7 White Dwarfs

There is a long list of topics that can be addressed by large samples of white dwarfs (WDs) drawn from the HES. These include:

- Testing the double-degenerate (DD) scenario for SN Ia progenitors, in which a binary, consisting of two white dwarfs of large enough mass, merges and produces a thermonuclear explosion. If this scenario is correct, it should be possible to identify SN Ia progenitor systems by searching for radial velocity (RV) variations in a large enough sample of WDs. Studies carried out so far suffer from too small sample sizes (see Maxted & Marsh 1999), and possibly from the fact that only DA white dwarfs were investigated (Renzini 1999, priv. comm.).

- Determination of the scale height and luminosity function of DA white dwarfs with a large, flux-limited sample of such stars. These quantities provide valuable information on the star formation history of the Galaxy (see e.g. Boyle 1989).

- Increasing the sample of pulsating DA white dwarfs (ZZ Ceti stars) for astroseismological investigations, which allow to study the interior of these stars. Bergeron et al. (1995) report that the ZZ Ceti instability strip consists of the temperature range 11 200–12 500 K. As can be seen in Fig. 47, DAs of such temperatures can very easily identified in the HES, since they have very prominent Balmer lines. However, the challenge in finding ZZ Cetis is to derive accurate effective temperatures directly from the survey material used, since the instability strip is very small. Hence, the selection efficiency for these stars is proportional to the temperature accuracy.

- Magnetic DBs can be used as cosmic laboratory: Quantum mechanical calculations of He I in strong magnetic fields can be tested *only*, since in terrestrial laboratories only magnetic fields up to ~ 10 MG can be produced.

- Finding more DZ white dwarfs. DZs are cool ($T_{\rm eff} \lesssim 10\,000$ K) white dwarfs with He rich atmospheres, exhibiting metal lines in their spectra. Accretion scenarios for the origin of metals in the photospheres of DZs predict a hydrogen-to-metal ratio *above* the solar value (see e.g. Dupuis et al. 1993), since the diffusion time scale for metals very short in He-rich atmospheres (e.g., $\sim 10^5$ yrs for Ca in a 15 000 K He-rich WD of 0.6 $M_\odot$; see Paquette et al. 1986), and hydrogen, being lighter than helium, is accumulated on the surface. However, the contrary is observed: the hydrogen-to-metal ratio in DZs is typically several orders of magnitude *below* the solar value (Dupuis et al. 1993). A larger sample of DZs would help to explore which mechanism could be responsible for this.

White dwarfs have been selected in wide angle surveys before, and also in the HES (see below). “Classical” UV excess surveys, like the (MCT; Demers et al. 1986; Lamontagne et al. 2000), or the Edinburgh-Cape survey (EC; Stobie et al. 1997; Kilkenny et al. 1997) can efficiently select complete samples of very hot stars, including white dwarfs. However, completeness at the *cool* end is either sacrificed for efficiency, as in the MCT (see Fig. 46), where only objects with $U-B < -0.6$ enter the sample of stars for which follow-up spectroscopy is obtained, or efficiency is sacrificed for completeness, as in the EC. The EC has been claimed to be 94 % complete for objects of $U-B < -0.4$ down to $B = 16.5$ (Stobie et al. 1997). An intermediate selection step based on photoelectric *UBV* photometry has to be used in the EC to eliminate the large fraction (~ 30 %; see Kilkenny et al. 1997) of “normal” F and G type stars. Some of these are metal-poor stars (see Beers et al. 1999), which are interesting in themselves, but as we have seen in Sect. 4, such stars are best selected spectroscopically.

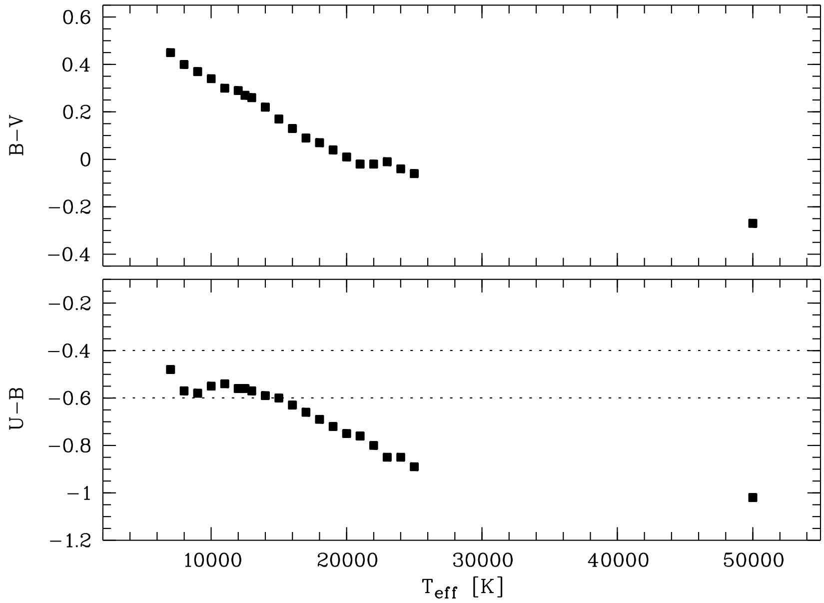

Figure 46: $U-B$ and $B-V$ DAs as a function of effective temperature, determined with model spectra. The selection criterion $U-B < -0.6$ used in the MCT survey leads to rejection of cool ($T_{\rm eff} \lesssim 16\,000$ K) DA white dwarfs.

