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ASTRONOMY AND ASTROPHYSICS

Rotation velocities of white dwarf stars*

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Abstract. The narrow Hα line cores observed with the Keck high resolution spectrograph of thirteen hydrogen-rich (DA) white dwarfs are analysed using line blanketed Non-LTE model atmospheres. The synthetic line profiles reproduce the observed line cores very well. Hence no evidence for additional line broadening due to rotation or to magnetic fields can be found. Statistical upper limits to the projected rotational velocities are derived by also taking into account inaccuracies of the atmospheric parameters. $v \sin i$ range from <8 km/s (40 Eri B) to <43 km/s (LB 5893). The programme stars sample almost the entire DA mass distribution indicating that the DA stars are slow rotators irrespective of their mass. Eight of our programme stars are members of the Hyades or Praesepe open clusters and have evolved from 2.5 $M_\odot$ to 3 $M_\odot$ mass stars. Our results add to a growing evidence that isolated white dwarfs are slowly rotating stars and that the angular momentum transfer from the core to the envelope of their precursors must have been efficient during post main sequence evolution (at least for masses of the order of 2.5 $M_\odot$ to 3.0 $M_\odot$ i.e. for Hyades and Praesepe stars).

Key words: stars: rotation – stars: magnetic fields – stars: atmospheres – stars: white dwarfs

1. Introduction

The existence of narrow absorption cores to the Hα and sometimes Hβ lines in DA white dwarf spectra was first discovered by Greenstein & Trimble (1972) and subsequently explained as caused by Non-LTE effects by Greenstein & Peterson (1973). They opened the way to measurements of wavelength shifts with much higher precisions than from the broad line wings. Many studies (e.g. Koester 1987; Wegner & Reid 1987) have used these narrow absorption cores to measure gravitational redshifts for DA stars in wide binary systems and common proper motion pairs. The most extensive set of gravitational redshifts was recently derived by Reid (1996) who observed 53 white dwarfs in binary systems and common proper motion pairs as well as in the Hyades and Praesepe open clusters using the HIRES spectrograph on the Keck telescope.

The existence of narrow absorption cores also allows projected rotational velocities to be determined (e.g. Greenstein & Peterson 1973; Pilachowski & Milkey 1984, 1987; Koester & Herrero 1988). These studies have provided evidence that the rotational velocities of the white dwarfs are remarkably small ($v \sin i < 60$km/s for a sample of about 25 stars), much lower than expected if the initial angular momentum of the progenitors were conserved.

Reid (1996) did not attempt to model the narrow cores of his large sample of DA white dwarfs to derive line-of-sight rotational velocities but recognized a clear correlation between the structure of the NLTE core and the effective temperature, with the core being narrowest for $T_{\rm eff}$ in the range 14,000 K to 17,000 K (e.g. 40 Eri B). He noted that none of the DA stars in this temperature range had NLTE cores noticeably broader than 40 Eri B, a very slowly rotating star ($v \sin i < 20$ km/s, Koester & Herrero 1988). This obviously implies that these stars also have comparably low projected rotational velocities. In this paper we attempt to derive projected rotational velocities (or upper limits) for all DA stars from Reid's sample hotter than 14,000K using line blanketed NLTE model atmospheres of Napiwotzki (1997). This allows, the stars with the narrowest cores to be analysed.

The lower temperature limit is imposed by the onset of convection, which is not treated in our NLTE model atmospheres.

Reliable atmospheric parameters (listed in Table 1) have been determined from optical spectra for all but two of our programme stars. For the remaining stars (LP 349-13 and LP 207-7) we obtained low resolution spectra at the Palomar 200" telescope and the double spectrograph (resolution: 6.7Å in the blue and 4.0Å in the red channel) covering the spectral range from 4030Å to 7400Å.

LP 349-13, which Reid (1996) classified as DAB and estimated $T_{\rm eff}$≈25,000 K, showed a spectrum dominated by He I lines, with Hα considerably weaker than He I 6678Å and Hβ hardly visible. Using the spectral atlas of Wesemael et al. (1993)

