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GRAVITATIONAL REDSHIFT AND MASS-RADIUS RELATION IN WHITE DWARFS[1]

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ABSTRACT

This paper presents gravitational redshifts obtained from observations of Hα in nine DA white dwarfs, which are members of wide binaries or common proper motion pairs. Within the error bars, the data follow the theoretical zero-temperature relation for the pure carbon models of Hamada and Salpeter. Due to the remaining relatively large errors in radii and the intrinsically narrow mass distribution of white dwarfs around a mean mass of 0.58 $M_\odot$ the results do not provide an empirical proof for the shape of the relation. Assuming the validity of this relation, it is possible to derive very accurate masses. Although the sample is small, it confirms results of other studies using larger, but less well-observed, samples.

The shifts obtained for CD $-38°10980$ are different from those obtained from the sharp ultraviolet features and indicate that they probably do not originate in the photosphere. Line shifts were also determined for two DB stars. The lines, however, are blueshifted due to the dominating influence of pressure broadening. The present state of the theory of Stark shifts in helium lines precludes an interpretation in terms of gravitational redshifts.

Subject headings: gravitation — relativity — stars: white dwarfs

I. INTRODUCTION

Since the appearance of general relativity theory, it has been a challenge to astrophysicists to determine the predicted gravitational redshifts in stars, and white dwarfs have been primary candidates due to their small radii and comparatively large masses. Adams (1925) was the first to attempt the extremely difficult observation for Sirius B—difficult due to the large amount of scattered light from the much brighter Sirius A. Although in 1925 the observed value was regarded as a confirmation of general relativity as well as of the theory of white dwarfs, we know today that the result was grossly in error. The reasons for this, as well as the results of a more recent determination by Greenstein, Oke, and Shipman (1971), have been discussed in great detail by Greenstein, Oke, and Shipman (1985) and Wesemael (1985).

In two pioneering papers, Greenstein and Trimble (1967) and Trimble and Greenstein (1972) measured the radial velocities of a large number of white dwarfs. By assuming that the intrinsic space motions are randomly distributed, they were able to separate these from the Einstein redshift, arriving at an average value of 58 km s^{-1} A similar study for a smaller sample of southern objects was conducted by Wegner (1974).

An alternative approach is to use white dwarfs in wide binary systems or common proper motion pairs, where the space velocity of the system can be determined from the companion. This approach has been used widely, by Wegner (1973, 1978, 1979) among others.

With the advent of modern detectors, notably the CCD, it has become feasible on large telescopes to study even faint white dwarfs at high resolution and good signal-to-noise ratios. High resolution is especially desirable since observations by Greenstein and Trimble (1972), Bessell and Wickramasinghe (1975), Greenstein *et al.* (1977), and Pilachowski and Milkey (1984) revealed the presence of sharp line cores in Hα, usually attributed to NLTE effects (Greenstein and Peterson 1973). The observation of these resolved cores eliminates the need to use the wings for the redshift determinations, which might be influenced by pressure effects and other possible sources of asymmetries (Schulz 1977).

Therefore, we thought it worthwhile to repeat a study of white dwarfs in wide binaries and common proper motion pairs, using high resolution observations of Hα. Besides the presence of the sharp core, Hα is also best suited for theoretical reasons. It is a well-known fact that hydrogen lines in dense plasmas are slightly redshifted and asymmetrical due to pressure effects (Wiese and Kelleher 1971). Theory (Grabowski, Madej, and Halenka 1986) predicts that these shifts should be smallest in Hα and, in fact, completely negligible in the core.

II. OBSERVATIONS

The observations—one spectrum each for the white dwarf and the companion—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 resolution obtained was 0.21 Å at Hα. The usual CCD reductions (flat fielding, extraction of orders, etc.) were done with the ESO reduction facilities in Munich; further reduction of one-dimensional spectra and determination of wavelength shifts were made in Kiel using software developed by G. Jonas.

Figure 1 shows Hα in the bright DA CD $-38°10980$; especially, the enlarged core region clearly shows the sharp, well-defined core. Line shifts were determined by fitting a Gaussian to the central 2–5 Å; the typical accuracy for a single object is estimated to be 0.03–0.10 Å, depending upon the signal-to-noise ratio of the spectrum. Spectra of the white dwarf and the companion were usually obtained within 2 hr using identical instrument configurations. Therefore, no attempt was made to reduce the velocities to a common scale; instead, only a relative shift between the two objects was determined, and this was interpreted as the gravitational redshift of the white dwarf.