In the HES, white dwarfs enter the quasar candidate sample if they have $U-B > 0.18$ (Wisotzki et al. 2000). However, HES quasar candidates are inspected manually at the computer screen, and in this process very hot stars, and stars clearly exhibiting stellar absorption lines (like e.g. DA white dwarfs having strong, broad lines over a wide temperature range; see Fig. 47) are rejected, and follow-up spectroscopy is not obtained for them in the course of the quasar survey. This results in a very efficient quasar selection: typically 70 % of the objects for which follow-up spectroscopy is obtained *are* quasars. The remaining 30 % are mainly hot subdwarfs, cool ($T_{\rm eff} \lesssim 20\,000$ K) helium-rich white dwarfs (DBs, DCs); a couple of very interesting peculiar objects, e.g., magnetic DBs (Reimers et al. 1998) and magnetic DAs (Reimers et al. 1994, 1996) have been discovered in this way, too. However, if it is intended to compile a *complete* samples of white dwarfs, other selection procedures, as described below, have to be employed.

The dominant population among UV excess objects are hot subdwarfs. In the UV excess sample of the EC, 44.9 % are sdOs or sdBs, and only 14.9 % are white dwarfs (Kilkenny et al. 1997). Ongoing projects in the HES are aiming at specifically selecting such stars. While I am writing these lines, Stefan Dreizler obtains moderate resolution follow-up spectroscopy of HES sdOs at the South African Astronomical Observatory, in order to identify PG 1159 stars among them. Astroseismological analysis of pulsating PG 1159 stars open the possibility to study their interior (Kawaler & Bradley 1994), and improve the general understanding of post-AGB evolution. Another project is devoted to the determination of the scale height, space density and birth rate of sdBs, to clarify their evolutionary origin. An efficient selection of WDs on the one hand, and hot subdwarfs on the other hand both require that these classes of stars can be separated from each other with a reasonable accuracy. In Fig. 48 it is demonstrated that the comparatively high spectral resolution helps a lot in accomplishing this. Automated selection procedures for hot subdwarfs have been developed, and exhaustively tested by simulations, and by using known objects present on HES plates. A description will be given in future publications.

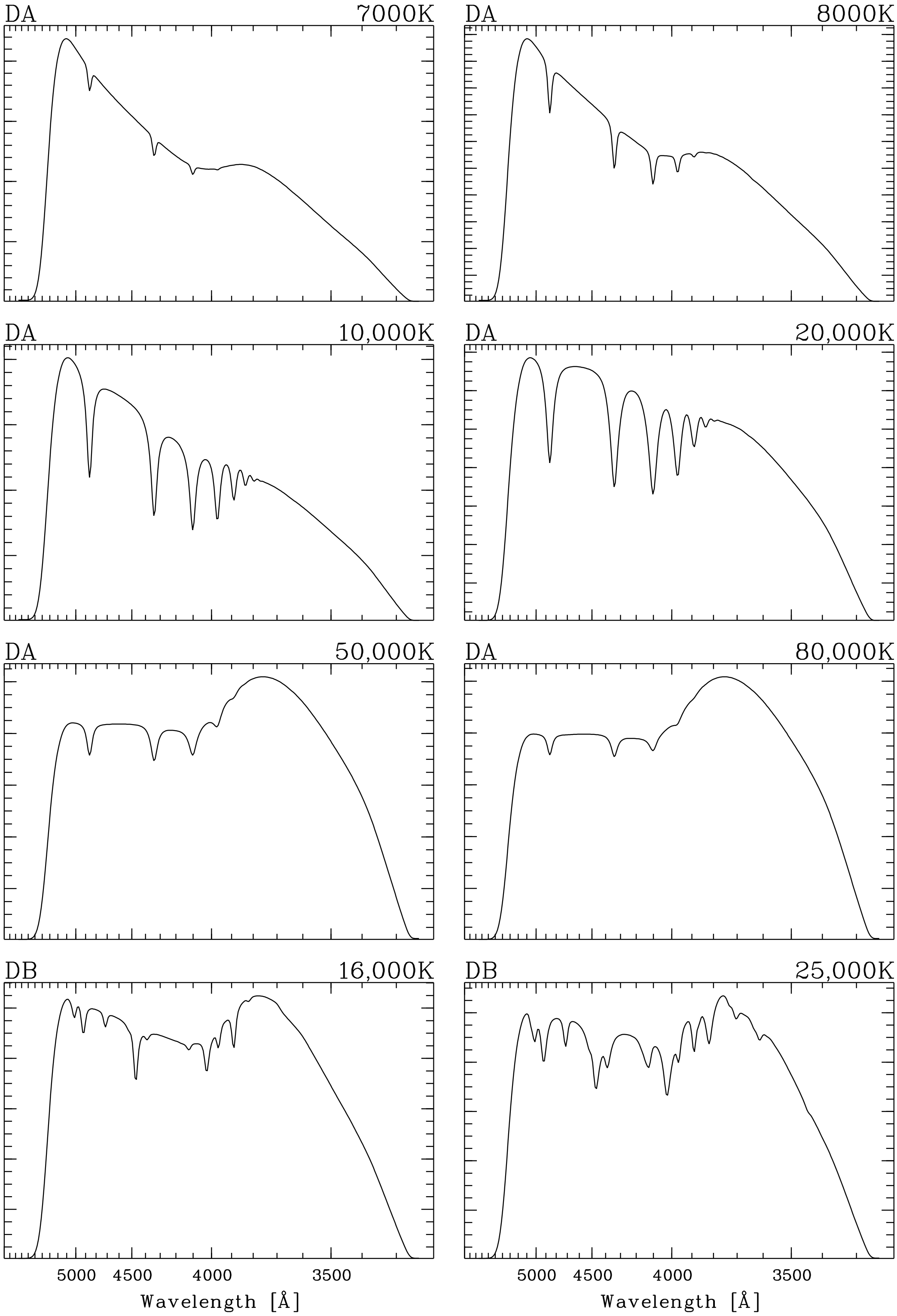

Figure 47: DA and DB White dwarf model spectra, converted to objective prism spectra.