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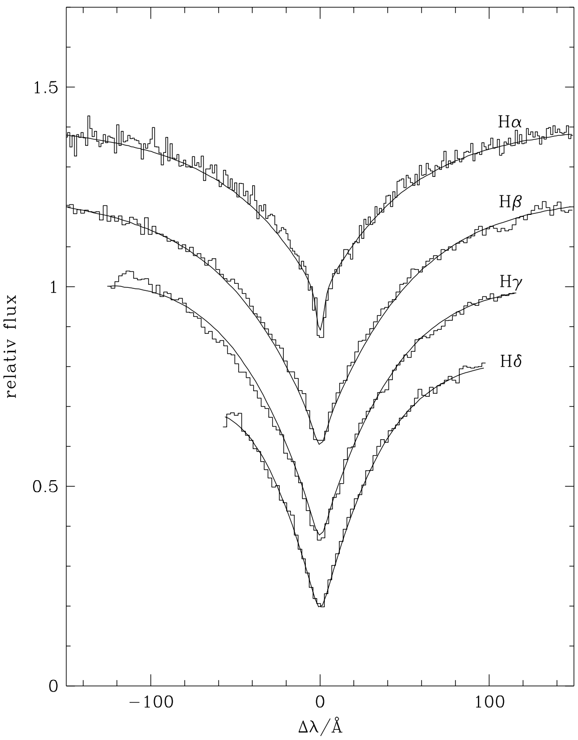

Fig. 1. Balmer line profile fits for LP 207-7 from low resolution Palomar spectra. $T_{\rm eff}$ = 13600 K, log g = 7.76

we reclassify it as DBA5 because the He I spectrum is similar to that of the DB5 star GD 124 indicating $T_{\rm eff}$ to be below 14,000K and hydrogen to be a trace element only. Therefore LP 349-13 was excluded from the analysis of its Hα line core.

For LP 207-7 the spectrum displays broad Balmer lines and no traces of helium. Hence its classification as a DA white dwarf is confirmed. By fitting the line profiles of the Balmer lines (Hα to Hδ) with the grid of NLTE model atmospheres described in the following section we derive $T_{\rm eff}$=13600 K and log g=7.76 (see Fig. 1). Note that these values are slightly extrapolated by 400K from the lowest temperature of our grid. Using the cooling tracks of Wood (1995) we derive a radius of log(R/ $R_\odot$)=-1.82 and a mass of M=0.48 $M_\odot$ from the spectroscopic results in accordance with the mass determined from the gravitational redshift (0.508 $M_\odot$, Reid 1996).

2. Model atmospheres

Previous calculations of Hα line profiles for DA white dwarfs (Pilachowski & Milkey 1984; Koester & Herrero 1988) used line blanketed LTE model atmospheres to determine the temperature – pressure – stratification of the atmosphere and subsequent NLTE line formation calculations to determine the departure coefficients and emergent line profiles. Koester & Herrero (1988) demonstrated that line blanketing effects are very important for the atmospheric structure and their neglect leads to unrealistic line profiles.

Unlike the previous studies, we consider line blanketing and Non-LTE effects selfconsistently as described by Napiwotzki (1997). We use the latest version of the NLTE code of Werner (1986) which is based on the Accelerated Lambda Iteration (ALI) technique (Werner & Husfeld 1985). A detailed description of the code can be found in Werner & Dreizler (1996). We want to point out that the accuracy of the occupation probability formalism for excited levels of the hydrogen atom (Hummer-Mihalas, 1988) is an important ingredient for the white dwarf models for the temperature range in question (see Bergeron, Liebert & Fulbright 1995). We extended the grid of models of Napiwotzki (1997) by calculating additional models with $T_{\rm eff}$ = 14 000, 15 000, 17 000, 20 000, 22 000, 25 000, 27 000 K and with gravities ranging from log g = 7 to 9 in steps of 0.25 dex. A very low helium abundance (appropriate for DA white dwarfs) of He/H = 10^{-6} was adopted.

As already mentioned the model grid cannot be extended to lower temperatures without substantial improvements of the code, most notable the inclusion of convective energy transport. Moreover, additional opacities, like H^- and Lyα satellites (Koester & Allard 1993) have to be included since they become important at temperatures lower than our grid. Some influence may already be expected for our lowest $T_{\rm eff}$ models. We briefly compare the theoretical profiles calculated from our selfconsistent models to those calculated from LTE models with subsequent NLTE line formation calculations similar to the procedure applied by Koester & Herrero. For this purpose a small grid of LTE models plus line formation was computed with the same code as used for the selfconsistent NLTE models (see Napiwotzki 1997 for details).

Fig. 2a-d displays the influence of the model assumption on the emergent Hα profiles for $T_{\rm eff}$ = 50 000 K, 30 000 K, 25 000 K and 20 000 K. LTE profiles are also shown for illustration. For temperatures as high as $T_{\rm eff}$ = 50 000 K (Fig. 2a) the line formation treatment results in too high central emission and too deep absorption near the line center. Hence the selfconsistent NLTE treatment is crucial for the analysis. Fig. 2b to d demonstrates that the deviation weakens with decreasing $T_{\rm eff}$ and the profiles become indistinguishable below $T_{\rm eff}$ = 20 000 K. Hence, the line formation treatment is fully applicable below $T_{\rm eff}$= 20 000 K.

