THE ASTROPHYSICAL JOURNAL, 332:910–916, 1988 September 15

NON–LOCAL THERMODYNAMIC EQUILIBRIUM LINE PROFILES, ROTATION, AND MAGNETIC FIELDS IN SEVEN DA WHITE DWARFS[1,2]

D. KOESTER
Department of Physics and Astronomy, Louisiana State University
AND
A. HERRERO
Instituto de Astrofisica de Canarias, La Laguna
Received 1988 January 25; accepted 1988 March 7

ABSTRACT

Non–LTE calculations of Hα line profiles are presented and applied to derive rotational velocities from high-resolution spectra of DA white dwarfs. This paper extends recent work by Pilachowski and Milkey to southern hemisphere objects and confirms their findings that all white dwarfs seem to be slow rotators. Of the seven objects in this study only one has $v \sin i = 30 \pm 20$ km s^{-1}, only marginally different from 0. The remaining objects are all fitted by $v \sin i = 0$, and upper limits of 20–40 km s^{-1} were obtained. Upper limits on magnetic fields of 2.5×10^4 G were determined for all objects from the absence of Zeeman splitting.

Subject headings: line profiles — stars: magnetic — stars: rotation — stars: white dwarfs

I. INTRODUCTION

When observed at low resolution, DA white dwarfs show the well-known extremely broad Balmer lines, extending over several hundred Å. These features make it very easy to recognize a DA, but on the other hand almost impossible to determine accurate wavelength shifts or rotational velocities. This picture changed dramatically, when Greenstein and Trimble (1972), and later Greenstein and Peterson (1973) and Greenstein *et al.* (1977) discovered very narrow line cores in Hα and sometimes Hβ in almost all DA's observed at higher resolution. This provided for the first time a means to determine wavelengths shift much more accurately than had been possible from the broad wings—which might be affected by asymmetries in the line profile (Schulz 1977) and possible pressure shifts (Grabowski, Madej, and Halenka 1987)—in the pioneering studies by Greenstein and Trimble (1967), Trimble and Greenstein (1972), and Wegner (1974). Koester (1987) and Wegner and Reid (1987) have recently successfully used this method to determine gravitational redshifts for DA's in wide binary systems and common proper motion pairs, where the space velocity of the system can be obtained from the companion.

Greenstein and Peterson (1973) also were the first to demonstrate that the sharp cores are non–LTE effects, which was quite unexpected at that time because of the high densities usually found in white dwarf atmospheres. However, as they pointed out, the cores of Hα—and to a lesser extent also Hβ—are formed very high up in the atmosphere, where densities and temperatures are low and photoionization marginally dominates collisions in destroying Hα photons.

Greenstein and Peterson (1973) used their theoretical spectra to determine rotational velocities from the sharp cores observed in two DA and found $v \sin i$ values of 40 and 50 km s^{-1}, which are remarkably small! values for white dwarfs. Assuming that the progenitor of 40 Eri B was a 2 $M_\odot$ main-sequence star with a rotational velocity of 100 km s^{-1}, they point out that the white dwarf would have a surface velocity of 500 km s^{-1}, if the angular momentum of the core had decoupled from the rest of the star at the end of the main-sequence evolution. On the other hand, with a constant angular momentum per unit mass, the surface velocity would be greater than or equal to 10,000 km s^{-1}!

These results strongly suggest that angular momentum can be transported from the deep layers toward the surface and that the star probably maintains solid body rotation for a significant part of its post–main-sequence evolution (Faber and Danziger 1970; Weidemann 1977). However, this result rested on only two objects, and since it is not possible to determine the inclination i independently, it was desirable to collect more observations with the final goal to obtain the distribution of rotational velocities.

Greenstein *et al.* (1977) observed 14 DA's, of which eight showed the narrow line cores indicative of very low rotation. Lack of a sufficiently large grid of non–LTE atmospheres, however, prevented them from obtaining more than upper limits on $v \sin i$ of the order of 40–70 km s^{-1}.

This work has been continued and extended in a series of recent papers by Pilachowski and Milkey (1984), Milkey and Pilachowski (1985), and Pilachowski and Milkey (1987) using high-resolution echelle spectra obtained with the Kitt Peak 4 m telescope and a CCD detector. In their most recent paper these authors compile a list of rotational velocities for 16 objects. Only two of these have $v \sin i \geq 50$ km s^{-1}; in most other cases the result is not significantly different from 0. These results are consistent with the low upper limit obtained by Wesemael, Henry, and Shipman (1984) for the hot white dwarf Feige 24, and with the large rotation periods derived for several magnetic white dwarfs (Angel, Borra, and Landstreet 1981; Schmidt *et al.* 1986).