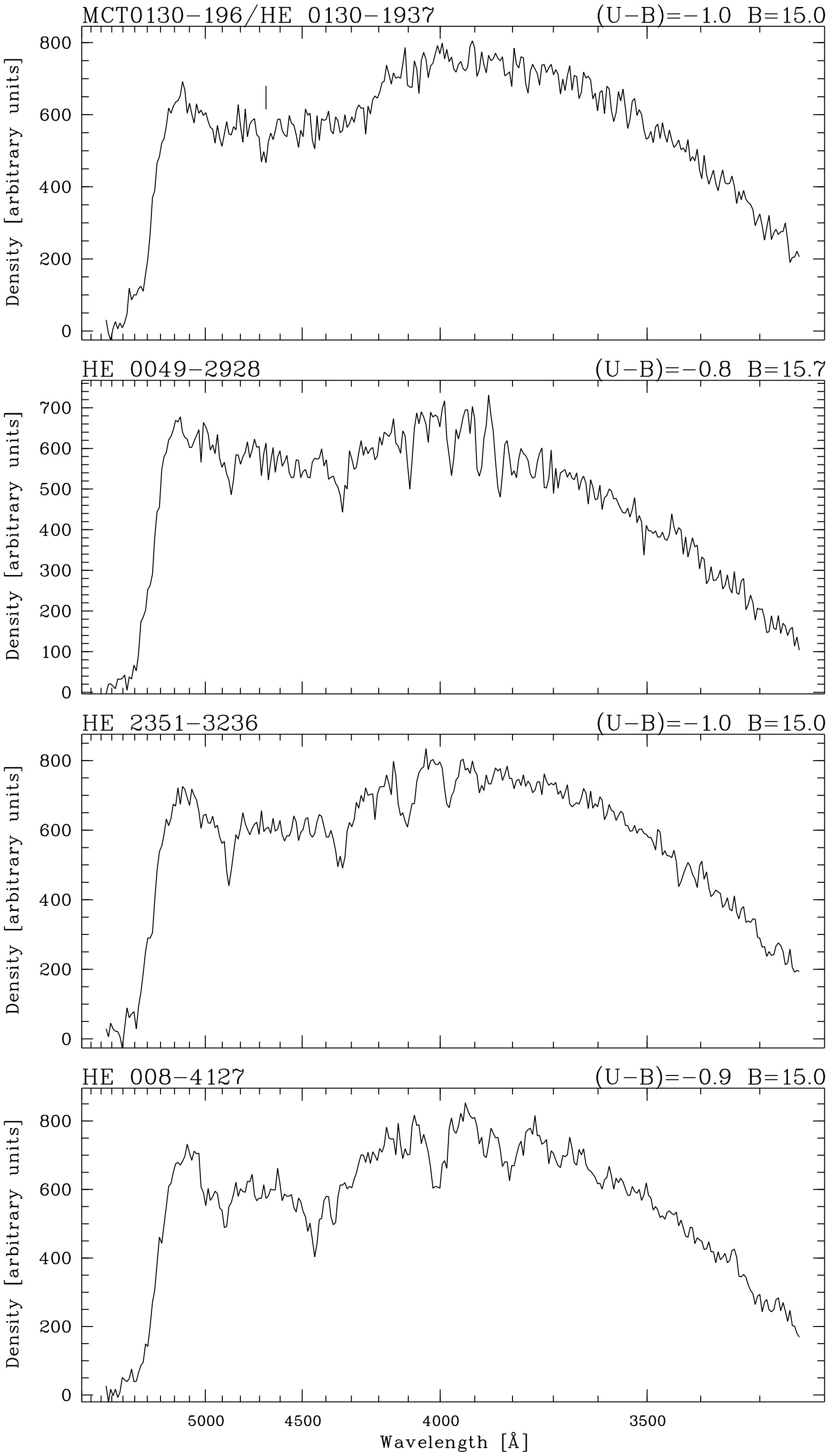

Figure 48: Example spectra of hot stellar objects. From top to bottom: MCT 0130-196, a PG 1159 star luckily showing the blend of He II λ4686 and [CIV] λ4660 (tickmark); HE 0049-2928, a subdwarf B star with prominent Balmer lines; HE 2351-3236, a hot DA white dwarf, showing broader Balmer lines than HE 0049-2928, and a less prominent Balmer jump; HE 0008-4127, a DB white dwarf with strong and broad He I lines.

One major shortcoming of WD selection in the HES may again be the epoch difference problem discussed in Sect. 5. Since most white dwarfs are even fainter than dCs (which have $M_V \sim 10$), the problem may even be more pronounced for WDs *with halo kinematics* then for halo dCs. On the other hand, the local space density of disk stars is ~ 500 times higher than space density of halo stars (Bahcall & Soneira 1984), so that disk WDs, having lower p.m.s, are expected to dominate the WD sample.

How large the incompleteness due to the epoch difference problem is can be roughly estimated from a cross-identification of the HES with the catalog of McCook & Sion (1999). It lists 2 187 objects. 1 633 have an available V measurement. Of these, 1 300 (or 80.0 %) lie in the HES magnitude range ($12 \lesssim V \lesssim 17.5$, assuming an average $B-V$ of zero). 604 objects are located in the southern hemisphere ($\delta < 2\overset{\circ}{.}5$), and at high galactic latitude ($|b| > 30^\circ$). Therefore, we expect ~ 480 WDs to be in the HES area, and detectable in the HES. Taking into account a loss of 20 % due to overlapping spectra, we expect 390 known WDs to be found on all 380 HES plates, and 330 WDs on the 329 plates used in this work. However, in a cross-identification procedure using a $10'' \times 10''$ search box, to compensate for the sometimes very inaccurate coordinates of McCook & Sion (1999), only 151 WDs were found. At the chosen search box width a "saturation" of identified objects was reached; by using a larger box, no further WDs were found. We conclude that the HES WD sample incompleteness is of the order of 50 %, if no special techniques for finding high p.m. objects are used. We describe such techniques in Sect. 7.4 below.