Fig. 3a and b display the temperature and gravity dependence of the synthetic Hα line cores calculated from the grid of selfconsistent NLTE models. The sharp core is only slightly sensitive to $T_{\rm eff}$ for temperatures below 20000K, whereas it becomes progressively weaker and broader for higher $T_{\rm eff}$. Fig. 3c and d demonstrate the influence of rotation at $T_{\rm eff}$ = 15000K and $T_{\rm eff}$ = 25000K. The cooler model profile is more sensitive to v sin i than the hotter one.

3. Spectral analysis and projected rotational velocities

For $T_{\rm eff}$ and log g we used the results of Bergeron, Liebert & Fulbright (1995), Claver, Liebert & Bergeron (1996) and the values derived above for LP207-7. Errors for $T_{\rm eff}$ were estimated from the repeated optical analyses of Bergeron, Liebert & Fulbright (1995) and Bergeron, Saffer & Liebert (1992) to be

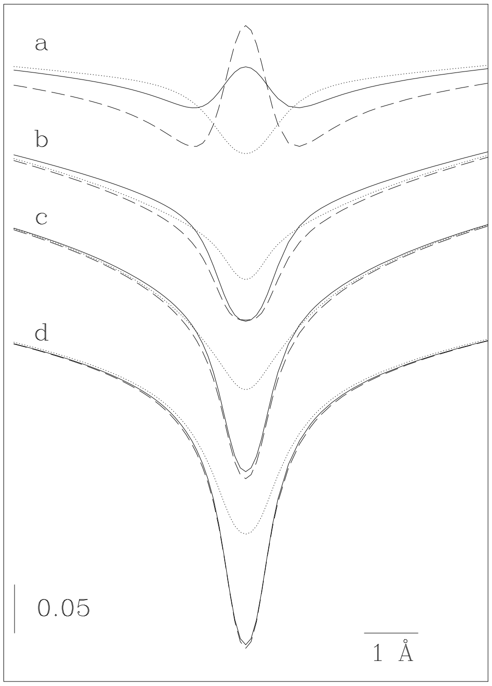

Fig. 2a–d. Comparison of Hα line cores calculated from selfconsistent NLTE models (full drawn), LTE models (dotted) and LTE models plus subsequent NLTE line formation (dashed) for four temperatures ($\log g = 7.5$): **a** $T_{\rm eff}$ = 50 000 K, **b** $T_{\rm eff}$ = 30 000 K, **c** $T_{\rm eff}$ = 25 000 K, **d** $T_{\rm eff}$ = 20 000 K.

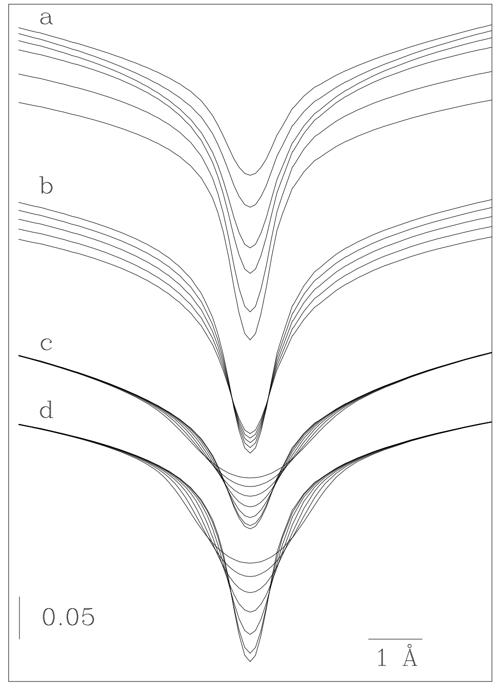

Fig. 3. **a** Dependence of synthetic Hα line cores on $T_{\rm eff}$ at $\log g$ =8: $T_{\rm eff}$ is decreasing from 27 000K to 15 000K from top to bottom profile. **b** Same for $\log g$ at $T_{\rm eff}$=20 000K. $\log g$ is increasing from $\log g$ =7.5 to 8.5 (weakest line wing to strongest line wing) in steps of 0.25 dex. **c** influence of projected rotation at $T_{\rm eff}$=25 000K and $\log g$ =8.0. v sin i is increasing from 0 km/s (deepest line core) to 60 km/s in steps of 10km/s. **d** Same as c but for $T_{\rm eff}$=15 000K.

2.5% and are listed in Table 1. We adopt an error of $\pm$0.1 dex for the gravities of all programme stars.