In this paper we add seven determinations of southern hemisphere objects to this list, of which two are in common with Pilachowski and Milkey (1987).

[1] Based on observations collected at the European Southern Observatory at La Silla, Chile.
[2] Louisiana State Observatory Contributions No. 210.

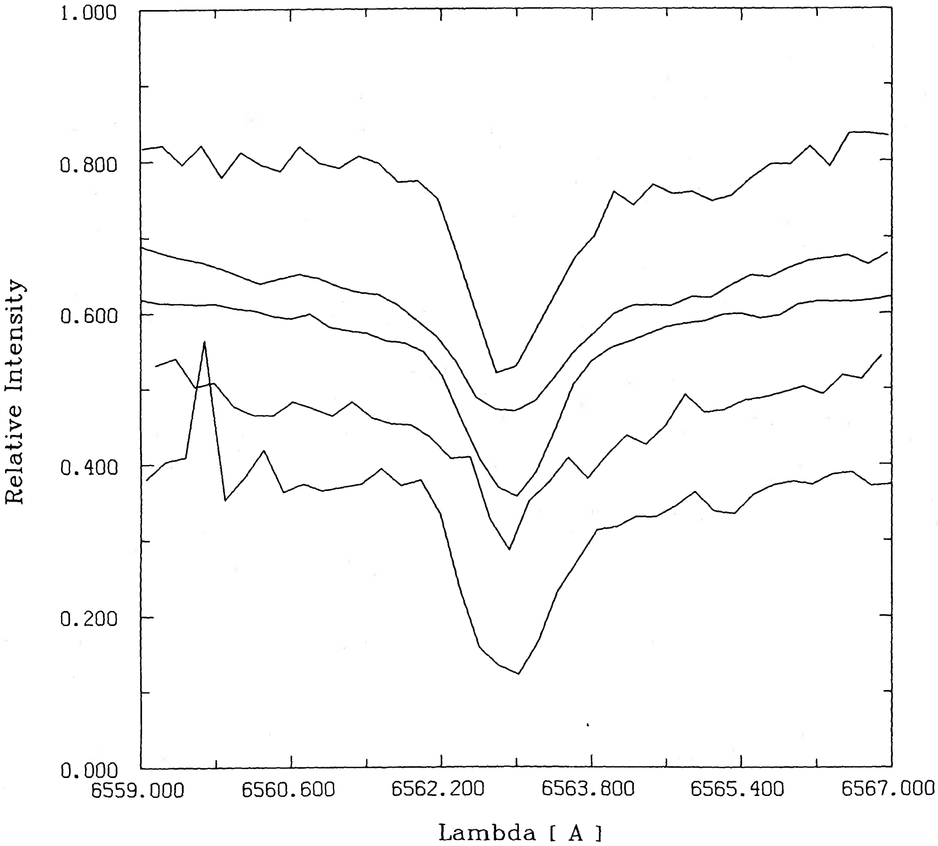

FIG. 1a

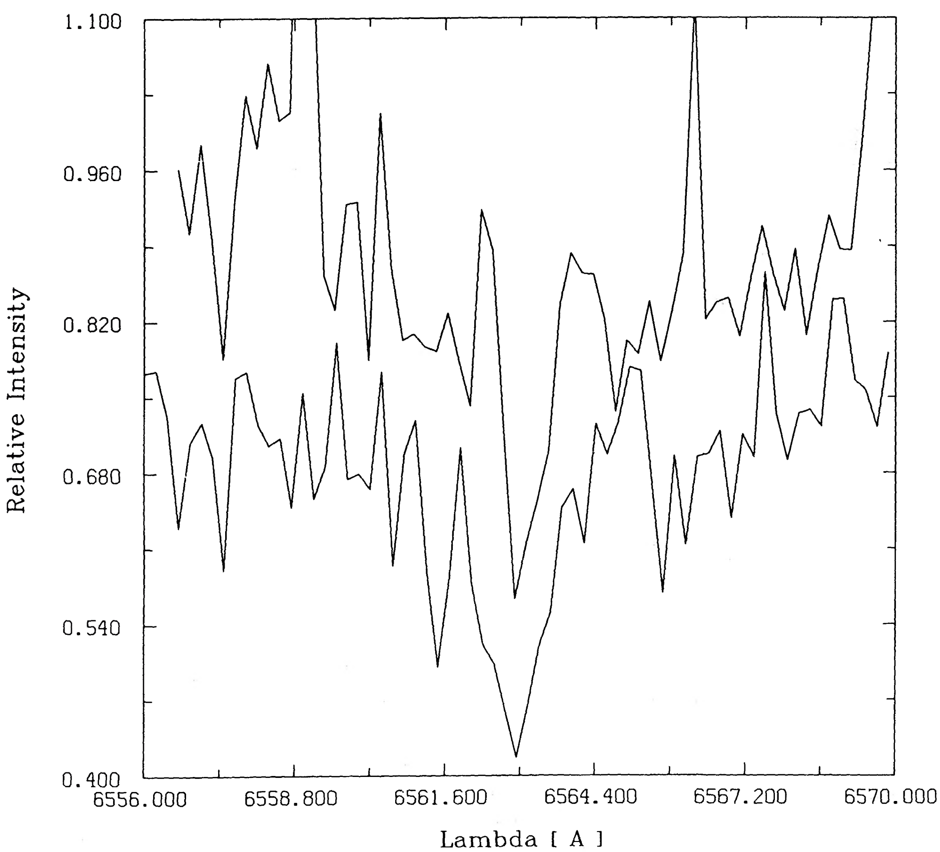

FIG. 1b

FIG. 1a.—Ob
arbitrarily shifte

ıserved spectra in the Hα core region for L268−92, CD−38°10980, 40 Eri B, CD−37°6571B, and W485A (*from top*). The spectra have been d vertically. (*b*) Spectra with low signal-to-noise ratio for L587−77A (*top*) and W672B, with arbitrary vertical shifts.

II. OBSERVATIONS

The observations were obtained in 1985 June and 1986 January with the CASPEC echelle spectrograph at the 3.6 m telescope of the European Southern Observatory (La Silla, Chile). The detector was a CCD with 520 × 337 pixels, the dispersion obtained was 0.21 Å per pixel at Hα, the actual resolution was slightly degraded by the use of a broader slit. The usual CCD reductions (flat fielding, extraction of orders, etc.) were done with the ESO reduction facilities in Munich; further reductions of one-dimensional spectra and determinations of wavelength shifts and line profiles were made at Louisana State University using the IRAF NOAO image processing package.

The primary aim of the observations was the determination of gravitational redshifts; for this reason all objects are members of wide binary systems or common proper motion pairs, and spectra of the companions were obtained at the same time. All DA's observed—covering a range in effective temperatures from 9000 to 25,000 K—showed the sharp Hα core, but only seven had a signal-to-noise ratio sufficient for a determination of rotation. Figure 1 shows the core regions of Hα in these objects.