This interpretation neglects any difference in the true space velocities of the two objects. In the case of wide binaries the

[1] Based on observations collected at the European Southern Observatory at La Silla, Chile.

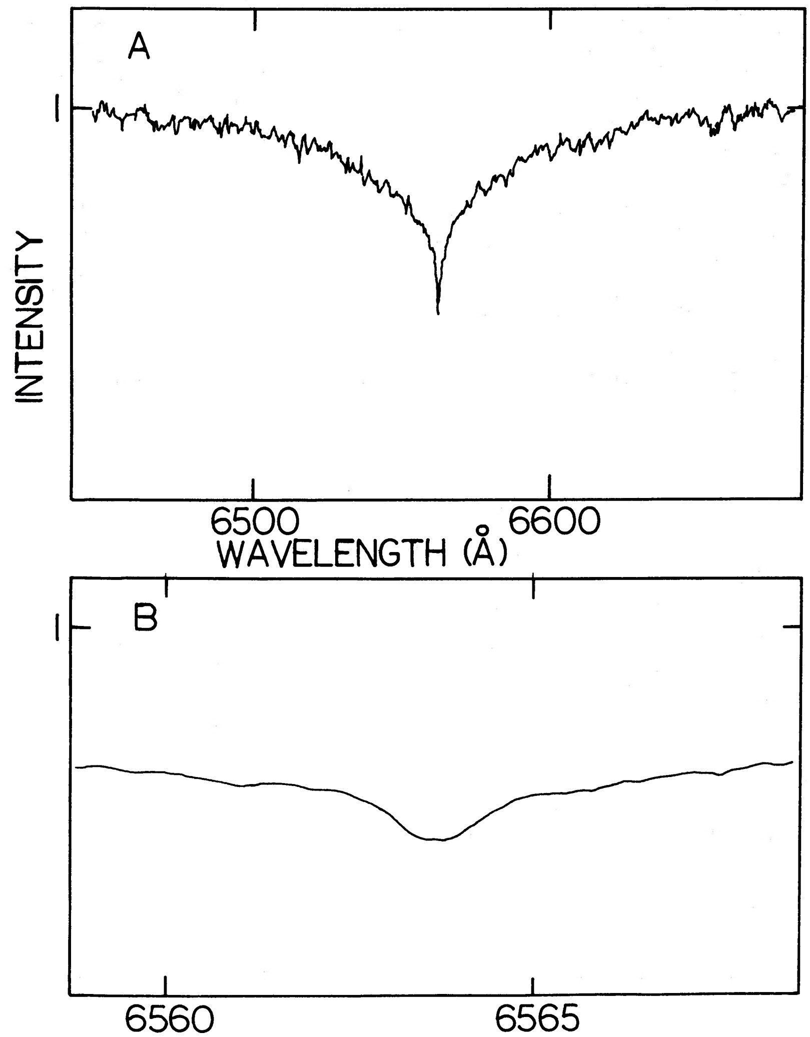

FIG. 1.—(*a*) Spectrum of CD $-38°10980$ showing the full width Hα extending over 4 orders of the echelle spectrum. (*b*) Enlarged part of the central region, showing the sharp core.

angular separations are $>7''$. Assuming circular orbits with radii given by the distance and the present angular separation, we may estimate the Keplerian velocities. These are all of the order of 1 km s^{-1}, well within the errors of our determinations. For the common proper motion pairs, which have much larger seperations, information on differences in the radial velocity are not available. We therefore have to assume that these differences are of the same order of magnitude (1 km s^{-1}). These possible error sources are not included in the errors given in Table 1, which summarizes the results for the DA stars.

We were also able to observe line shifts in the DB star BPM 18164, which has a common proper motion with the G0 V star HR 2274, and for the wide binary LDS 749A–LDS 749B. However, in this case, the shifts are negative (blueshift) and also different for different spectral lines measured. The results for individual lines are given in Table 2 and discussed in the next section.