Hα profiles were interpolated from the grid of synthetic profiles (convolved with the instrumental profile, a Gaussian with 0.14Å FWHM) and compared to the innermost part of the observed profiles (Fig.3 and 5). Their wavelengths scales were adjusted by cross correlating the observed and the synthetic profile. The observations are shown without applying any binning, hence one pixel corresponds to 0.05Å. Since no continuum points can be found anywhere close to the line center, the observation and the synthetic profiles were adjusted at some preselected wavelengths outside of the spectral range shown in Fig. 4 and 6. This is no restriction since only the sharp line cores (i.e. the innermost $\pm$2Å) are sensitive to rotational broadening.

As can be seen, the synthetic line profiles reproduce the observed line cores well. Therefore no evidence for additional line broadening due to rotation or to magnetic fields can be found. Hence we can derive upper limits to the projected rotational velocities only. The rotational profile function as given by Gray (1992) was used and a limb darkening coefficient of ϵ=0.15 was adopted following Pilachowski & Milkey (1984). Upper limits were derived by convoluting the synthetic spectra for various values of the projected rotational velocities and calculating the χ^2 deviations using a modified version of Bergeron and Saffer's computer program (Saffer et al. 1994). The upper limits listed in Table 1 are 3σ limits when accounting for the error limits in $T_{\rm eff}$ and $\log g$ and range from to 8km/s (40 Eri B) to 43km/s (LB 5893). The procedure is described for four cases in Sects. 3.1 to 3.4, which include the best case (40 Eri B), the worst case (LB 5893), the hottest case (HZ 43) and a special case (HZ 7). The line profile comparison for the remaining nine DA stars is displayed in Fig. 6.

3.1. 40 Eri B

40 Eri B was the first white dwarf for which the narrow Hα line core was found (Greenstein & Trimble 1972). It has repeatedly been studied for its gravitational redshift as well as for its atmospheric parameters. Being the brightest star in our sample its spectrum has the highest S/N and its atmospheric parameters are probably know to the highest accuracy in the sample. In Fig. 4 we compare the observed line core to the synthetic line profile neglecting any rotational broadening. Fig. 5 plots χ^2 as a function of $v \sin i$ with respect to $\chi^2(v \sin i = 0)$, i.e. $\delta\chi^2 = \chi^2(v \sin i) - \chi^2(v \sin i = 0)$, for various combinations of $T_{\rm eff}$ and $\log g$ defined by the error box. The upper limit at the 3σ level is read off for the worst case, resulting in $v \sin i$ <8km/s. This limit is considerably lower than any previous determination confirming that 40 Eri B is a very slow rotator, indeed. Its rotational period, therefore, would exceed 2 hours, if seen equator on.