The instrumental profile was determined from lines in the comparison thorium/argon spectrum and fitted with a Guassian with $\sigma = 0.25$ Å.

III. THEORETICAL CALCULATIONS

The temperature and pressure structure of our DA atmospheres was determined from plane-parallel models in hydrostatic equilibrium and with almost pure hydrogen (He/H was 10^{-4} respectively 10^{-5} by number). Two different sets of models were studied.

1. LTE models including the blanketing effects of Stark broadened hydrogen lines and convection (see Koester, Schulz, and Weidemann [1979] for a description), and

2. Non–LTE models with a hydrogen model atom with 16 levels (five in non–LTE). These models include only Doppler broadening (Kudritzki 1976). (For the line profile calculations described below, of course Stark broadening was included!)

Based on the temperature and pressure structure obtained from these models we have calculated the non–LTE line formation for hydrogen, again using a 16-level model atom plus continuum. The method of solution was the accelerated lambda iteration (Werner and Husfeld 1985) based on Scharmer's (1981) work, but including the effect of Stark broadening in the statistical equilibrium equations as described by Herrero (1987). The 10 lowest levels are treated in non–LTE and all radiative and collisional transitions coupling them are included in the calculations. All transitions with upper levels ≤8 are considered with Stark broadening leading to a total number of 539 frequencies to describe the hydrogen spectrum.