III. DISCUSSION

a) *DA Stars*

According to the general theory of relativity, the gravitational radial velocity is given by $v_g = 0.635(M/M_{\odot})/(R/R_{\odot})$ (km s^{-1}). Using the radius determined photometrically from effective temperatures and distances, we may thus derive a mass without assuming the validity of the mass-radius relation. Table 3 gives the results for the DA included in this study. The last column gives the references for the radii, taken mainly from Koester, Schulz, and Weidemann (1979).

Figure 2 shows these results in a mass-radius diagram together with the theoretical relations for pure He and C com-

TABLE 1

RESULTS OF VELOCITY DETERMINATIONS FOR DA STARS

WD	Object	Companion	Date	v (km s^{-1})
0326−278	L587−77A	L587−77B	1986 Jan 19	36.1 ± 3.2
1105−048	L970−30	L970−27	1985 May 25	20.1 ± 3.2
1327−083	W485A	W485B	1985 May 25	24.9 ± 3.2
1334−160	LDS 455B	LDS 455A	1986 Jan 18	51.2 ± 12
1348−273	L619−50	L619−49	1985 May 26	23.3 ± 5.0
1544−377	L481−60	CD −37°6571	1985 May 25	27.9 ± 3.2
1620−391	CD −38°10980	HR 6094	1985 May 25	37.9 ± 2.0
1659−531	L268−92	HR 6314	1985 May 26	30.2 ± 5.0
1716+020	W672B	W672A	1985 May 27	22.0 ± 6.0

TABLE 2

OBSERVED LINE SHIFTS FOR THE DB STARS BPM 18164 AND LDS 649B[a]

LINE (He)	SHIFT BPM 18164 (Å)	LDS 749B (Å)
λ4026	−0.20	...
λ4471	−0.35	−0.49
λ4713	−0.29	...
λ4922	−0.55	−0.43

[a] BPM 18164 (WD 0615−591) was observed on 1986 Jan 17; LDS 649B (WD 2129+000) was observed on 1985 May 27.

positions (Hamada and Salpeter 1961). To avoid confusion in the figure, errors have only been indicated for CD −38°10980, the star with the smallest errors, and for W672B, whose errors are representative of the errors of the other objects (for LDS 455B no error estimate for the radius is available). It is very encouraging that within the error margins all objects seem to follow the theoretical relation. The deviations would be much larger had we had to use the spectroscopically determined surface gravity instead of the gravitational velocity to determine the empirical relation.

With the exception of two objects (one of which—LDS 455A—may be quite uncertain) all DA stars seem to have systematically larger radii than predicted by the theory. This might partly be explained by two effects not included in the Hamada-Salpeter relations:

1. The models are calculated assuming pure He or C composition. In a DA Star, however, the observed outer layer is pure hydrogen, probably with an underlying He shell and a carbon and oxygen core. These outer layers would increase the radii even for zero-temperature models by 3%–5% (Hamada and Salpeter 1961).

2. A real DA is not a zero-temperature object. The increase in radius by finite-temperature outer H layers depends strongly on the amount of hydrogen present, which is not known with certainty (Iben and Tutukov 1984; Koester and Schönberner 1986). If this H mass were as high as $10^{-4}\ M_{\odot}$ the corresponding increase in radius could be 10%–20% in the temperature range of the observed DA and thus explain the apparently systematic deviations. In view of the large errors of the