7.1 DA White Dwarfs

In this section we describe two methods for selection of DA white dwarfs in the HES, and give completeness estimates.

7.1.1 Selection by Automatic Classification

A complete search for the best feature combination was run on a set of 14 features. The optimization criterion was the number of misclassifications between the white dwarf classes (10–17), and the remaining classes (1–9). That is, misclassifications between any of the classes 10–17 themselves, and any of the classes 1–9 where *ignored*, since we were mostly interested in separating DA white dwarfs from the remaining stars. The feature combinations found are shown in Tab. 22. As for the previously described applications, there is a tendency to use more features for classification at lower S/N, and to use more continuum shape or broad band colour features.

Stars assigned to classes $\Omega_i, i \geq 10$ were selected; no rejection criterion was applied. The selection was tested on 42 HES fields. In these fields, 18 DA white dwarfs from McCook & Sion (1999) are present; 16 of them (or ~ 90 %) have been re-discovered. An additional test sample were 17 DAs found in the course of the search for FHB/A candidates. 2 of them are also present in the catalog of McCook & Sion (1999). Of these 17 stars, 12 (or ~ 70 %) have been selected. Combining both test samples, we arrive at a completeness estimate of 79 % (26 of 33 stars found). Note that these completeness estimates are *relative* to the sample of McCook & Sion (1999), i.e., we do not know how many stars we miss of those potentially systematically missing in McCook & Sion (1999).

The stars not found were generally assigned to late type star classes. Closer inspection of the reasons for the misclassification revealed that the feature detection failed in both cases; the measured Balmer line equivalent widths are much to low. This is because the feature detection algorithm in its present form is not appropriate for the broad lines of white dwarfs. The algorithm makes use of the assumption that the spectral lines are not resolved, i.e., that the line profile is dominated by the instrumental profile. The line profile widths is held *constant* at the measured widths of the instrumental

i	Class	N	Remarks
1	A5–8	39	
2	A9–F2	67	
3	F3–6	130	
4	F7–G0	119	
5	G1–K0	134	
6	K1–3	65	
7	K4–9	67	
8	SdFearly	33	
9	mphs	100	MPHS-Modell
10	DA07	90	DA, $T = 7\,000$ K; 3 different SSCs
11	DA08	90	DA, $T = 8\,000$ K; 3 different SSCs
12	DA10	90	DA, $T = 10\,000$ K; 3 different SSCs
13	DA15	90	DA, $T = 15\,000$ K; 3 different SSCs
14	DA20	90	DA, $T = 20\,000$ K; 3 different SSCs
15	DA25	90	DA, $T = 25\,000$ K; 3 different SSCs
16	DA50	90	DA, $T = 50\,000$ K; 3 different SSCs
17	DA80	90	DA, $T = 80\,000$ K; 3 different SSCs

Table 21: Learning sample for search of DA white dwarfs. The total sample size is 1 474. Non-DA classes are needed in the learning sample since DAs shall be distinguished from them.

Feature	S/N					
	orig.	25	20	15	10	5
`all5160eqw`	1	1	0	0	1	0
`all4861eqw`	1	1	0	1	1	1
`all4388eqw`	0	1	1	1	1	1
`all4340eqw`	0	0	1	1	0	1
`all4300eqw`	1	1	0	1	1	0
`all4261eqw`	0	0	1	0	0	1
`all4227eqw`	0	0	0	0	1	1
`all4102eqw`	0	0	0	1	1	1
`all3969eqw`	1	1	1	0	1	1
`all3934eqw`	0	0	1	0	1	1
`klcomp_1`	1	1	0	1	1	1
`klcomp_2`	0	0	1	1	0	0
`dx_hpp1`	0	0	0	0	1	1
`dx_hpp2`	0	0	0	0	0	0
$N =$	5	6	6	7	10	10

Table 22: Best feature combinations for compilation of a complete sample of DA white dwarfs.

profile. Moreover, the assumed profile *form*, i.e. a Gaussian profile, is not appropriate for the lines of white dwarfs, which show broad wings.

On 10 of the 42 test fields we inspected the raw candidate sample (typically 30–40 spectra per field) closely. 52 stars were identified as white dwarfs; for some of the hotter stars, it is not possible to say with certainty from the HES spectra alone if they are DAs or DBs.

7.1.2 Selection by Cutoff Lines in Colour-Colour and Feature Space

For the development of an alternative selection method for white dwarfs (and also for the selection of hot stars), we investigated to what extent different types of hot stars can be distinguished in the HES in a two-colour diagram ($U-B$ versus $B-V$), and in the two-dimensional feature space c_1 versus `balmsum`. Using various catalogs, we then identified 521 hot stars in the HES. The catalogs are: (Kilkenny et al. 1997), Wilhelm et al. (1999), an updated version of the Kilkenny et al. (1988) subdwarf catalog (Heber 2000, priv. comm.), and McCook & Sion (1999). Additionally, 39 HES A-type stars with known stellar parameters were included. Since $U-B$, and especially c_1 can be easily confused by overlaps, and our colour calibrations are not valid for saturated stars, we excluded stars above the saturation threshold, and we applied a harder rejection criterion for overlaps (i.e., *no* overlapping object detected, instead of allowing for overlapping objects at $x > 3000$, corresponding to $\lambda < 3830$ Å).