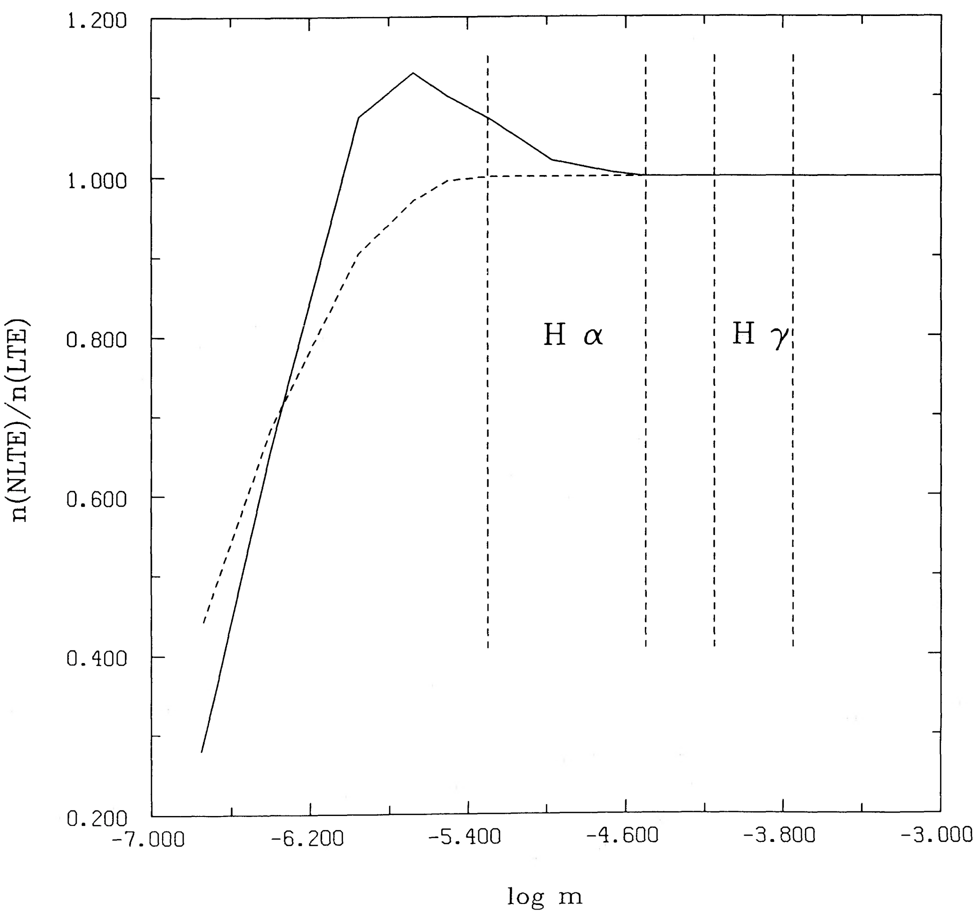

FIG. 2.—Departure coefficients (non–LTE divided by LTE occupation numbers) for levels 2 (*dashed*) and 3 (*solid*) of hydrogen. Dashed vertical lines indicate the formation regions of the cores of Hα and Hγ ($\tau = 1$).

