Ly\,\beta$ and $Ly\,\alpha$ and a lower residual intensity in the center of the satellites, again in complete accordance with theory. The coolest object, 40 Eri B, roughly defines the cool end of the visibility range. The satellite is still very strong, in observation and theory, but at slightly cooler temperatures the absorption of $Ly\,\beta$ and the higher Lyman lines becomes so strong that no observable flux is left shortward of 1100 Å. According to the theoretical models, this should occur around $T_{\rm eff} \approx 14000$ K.

The enlargements in the right column of Fig. 2 shows that the detailed agreement in the satellite region is good, but not perfect. As was to be expected, the new profiles with better input physics fit the line wings even better than the older calculations. In the case of WD1134+300, stronger deviations near the center of $Ly\,\beta$ can be seen, probably due to an incorrect background subtraction, as can be suspected from the left panel. The magnitude of the satellite features, the amplitude between maximum and minimum, is also reproduced better by the new calculations.

For the HUT spectrum of Wolf 1346, which was already analyzed in Koester et al. (1996), the comparison shows that the far UV spectra are very well fit by models at the parameters determined in a completely different wavelength range. This again proves the claim made in the introduction, that state-of-the-art model atmospheres for DA white dwarfs provide a consistent fit to the observations over the whole range from 1000 to 10000 Å.

The good agreement between the observations of the higher Lyman lines and the profiles predicted from a rather complicated broadening theory is a remarkable success. The observations of a pure hydrogen plasma in the far UV with parameters leading to the appearance of the $Ly\,\beta$ satellites has only been possible in white dwarfs and not yet in a terrestrial laboratory.

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