It turned out that high gravity stars (white dwarfs, sdBs, and sdOs) can be distinguished quite reliably from lower gravity stars (main-sequence and horizontal branch stars). By defining selection boxes in the two-colour space, and c_1 versus `balmsum` feature space, it is possible to select DA white dwarfs, and a large fraction of the DBs present in the "learning sample" of 521 objects (see Fig. 49).

We tested this selection with an enlarged sample of 59 DAs and 5 DBs from McCook & Sion (1999) present on HES plates, and 15 of the 17 DAs from the FHB/A candidate set used for evaluation of the automatic classification selection. The enlarged test sample includes 17 of the 18 objects from the previously used McCook & Sion (1999) sample. The remaining objects were excluded by the tighter overlap rejection criterion.

72 of the 74 DAs (or 97 %) and 3 of the 5 DBs (60 %) have been selected by the cutoff line approach. The DBs have probably been selected either because some He I lines are not very far away from the Balmer lines (e.g., He I 4921, 4387), or because of noise. In applications in which DBs are unwanted objects, the DA sample contamination can likely be reduced by applying a higher selection threshold for the sum of Balmer line equivalent widths. However, because DBs are highly desired in the SN Ia progenitor project (see above), we decided to use a rather relaxed criterion ($W_\lambda(\mathrm{H}_\beta+\mathrm{H}_\gamma+\mathrm{H}_\delta) > 0$).

One of the DAs not selected by automatic classification (HE 0315-3314) has been excluded from the test sample by the stronger overlap rejection criterion. It would *not* have been selected if it would have been included into the enlarged test sample. However, from our close inspection of this object we know that the presence of an overlapping object is not the reason for both selection algorithms to fail.

Four objects have not been selected by automatic classification, but selected by the cutoff method. For two of them, it is likely that the usage of the sum of three Balmer lines in the selection was able to compensate the deficiency of the feature detection algorithm described above: The objects have $S/N = 25.2$ and $S/N = 37.3$, respectively, so that they were classified by using the equivalent widths of Hβ and $H\epsilon$ only (see Tab. 22). We hence conclude that the sum of Balmer line equivalent widths is a more stable feature than the usage of one (or two) Balmer lines only. The other two objects are rather noisy ($S/N > 10$), and for one of them the identification of as DA is uncertain.

One object has been selected by automatic classification, but *not* by the cutoff method. It is again a faint object ($B_J = 17.3$; $S/N = 5.7$).

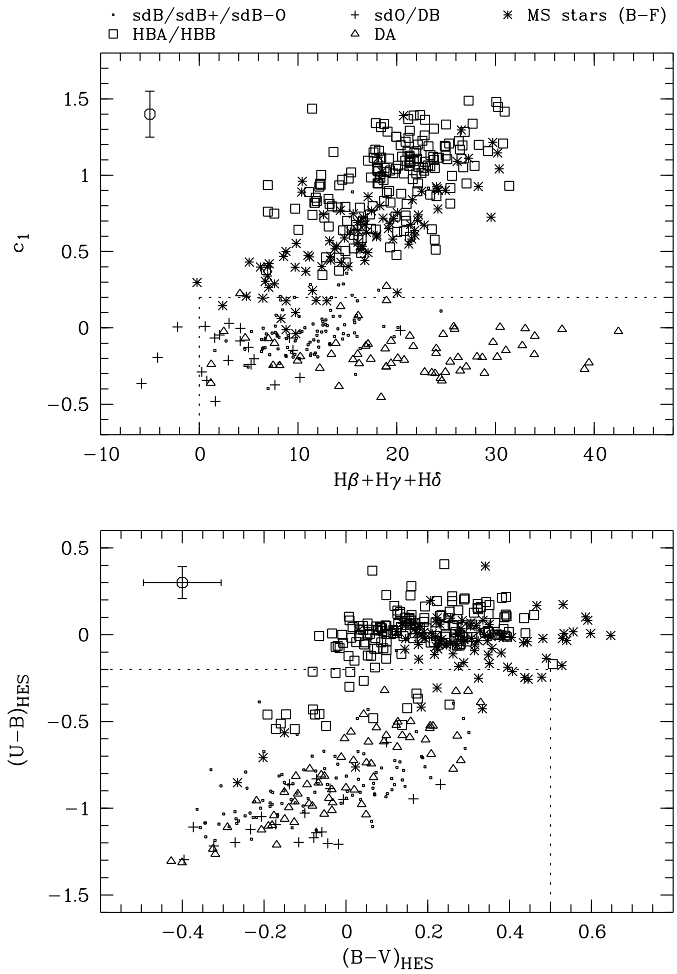

Figure 49: DA selection in colour-colour space and c_1 versus Balmer line sum feature space. In the upper left corner, error bars for c_1, $U-B$ and $B-V$ are displayed.

7.1.3 Discussion

Since 4 DAs have been selected by the cutoff method, but not by automatic classification, but only one object has not been selected by the cutoff method, but by automatic classification, we conclude that the former selection method might currently lead to slightly more complete DA samples than automatic classification. However, based on the tests carried out, it is not possible to attribute the superiority of the cutoff selection to the algorithm itself, since in both of the two cases in which we can rule out noisy spectra to be the likely reason for the non-selection, we have indications that the usage of a set of more stable features may have lead to selection.

Our completeness estimates for the cutoff method (97 % for DAs, and 60 % for DBs) are *relative* to a sample of southern hemisphere white dwarfs from catalog of McCook & Sion (1999), since most of the test objects (59 of 74) are from that source. The catalog lists objects from many different sources, and it is not clear if any selection biases are present in our test sample. Therefore, we can not exclude that we are systematically missing objects that have already been missed in previous surveys, and we can only derive an estimate of the *relative* completeness. Estimations of the *absolute* completeness can only be derived by simulations in which model atmospheres covering the whole possible range of stellar parameters are converted to objective prism spectra, and processed by the selection algorithm.