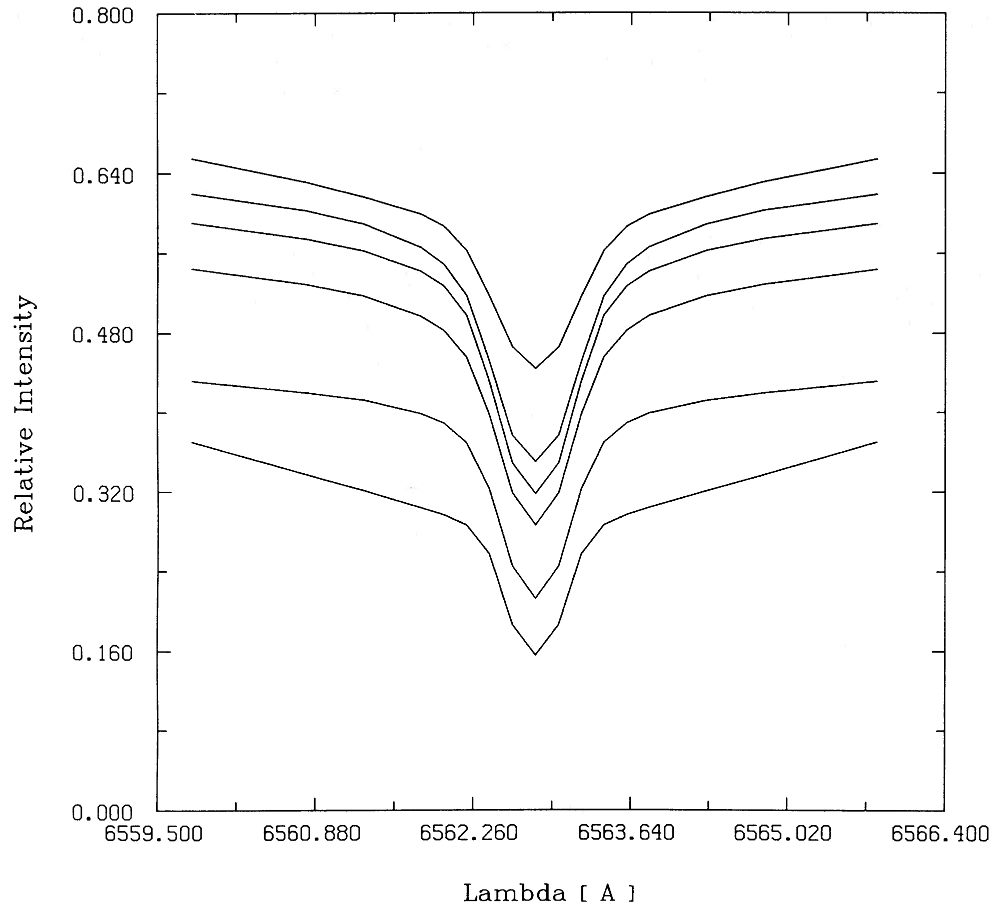

FIG. 3.—Hα line profiles (central cores) in $\log g = 8$ models with effective temperatures of 25,000, 17,000, 15,000, 13,000, 10,000, and 8000 K (*from top to bottom*).

The approximate lambda operator was taken in the form proposed by Olson, Auer, and Buchler (1986) as applied by Puls and Herrero (1988) and different from that used by Werner and Husfeld (1985). It is given by

$$\Lambda^*[S_\nu] = \int_{\Delta\tau}^{\infty} \frac{S_\nu \Delta\tau \, dx}{x^2 + 2(1 - e^{-x})} .$$

Here S_ν is the monochromatic source function, τ the optical depth, $x = \Delta\tau/\mu$, and μ is the usual cosine of the angle between the normal and the direction of propagation.

Our experience with this method shows that the convergence of the occupation numbers is clearly much faster and more stable than the approximate lambda operator method of Werner and Husfeld (1985).

The calculations reproduce the observed sharp cores of Hα. Comparing with LTE line formation calculations, which do not give sharp cores, it is clear that this is a non–LTE effect, as was already shown by Greenstein and Peterson (1973). The reason (see Fig. 2) is the repopulation—to departure coefficients slightly greater than 1—of the $n = 2$ level in the outer layers, where Hα is formed, whereas Hγ, formed deeper in the photosphere, does not show the sharp core. Although LTE is usually a good approximation in white dwarfs due to their high densities and comparatively low temperatures (thus allowing collisions to dominate the transitions), this is not true for the optically thick core of Hα, formed in a region dominated by radiative processes as a consequence of the density decrease in the outer photosphere.

In order to decide which of our two sets of model atmospheres is more appropriate, we performed three tests.

1. Non–LTE line profiles were calculated for a non–LTE and a line-blanketed LTE model of 25,000 K effective temperature, $\log g = 8$. The profiles were quite different, with the LTE model having a broader and shallower core. This difference would certainly have a significant effect on the determination of rotational velocities.

2. Non–LTE line formation calculations for nonblanketed LTE and for non–LTE models were compared. The differences in the line profiles were very small, indicating that blanketing effects dominate over non–LTE effects on the model.

3. The theoretical profiles were compared to the observations of the DA white dwarf CD$-38°$10980, which has $T_{\rm eff} = 24{,}700 \pm 250$ K and $\log g = 7.95 \pm 0.15$ according to Holberg *et al.* (1985). The profiles using a LTE line blanketed model plus non–LTE line formation give by far the best fit to the observations.

We therefore decided to use the set of LTE line blanketed models as the basis of our line profile calculations. It should be stressed, however, that this is justified only for the model structure; for the line formation non–LTE calculations are essential because only these can reproduce the sharp cores.

Hα profiles were then calculated for nine models in the range of effective temperatures from 9000 to 25,000 K and log