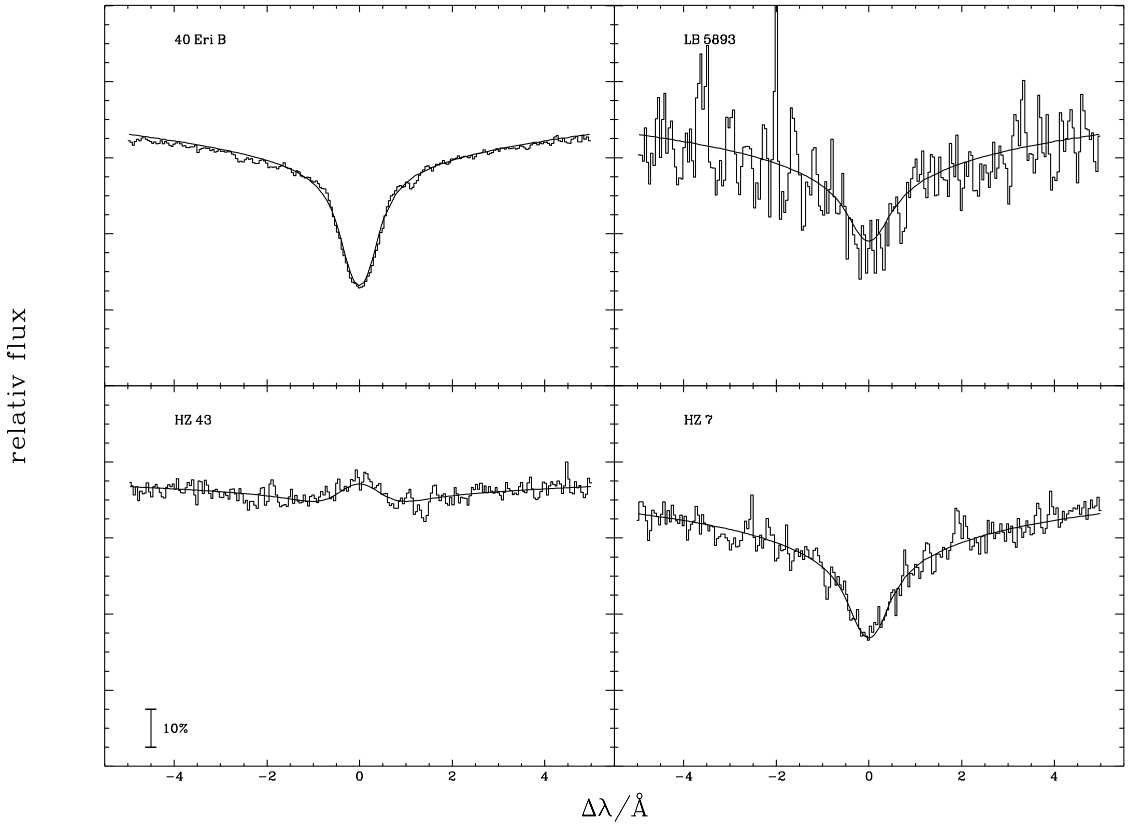

Fig. 4. Comparison of synthetic Hα cores to the observations of 40 Eri B, LB 5893, HZ 43 and HZ 7. The theoretical profiles are convolved with an instrumental profile. No extra broadening due to rotation is accounted for. The atmospheric parameters of the models are given in Table 1.

Table 1. Atmospheric parameters, masses (as derived from gravitational redshifts, Reid 1996 and from spectroscopic analyses, respectively) and projected rotational velocities of the programme stars

star	WD-No.	EG	$T_{\rm eff}$	$\log g$	M/$M_\odot$ redshift	M/$M_\odot$ spectr.	ref	$v \sin i$ km/s
Hyades members:								
HZ 4	0352+096	26	14770±370	8.16	0.743	0.717	1	<21
LB 227	0406+169	29	15190±380	8.30	0.803	0.801	1	<28
VR 7	0421+162	36	19570±490	8.09	0.696	0.679	1	<18
VR 16	0425+168	37	24420±610	8.11	0.691	0.680	1	<26
HZ 7	0431+125	39	21340±530	8.04	0.671	0.652	1	<35
HZ 14	0438+108	42	27390±680	8.07	0.662	0.683	1	<28
Praesepe members:								
LB 5893	0836+197	–	21900±550	8.45	0.912	0.908	3	<43
LB 393	0837+199	61	17100±430	8.32	0.798	0.801	3,4	<29
field stars:								
40 Eri B	0413-077	33	16570±420	7.86	0.564	0.543	1	< 8
LP207-7	0726+393	–	13600±350	7.76	0.508	0.48	4	<18
G148-7	1143+321	83	15489±390	7.97	0.623	0.601	1	<12
HZ43	1314+293	98	49000±1220	7.70	0.673	0.53	2	<29
G142-B2B	1911+135	130	14040±350	7.83	0.608	0.526	1	< 9

1: Bergeron, Liebert & Fulbright (1995)
2: Napiwotzki et al. (1993)
3: Claver, Liebert & Bergeron (1996)
4: this paper