It has not yet been tested how *clean* the samples of DAs (or DAs and DBs in case of the cutoff method) are. This requires spectroscopic follow-up observations.

A *rough* surface density estimate of DAs can be derived by using our sample selected by automatic classification. The sample selected by the cutoff method cannot be used for these purposes, since the harder overlap criterion results in a decrease of the effective HES area, which we have not yet quantified. 19 of the 52 white dwarfs we selected are DAs with $B < 16.4$. We follow the arguments of Homeier et al. (1998) and apply a correction of $-3.4\,\%$ to our counts ($\sigma_{B_J} = 0.2$ in the HES), to account for scatter of faint objects into our sample by photometric errors, so that we arrive at 18 DAs. The predicted number of DAs from the PG survey (Green et al. 1986) for our 10 fields, assuming an average effective area of $20\,\mathrm{deg}^2$ per plate, is 11. We hence confirm the result of Homeier et al. (1998), who suspected that the DA sample from the PG survey is incomplete by a factor of the order of 2. Our result is *conservative*, since we have not corrected our counts for incompleteness.

As has already been suspected by Goldschmidt et al. (1992) for the quasar sample drawn from the PG, the reasons for the survey being incomplete are inaccurate, and systematically too bright B magnitudes, and inaccurate colours. Köhler et al. (1997) confirm the incompleteness of the PG quasar sample by using a complete sample of quasars drawn from the HES. They found a 3.6 times higher surface density of quasars at $B = 16$. Wisotzki (1998) later derived a somewhat lower surface density discrepancy (i.e., a factor 1.48 higher surface density than found by the PG), by using a larger HES quasar sample, to which a correction for Galactic extinction was applied.

The selection criterion for UV excess stellar objects in the PG was $U - B < 0.46$ where $U - B$ has an error of $\sigma_{U-B} = 0.38$ (Green et al. 1986). As can be seen from Fig. 46, this means that a considerable fraction of DA white dwarfs below $\sim 15\,000$ K are likely not found by the PG. 23 of the 69 DA white dwarfs (or $1/3$) listed in Homeier et al. (1998) have $T_{\mathrm{eff}} < 15\,000$ K, so that the incompleteness of the DA sample drawn from the PG found by Homeier et al. (1998) can at least partly explained by missing cool DAs.

7.2 Magnetic DBs: A Cosmic Laboratory

Reimers et al. (1998) reported the discovery of four magnetic DBs in the HES. Unfortunately, based on higher quality spectra, three out of the four stars published in Reimers et al. (1998) turned out to be a rare type of binary system, i.e. a hot subdwarf with K-type secondary. However, one of the stars, HE 0241-0155, is *really* a magnetic DB, with field strengths of ~ 25 MG. Using this star, we implemented a selection algorithm that uses a feature at ~ 4200 Å, which is a stationary He I feature (Jordan 2000, priv. comm.), and a further feature at ~ 4200 Å (see Fig. 51). A search on 104 HES plates revealed 8 highly ranked candidates. Spectroscopy of these candidates is currently being obtained at ESO.

7.3 DZ White Dwarfs

Three DZ white dwarfs, HE 0122-2244, HE 0446-2531 and HE 0449-2554, entered the HES quasar candidate sample because of their blue continuum (see Fig. 53). HE 0449-2554 and HE 0122-2244 have been observed in October 1997 with the ESO 1.52 m telescope at low spectral resolution (~ 15 Å), and limited S/N. These spectra confirmed their DZ nature.

In order to increase the sample of DZs, we implemented a selection algorithm which looks for hot objects ($B-V < 0.4$) showing weak or absent Balmer lines, and a strong Ca K line. Application of this