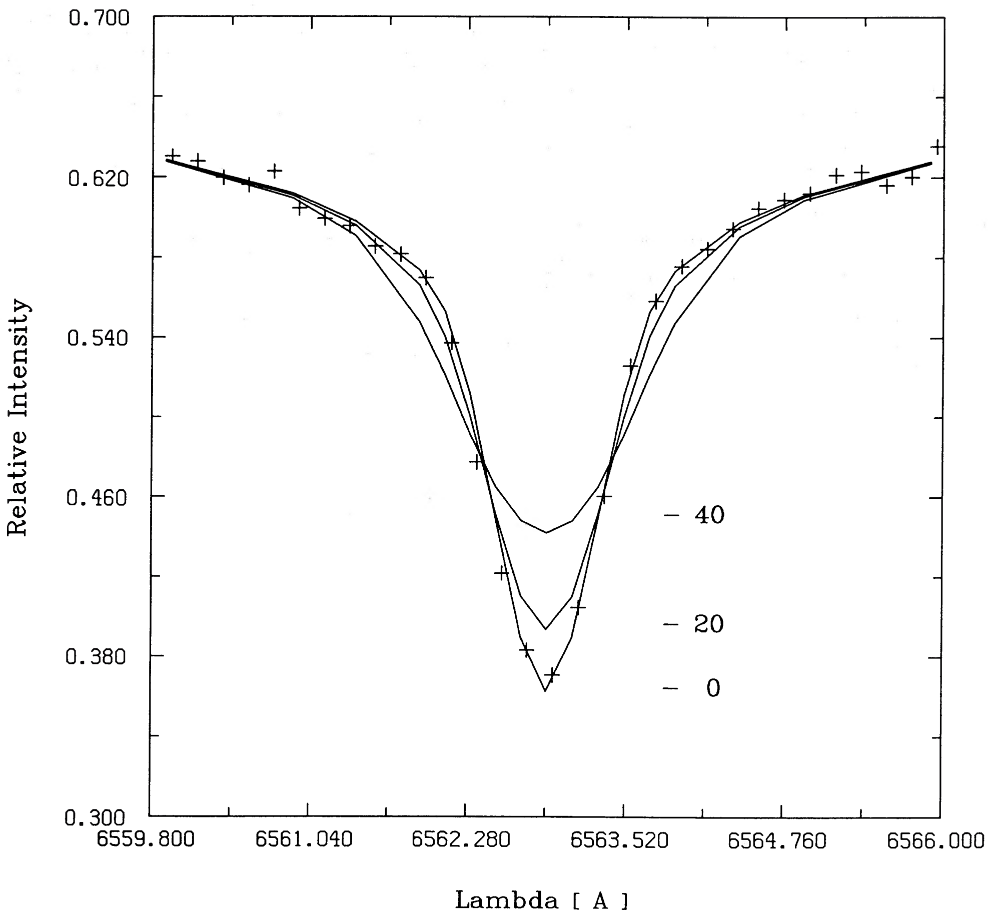

FIG. 4.—Central region of Hα in 40 Eri B (+ + +), and comparison with theoretical calculations at three different rotational velocities. (Model data T_{eff} = 17,000 K, log g = 7.75).

g = 8.0. In addition one model with T_{eff} = 17,000 K and log g = 7.75 was calculated for the interpretation of the 40 Eri B observations. Figure 3 shows most of the profiles for log g = 8.0. As can be seen from this figure, the absolute depth of the profile is of course strongly temperature dependent. However, the depth also of the central core relative to the line profile 1 Å away from the line center varies significantly with temperature. As we will see in the next section, the determination of rotational velocities relies strongly on this quantity. It is therefore essential to use models representing as closely as possible the actual temperature of the object. The use of only one or two models for the whole range from 23,000 K to 13,500 K (Pilachowski and Milkey 1987) could introduce spurious results.

IV. ANALYSIS AND RESULTS

a) Rotation

From the set of line profiles we constructed rotationally broadened profiles by convolving them with the broadening function

$$A(x) = \frac{2/\pi\sqrt{1 - x^2} + \beta/2(1 - x^2)}{1 + 2/3\beta}$$

(Unsöld 1955), where β, the coefficient of linear limb darkening was taken as 0.15, following Pilachowski and Milkey 1984). As long as $\beta \leq 0.5$, it has no influence on the result. The value x is the distance from the line center, measured in units of the maximum broadening $b = (\lambda/c)\, v \sin i$. These profiles were then folded with the instrumental profile as determined in § II and compared to the observations.

The effective temperature for the observed objects were taken from Koester, Schulz, and Weidemann (1979) and Holberg *et al.* (1985). The uncertainties given in those papers are usually 200 to 400 K, and the model temperature used is always within 1000 K of the observed T_{eff}. Within these limits the dependence of the theoretical profiles on temperature mentioned above is negligible.

The fits that could be achieved were very good even without any adjustments, with differences between theory and observations outside the narrow core of less than 3%. These small discrepancies can easily be explained by small differences in the effective temperature and a slight inaccuracy in the placing of the continuum. The Hα lines extend over at least 4 orders of the Echelle spectrum and the continuum had been determined by interpolation from neighboring orders. Since the main effect of rotation is shown in the depth of the core relative to the profile at 1 to 2 Å distance from the line center, we therefore made small adjustments to the observed profiles to fit them to the theoretical ones in this range.