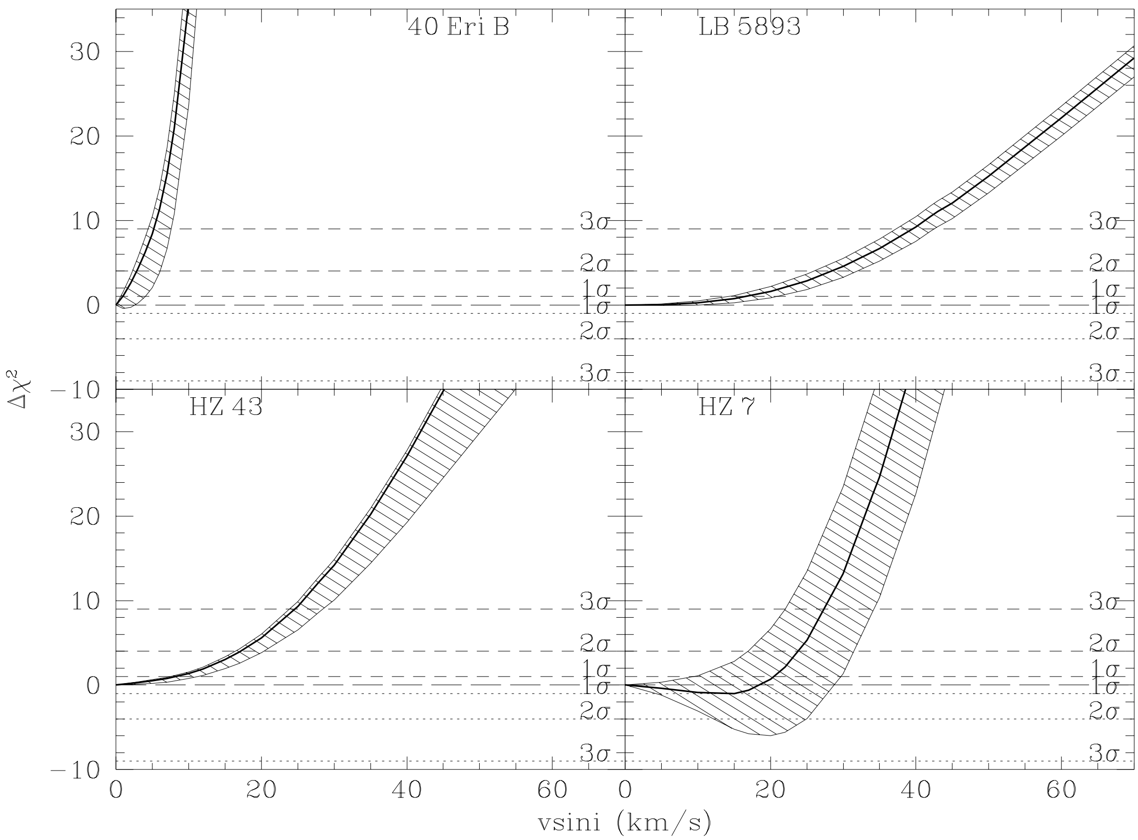

Fig. 5. Run of χ^2 with $v \sin i$ with respect to $\chi^2(v \sin i = 0)$ for 40 Eri B, LB 5893, HZ 43 and HZ 7 for various combinations of $T_{\rm eff}$ and $\log g$ defined by their error boxes. The thick lines are calculated for temperatures and gravities as given in Table 1.

3.2. LB 5893

The Praesepe member LB 5893 has to be considered the worst case because (i) the S/N of its spectrum is rather low since the star is faint (V=$17^{\rm m}_{\cdot}57$) and (ii) it lies in a temperature regime ($T_{\rm eff}$>20000 K) where the NLTE line cores are sensitive to $T_{\rm eff}$ (see Figs. 1 and 3). This results in the largest upper limit of $v \sin i$ <43km/s for any star in our sample. The comparison with the synthetic spectrum is shown in Fig. 4 without any rotational broadening. Fig. 5 plots χ^2 as a function of $v \sin i$ with respect to $\chi^2(v \sin i = 0)$ for various combinations of $T_{\rm eff}$ and $\log g$ defined by the error box.

3.3. HZ 43

HZ 43 is by far the hottest star in our sample and unlike the other stars shows a central emission, which is very well reproduced by the synthetic line profile using the atmospheric parameters of Napiwotzki et al. (1993, see Fig. 4). Again, in Fig. 5 we plot χ^2 as a function of $v \sin i$ with respect to $\chi^2(v \sin i = 0)$ for various combinations of $T_{\rm eff}$ and $\log g$ defined by the error box from which an upper limit of 29 km/s is read off.

3.4. HZ 7

HZ 7 is a special case. The run of χ^2 with $v \sin i$ relative to $\chi^2(v \sin i = 0)$ (Fig. 5) seems to indicate some rotation near 15km/s to 20km/s at the 2σ level for appropriate combinations of $T_{\rm eff}$ and $\log g$. We regard this as marginal because the significance is too low and other combinations of atmospheric parameters do not produce similar minima (see Fig. 5). Hence we read off an upper limit of $v \sin i$ <35km/s for HZ 7.

3.5. Magnetic fields

3.5.1. LB 393

LB 393 was recently discovered to display Zeeman splitting of the Hβ line (Claver, Liebert & Bergeron 1996) implying a magnetic field strength of 3 MG. The predicted line splitting for Hα is about ±60Å which shifts the σ components into the gaps between the spectral orders adjacent to the Echelle order (containing the unshifted Hα line) studied by us. For this reason the Hα splitting was not discovered by Reid (1996) when he determined the gravitational redshift for LB 393. We fitted the line core of Hα ignoring all effects caused by the magnetic field. Despite of this shortcoming the model profile fit to the observed Hα line core (see Fig. 6) is as good as for the non-magnetic