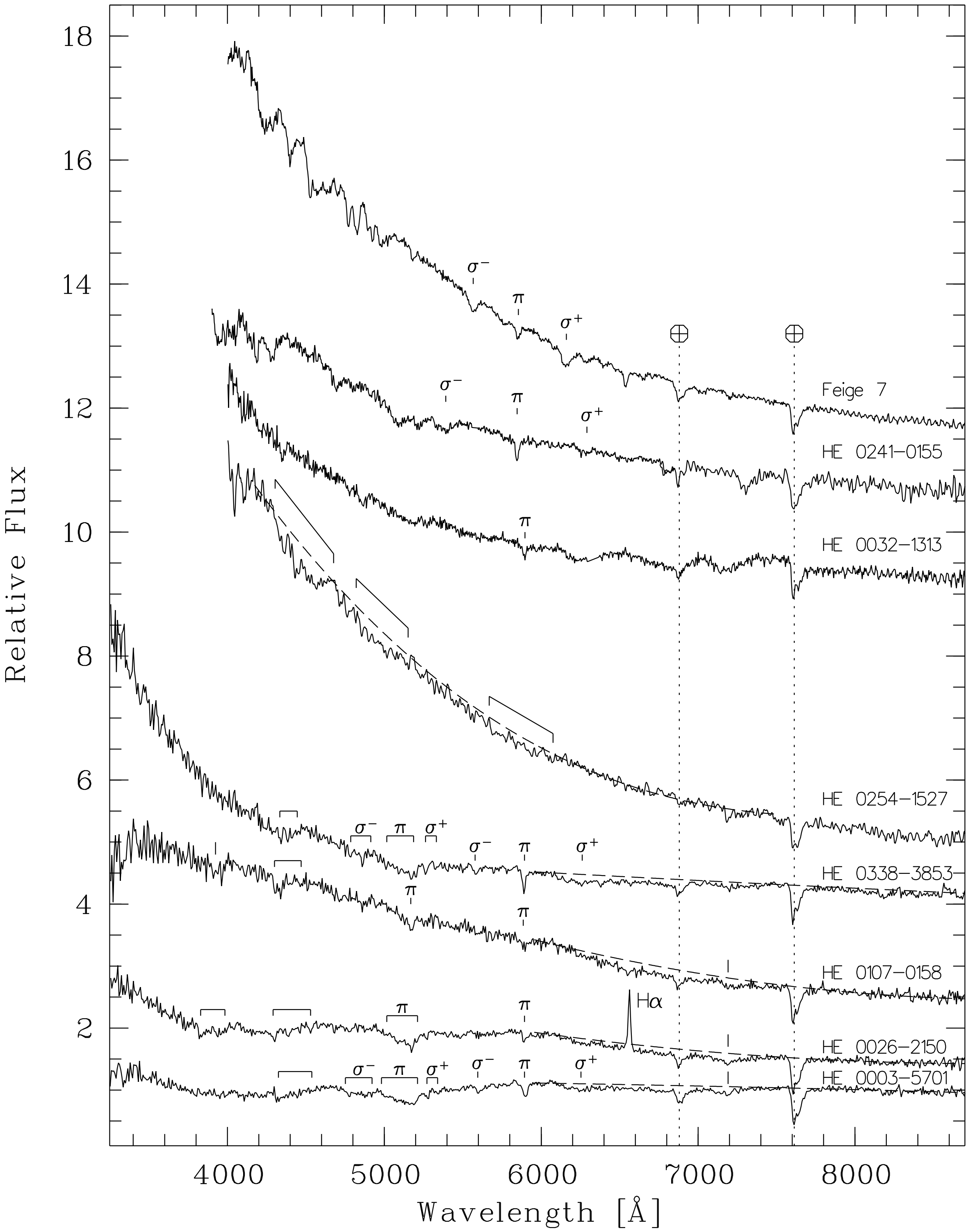

Figure 50: Spectra of the magnetic DB white dwarfs Feige 7, and HE 0241-0155. The lower four objects turned out to be binaries, and *no* magnetic DBs. The lines identified as π component of He I 5876 are Na I D in reality; the band-like features are MgH bands of K dwarf secondaries. The nature of HE 0032-1313 is still unclear.

Passband	Use for band index	
	`magDBidx1`	`magDBidx2`
4370–4636 Å		cont
4167–4307 Å		flux
4065–4141 Å	cont	cont
4029–4065 Å	flux	

Table 23: Wavelengths of passbands used for computation of indices for stationary He I features.

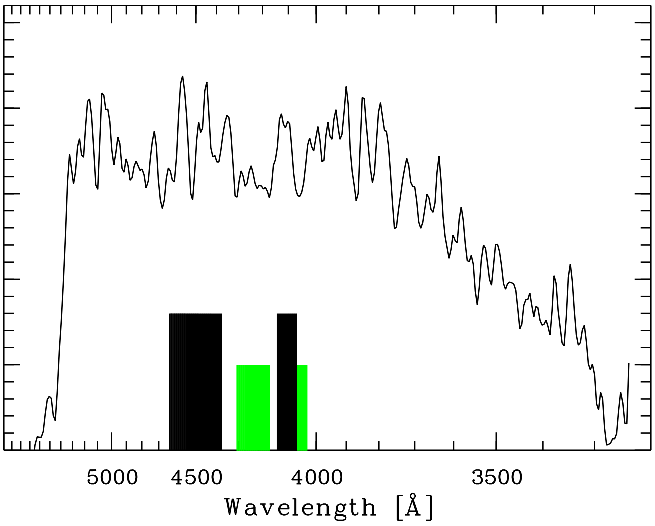

Figure 51: Smoothed HES spectrum of the magnetic DB HE 0241-0155, illustrating the positions of continuum (black, high boxes) and line (grey, low boxes) bandpasses defining the feature indices used for the selection of magnetic DBs.

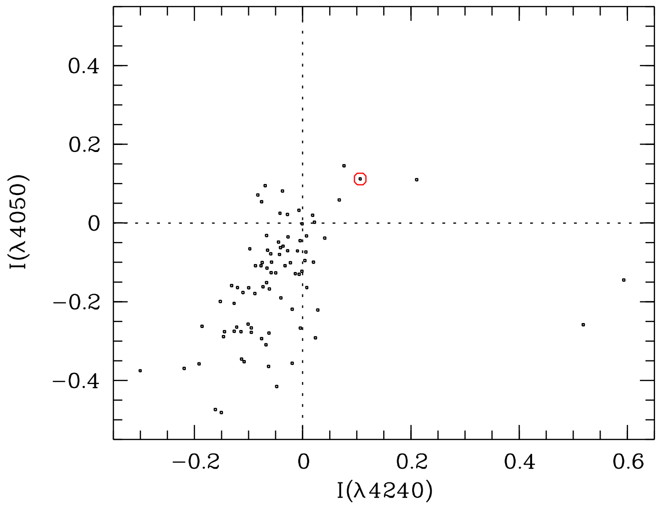

Figure 52: Feature index selection box for magnetic DBs. Dots are all objects with $B-V <$ 0.3 on one HES plate; HE 0241-0155 is encircled.