Results for the two brightest objects—40 Eri B and CD−38°10980—are shown in Figures 4 and 5. Results for all

TABLE 1

VELOCITY DETERMINATIONS

WD No.	Name	T_{eff}	$v \sin i$
1620−391.........	CD−38°10980	25000	<20
0413−077.........	40 Eri B	17000	<20
1659−531.........	L268−92	15000	<20
1327−083.........	W485A	14000	<20
1716+020.........	W672B	14000	<30
1544−377.........	CD−37°6571B	10000	30 ± 20
0326−278.........	L587−77A	9000	<40

NOTE.—The effective temperatures are those of the model that most closely matches the effective temperature of the star as taken from the literature, in most cases from Koester, Schulz, and Weidemann 1979. Log g is 8.0 in all cases except for 40 Eri B, where 7.75 was used.

objects, together with the effective temperatures used for the model calculations, are given in Table 1.

Estimates of upper limits or errors are eye estimates, based on what we believe can be definitely excluded considering the observational uncertainties. They do not include any systematic uncertainties in the relative core depths of the models, for which we have no estimate available at the present time.

Two objects, 40 Eri B and W485A, were also included in the paper by Pilachowski and Milkey (1987). Our value for 40 Eri B is compatible with their result (10 ± 10), whereas for W485A they found 42 ± 9, which is not consistent with our data. In general, however, our study confirms their finding of the predominance of very low rotational velocities. With about 25 objects studied now the possibility that this is a chance effect caused by the projection factor sin i can certainly be excluded. With our present sample extending from T_{eff} = 25,000 K to ~9000 K, corresponding to cooling ages of $\sim 5 \times 10^7$ to $\sim 10^9$ yr, it is also not very likely that mass loss and magnetic breaking leads to a decrease of rotational velocities *during the lifetime* of the white dwarf. The inevitable conclusion seems to be—as discussed in the Introduction—that the interior parts of stars are able to transfer most of their original angular momentum to the outer layers even after they have left the main sequence.

b) *Magnetic Fields*

Any magnetic fields present would to first approximation broaden the central core through the Zeeman splitting. For a field of 10^6 G the splitting from the linear term amounts to 46 cm^{-1} or 19.81 Å at Hα; the quadratic term is negligible (Angel 1977). Figure 3 shows that the typical full width of the sharp core is less than or equal to 1 Å, if measured at a residual intensity midway between the central minimum and the onset of the broad wings. A Zeeman splitting of 0.5 Å would double the core width, which can definitely be ruled out from the

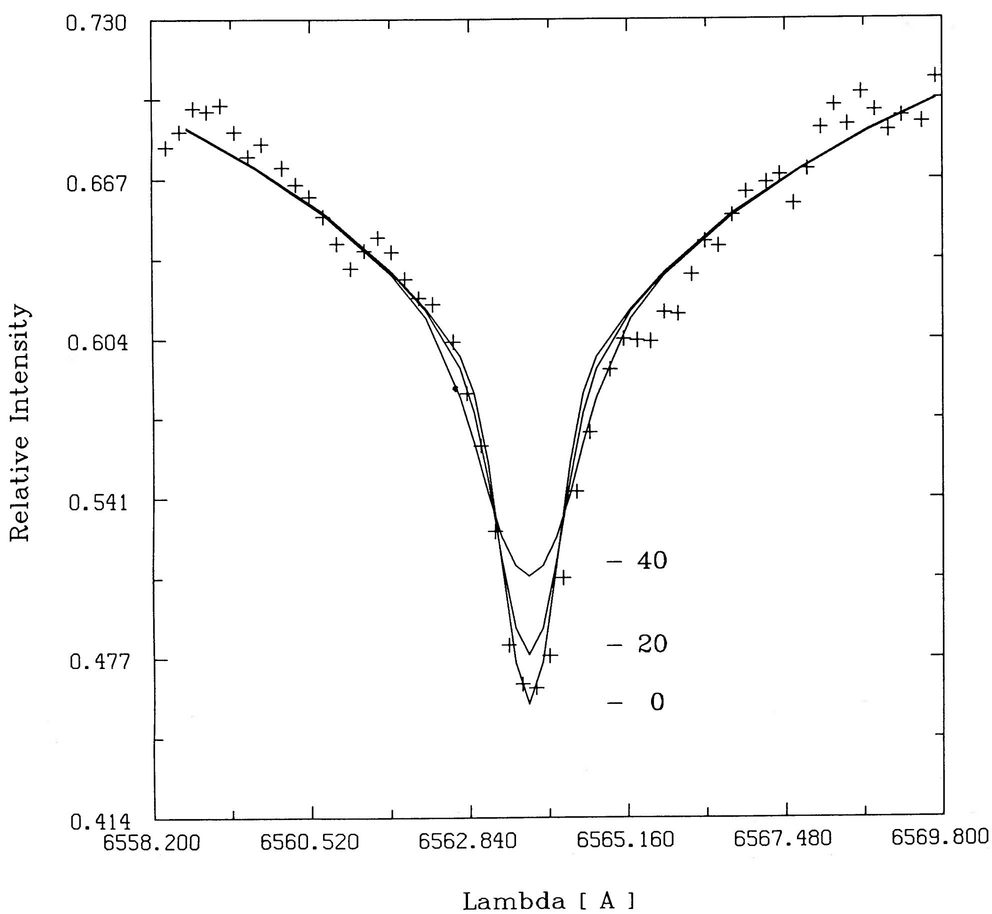

FIG. 5.—Same as Fig. 4, but for CD−38°10980. (Model data T_{eff} = 25,000 K, log g = 8.0).