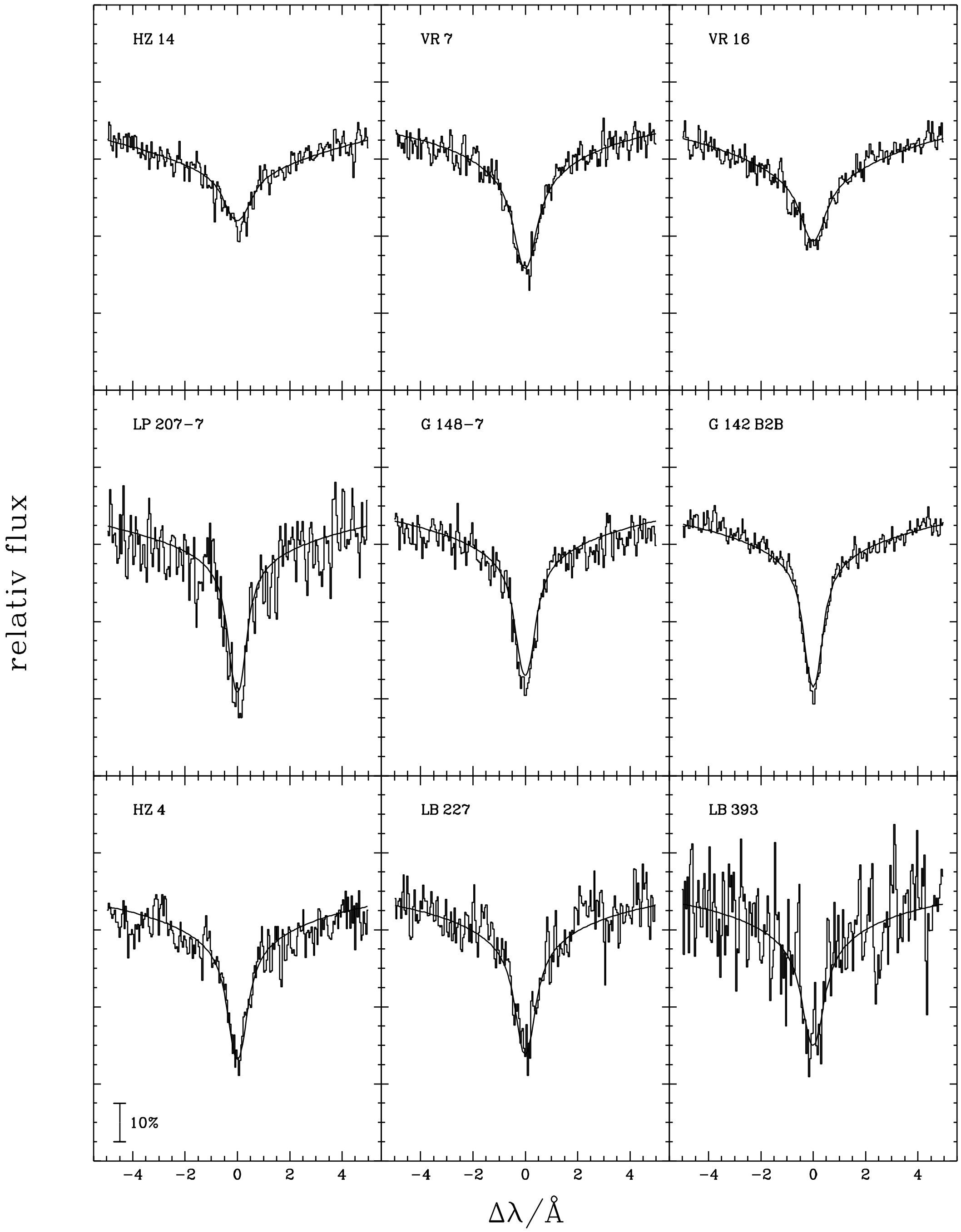

Fig. 6. Comparison of synthetic Hα cores to the observations of nine white dwarfs. The theoretical profiles are convolved with an instrumental profile. No extra broadening due to rotation is accounted for. The atmospheric parameters of the models are given in Table 1.

DAs and we derive an upper limit for the projected rotational velocity of 29 km/s.

Reid (1996) derived the mass of LB 393 from the gravitational redshift not knowing that it is a mgnetic DA. However, the magnetic field strength (3 MG) is so large that the quadratic Zeeman effect has to be taken in account, since it causes a blueshift of the Hα line center by 0.309Å (using the formula given by Lang 1974). Correcting for this blueshift and using the radius from Wood's (1995) cooling tracks (mixed C-O core, envelope: $10^{-2}\,M_\odot$ He, $10^{-4}\,M_\odot$ H), we derive a mass from the gravitational redshift of $0.798\,M_\odot$ in perfect agreement with the spectroscopically determined mass ($0.801\,M_\odot$, Claver, Liebert & Bergeron 1996).

3.5.2. Other programme stars

A survey for magnetism amongst white dwarfs has been carried out for a magnitude-limited sample of nearly 170 DA stars by Schmidt & Smith (1995) using Zeeman spectropolarimetry. Eight stars from our sample are covered by the Schmidt & Smith survey. None of them were found to be magnetic, with a mean uncertainty for the sample of σ_{B_e} = 8.6 kG. For 40 Eri B the upper limit could be pushed down to 2 kG.