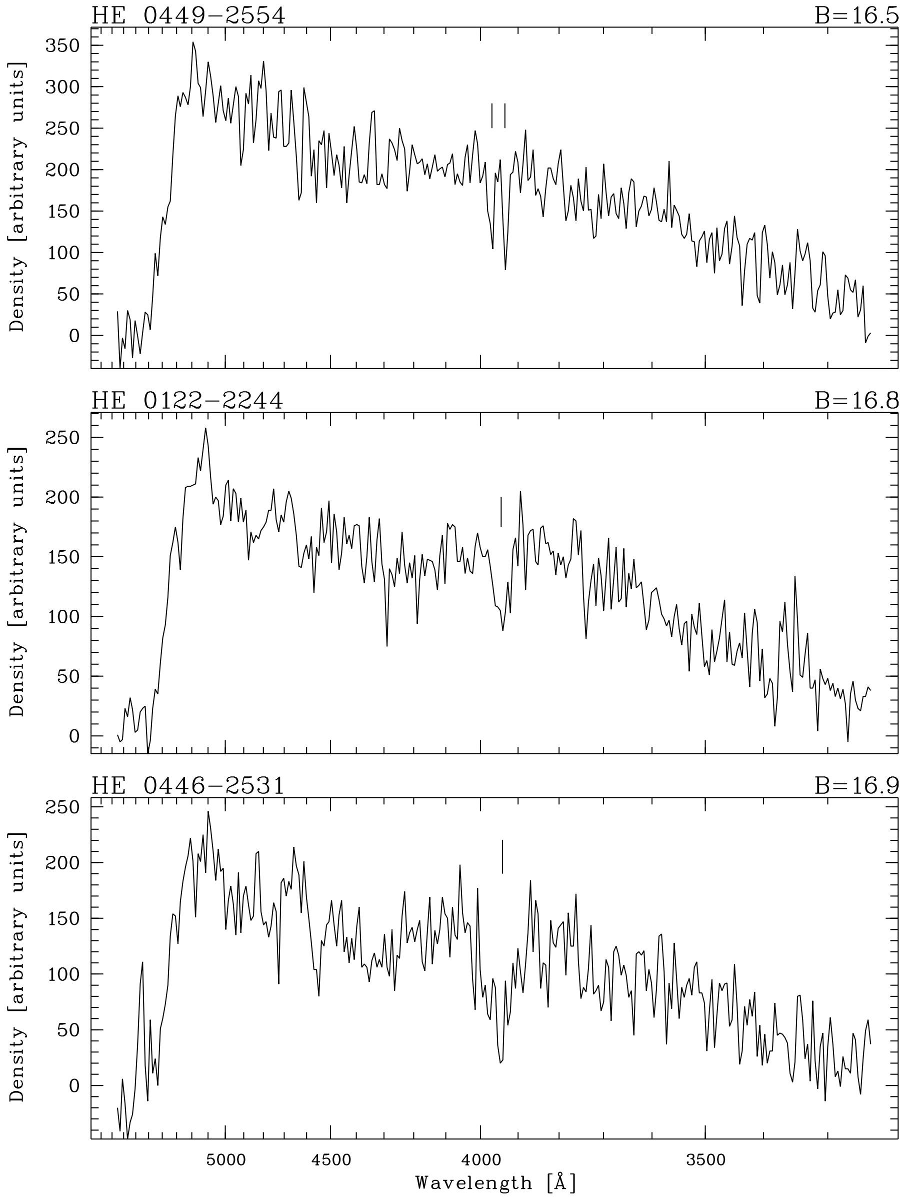

Figure 53: HES spectra of three DZ white dwarfs that entered the HES quasar candidate sample. Note the strong Ca H+K absorption feature at $\sim$ 3950 Å. In the spectrum of HE 0449-2554, Ca H and Ca K are resolved.

selection to 131 HES fields yielded 17 new candidates for DZs.

Better quality spectra of HE 0122-2244, HE 0446-2531 and HE 0449-2554, and 2 of the 17 newly selected DZs were obtained by the author in the night November 27–28, 1998, with DFOSC attached to the ESO-Danish 1.54 m telescope. Grism #4 and a 5$''$ slit, rotated to parallactic angle, was used, yielding a seeing-limited spectral resolution of 10 Å and a covered wavelength range of 3500 Å $< \lambda <$ 7000 Å. Before each observation the slit was rotated such that it was in parallactic angle after half of the exposure time.

HE 0446-2531 was confirmed as DZ, but the two new DZ candidates turned out to be normal stars. Follow-up observations of the remaining objects is under way.

7.4 Outlook

The solution of the epoch difference problem is simple in principal: One just has to take a look at all HES spectra that potentially belong to mis-extracted objects, i.e., spectra with very low S/N, that *should* have a higher S/N according to the brightness on the direct plate. For these objects, the DSS-I positions could be compared with positions on a plate taken at another epoch (that data can be easily retrieved from online archives). This should yield a p.m. for most of the stars, which can be used to compute the coordinates at the HES plate epoch. These provide the information where to extract the HES spectrum. This procedure should not only reveal most of the missed WDs, but also a lot of other interesting objects, e.g. dwarf carbon stars.

A refined feature detection algorithm adapted for the broad lines of white dwarfs will also soon be implemented.

Even *without* solving the p.m. problem, we expect to find ~ 2000 white dwarfs in the HES, when we extrapolate the number of white dwarfs found by automatic classification (52 in 42 fields), to the total survey. McCook & Sion (1999) list a total 1715 white dwarfs of type DA or DB; 662 of them are in the southern hemisphere ($\delta < +2\overset{\circ}{.}5$). This means that the HES is able to at least *double* the total number of known white dwarfs, and to at least *triple* their number in the southern hemisphere.

A survey program for radial velocity variations of WDs using UVES at VLT UT1 has been approved by ESO as a Large Programme. However, in difference to usual Large Programmes, our project has low priority; i.e., our targets will be observed only when the weather conditions on Paranal do not fulfill the requirements specified in other programs. As has been pointed out by Gilmozzi (1999), in period 63 (April–September 1999) there was a very small number of programs that could be carried out at seeing $> 1''$, full moon, or under non-photometric conditions. Therefore, we are optimistic to receive a considerable amount of data.

Acknowledgements

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