comparison of observation and theory. From this limit we derive an upper limit of 2.5×10^4 G for the magnetic field in all objects.

The most accurate measurement available for 40 Eri B is -1.0 ± 1.7 kilogauss (Angel, Borra, and Landstreet 1981) from photoelectric measurements of circular polarization in the wing of Hα. For fainter objects the typical limits are 5×10^4 to 3×10^5 G. The use of high-resolution spectroscopy thus has the potential to lower the observable limits significantly for DA stars that show the narrow core.

We gratefully acknowledge stimulating discussions with R. Kudritzki, who firmly believed in the importance of non–LTE effects even in white dwarfs and suggested these calculations. A. H. wants to thank the Spanish Ministerio de Educacion for a Beca de Reincorporacion.

REFERENCES

Angel, J. R. P. 1977, *Ap. J.*, **216**, 1.
Angel, J. R. P., Borra, E. F., and Landstreet, J. D. 1981, *Ap. J. Suppl.*, **45**, 457.
Faber, S. M., and Danziger, I. J. 1970, in *Stellar Rotation*, ed. A. Slettebak (Dordrecht: Reidel), p. 39.
Grabowski, B., Madej, J., and Halenka, J. 1987, *Ap. J.*, **313**, 750.
Greenstein, J. L., Boksenberg, A., Carswell, R., and Shortridge, K. 1977, *Ap. J.*, **212**, 186.
Greenstein, J. L., and Peterson, D. M. 1973, *Astr. Ap.*, **25**, 29.
Greenstein, J. L., and Trimble, V. L. 1967, *Ap. J.*, **149**, 283.
———. 1972, *Ap. J. (Letters)*, **175**, L1.
Herrero, A. 1987, *Astr. Ap.*, **171**, 189.
Holberg, J. B., Wesemael, F., Wegner, G., and Bruhweiler, F. C. 1985, *Ap. J.*, **293**, 294.
Koester, D. 1987, *Ap. J.*, **322**, 852.
Koester, D., Schulz, H., and Weidemann, V. 1979, *Astr. Ap.*, **76**, 262.
Kudridtzki, R. 1976, *Astr. Ap.*, **52**, 11.
Milkey, R. W., and Pilachowski, C. A. 1985, *Pub. A.S.P.*, **97**, 634.
Olson, G. L., Auer, L. H., and Buchler, J. R. 1986, *J. Quart. Spectros. Rad. Transf.*, **35**, 431.
Pilachowski, C. A., and Milkey, R. W. 1984, *Pub. A.S.P.*, **96**, 821.
———. 1987, *Pub. A.S.P.*, **99**, 836.
Puls, J., and Herrero, A. 1988, in preparation.
Scharmer, G. B. 1981, *Ap. J.*, **249**, 720.
Schmidt, G., West, S. C., Liebert, J., Green, R. F., and Stockman, H. S. 1986, *Ap. J.*, **309**, 218.
Schulz, H. 1977, *Astr. Ap.*, **54**, L315.
Trimble, V. L., and Greenstein, J. L. 1972, *Ap. J.*, **177**, 441.
Unsöld, A. 1955, in *Physik der Sternatmosphären* (Berlin: Springer), p. 509.
Wegner, G. 1974, *M.N.R.A.S.*, **166**, 271.
Wegner, G., and Reid, I. N. 1987, in *IAU Colloquium 95, The Second Conference on Faint Blue Stars*, ed. A. G. D. Philip, D. S. Hayes, and J. Liebert (Schenectady: L. Davis), p. 649.
Weidemann, V. 1977, *Astr. Ap.*, **59**, 411.
Werner, K., and Husfeld, D. 1985, *Astr. Ap.*, **148**, 417.
Wesemael, F., Henry, R. B. C., and Shipman, H. L. 1984, *Ap. J.*, **287**, 868.

ARTEMIO HERRERO: Instituto de Astrofisica de Canarias, E-38200 La Laguna, Tenerife, Spain

DETLEV KOESTER: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803-4001