Any extra broadening of the Hα line core could also be caused by a magnetic field of several kG magnetic field strength rather than by stellar rotation. Hence upper limits on the magnetic field strength of our programme stars can be placed. Following Koester & Herrero (1988), an extra broadening of the line cores by more than 0.2Å, which corresponds to a magnetic field strength of 10kG, can be ruled out by our observations. This is consistent with the results from the spectropolarimetric survey (Schmidt & Smith 1995) but does not improve on their limits.

4. Discussion

We have analysed the narrow Hα line cores of hydrogen-rich white dwarfs. All observations are consistent with the predictions from line blanketed non-LTE model atmospheres with no need for extra line broadening due to rotation or magnetic fields. Hence upper limits to the projected rotational velocity were determined. The DA stars in our sample have quite different masses ranging about 0.5 $M_\odot$ (LP207-7, 40 Eri B) to 0.8 $M_\odot$ (LB 227) or even 0.9 $M_\odot$ (LB 5893). Finley (1995) finds that the main part of the DA white dwarf mass distribution is well represented by a Gaussian with a mean of 0.562 $M_\odot$ and a dispersion of 0.137 $M_\odot$ for the Bergeron, Saffer & Liebert (1992) sample (129 stars) and a mean of 0.601 $M_\odot$ and a dispersion of 0.166 $M_\odot$ for the unpublished Finley, Koester & Basri sample (177 stars). Thus our observations sample almost the entire DA white dwarf mass distribution and we can conclude that DA stars are slow rotators irrespective of their mass.

Our finding contributes to the growing evidence that the isolated DA white dwarfs (i.e. white dwarfs that are not in close-binary systems such as cataclysmic variables) are slowly rotating stars. Our analysis puts limits on $v \sin i$ that are considerably tighter than derived by any previous spectroscopic investigation (Pilachowski & Milkey 1987; Koester & Herrero 1988). About three dozen DA stars have spectroscopic estimates of the projected rotational velocity or upper limits thereof, none exceeding 60 km/s. The upper limits we derived are consistent with rotational periods exceeding about one hour (if seen equator on). This is in line with the rotational ephemerides of isolated magnetic white dwarfs derived from polarimetric monitoring (Schmidt and Norsworthy 1991) which span the period range from 99 minutes to 17.9 days. Schmidt & Norsworthy argue that some magnetic white dwarfs may have very long rotation periods ($>$ 100yr) since their polarization is constant for at least ten years.

A sample of nearly 80 helium-rich (DB) white dwarfs has recently been analysed spectroscopically by Beauchamp et al. (1996). All but one stars could be fitted very well with their new synthetic spectra. Hence no evidence for rotation was found. The limits on $v \sin i$ are less stringent than for the DA stars, because of the lack of sharp line cores and the lower resolution of the observations. The spectra of the DBA LB 8827, however, could not be reproduced and Wesemael et al. (1995) attributed this mismatch to a high projected rotational velocity of about 600 km/s. While magnetic broadening could be ruled out, Wesemael et al. point out that other alternatives, including the possibility that LB 8827 is a binary system, need to be explored before the nature of LB 8827 can be revealed.

Asteroseismology allowed the rotation period of the hot, hydrogen-deficient pulsating white dwarfs PG 1159-035, PG 0122+200 and the DB GD 358 as well as a hydrogen-deficient pre white dwarf (the WC4 central star of the planetary nebula NGC 1501) to be determined. All of them are also slow rotators with periods of 1.3 days (PG 1159-035, Winget et al. 1991), 1.6 days (PG 0122+200, O'Brien et al. 1996), 1.17 days (NGC 1501, Bond et al. 1996) and a differential rotation of 0.8d to 1.6d (GD 358, Winget et al. 1994).

All these investigations find that isolated white dwarfs are slowly rotating stars indeed, giving growing evidence that an efficient transport of angular momentum from the stellar core to the envelope must have occured in the precursor's post main-sequence evolution (e.g. Greenstein & Peterson 1973, Weidemann 1977). Six of our programme stars are well established members of the Hyades and have evolved from 2.5 $M_\odot$ to 3.0 $M_\odot$ mass main sequence stars (Weidemann et al. 1992). Since the turn-off mass for Praesepe is very similar to that of the Hyades, the same must be true for the two Praesepe white dwarfs LB 5893 and LB 393. Hence, we can conclude that stars in the mass range 2.5 $M_\odot$ to 3.0 $M_\odot$ transfer angular momentum from the stellar core to the envelope more efficiently than predicted by simple evolution theory.

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