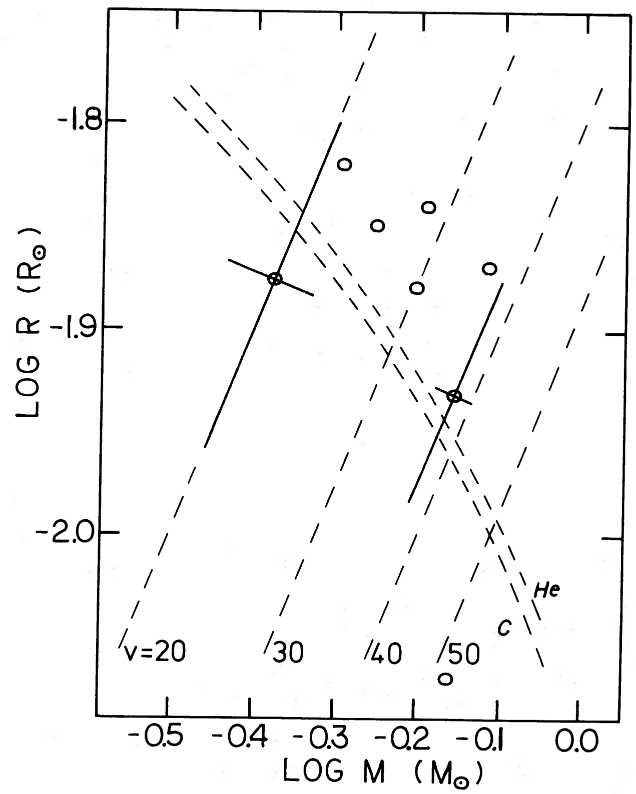

FIG. 2.—Mass-radius diagram for white dwarfs. The curves marked He and C are the zero-temperature relation of Hamada and Salpeter 1961. The two stars with error bars are CD −38°10980 and W672B. The straight dashed lines show the gravitational velocities in km s^{-1}.

observed radii, however, it is not possible to draw any conclusions.

It is somewhat disappointing that the empirical evidence for Chandrasekhar's mass-radius relation has been far from convincing in the past; the present study is no exception, although it presents—if one excludes the classical binaries Sirius B and 40 Eri B—the most precise data points in the diagram known today. The difficulties that prevent the final "proof" are:

a) uncertainties in the radii, mainly from uncertainties in the parallaxes, and

b) the intrinsic mass distribution of white dwarfs, which seems to be very narrow, with a maximum around 0.6 $M_{\odot}$. (Koester, Schulz, and Weidemann 1979) and very few objects around 1 $M_{\odot}$.

The latter difficulty might be overcome in the future, if it is possible to obtain spectra with higher resolution for the apparently high-mass white dwarfs found in open clusters, e.g., NGC 2516 (Reimers and Koester 1982).

On the other hand, if we believe in the validity of the theoretical relation, we might use it (e.g., the C relation) to obtain very precise masses for DA stars. These masses are also given in Table 3, and the errors show that the stars are, in fact—with the exception of the three classical binaries—the best determined masses for white dwarfs. Although the sample is quite small, it is encouraging that the average taken for the nine objects yields a mean mass of 0.58 $M_{\odot}$, exactly the value determined for a much larger, but less well-observed, sample by completely different methods (Koester, Schulz, and Weidemann 1979).

TABLE 3

RADII AND MASSES FOR DA WHITE DWARFS

WD	log $R/R_{\odot}$	$M(R, v)/M_{\odot}$	$M(v)/M_{\odot}$	References
0326−278	−1.87 ± 0.08	0.77	0.65 ± 0.04	1
1105−048	−1.88 ± 0.08	0.42	0.45 ± 0.04	1
1327−083	−1.85 ± 0.05	0.56	0.52 ± 0.04	1
1334−160	−2.07	0.69	0.79 ± 0.16	2
1348−273			0.49 ± 0.07	
1544−377	−1.84 ± 0.06	0.64	0.56 ± 0.04	1
1620−391	−1.93 ± 0.09	0.70	0.67 ± 0.03	3
1659−531	−1.88 ± 0.08	0.63	0.58 ± 0.07	1
1716+020	−1.82 ± 0.15	0.53	0.47 ± 0.08	1

REFERENCES.—(1) Koester, Schulz, and Weidemann 1979; (2) Shipman 1979; (3) Holberg *et al.* 1986.

b) CD −38°10980

This object is especially interesting since it shows sharp lines of Si II and Si III in the ultraviolet part of the spectrum obtained with *IUE* (Holberg *et al.* 1985) The reshift determined from these lines by Holberg *et al.* (1985) is 28.4 ± 4.8 km s^{-1}. They interpret this as gravitational redshift, but point out a possible discrepancy with redshifts determined from the optical spectrum (Wegner 1973, 1978). The newly determined redshift 37.9 km s^{-1} is compatible with Wegner's (1978) result and confirms that the ultraviolet metal lines do not originate in the photosphere but probably at some distance from the star in a stellar wind as discussed by Bruhweiler and Kondo (1983), Bruhweiler (1984), and Holberg *et al.* (1985).

The interpretation of observations for this object is, however, further complicated by the fact that a recent determination of an astrometric parallax by Ianna (cited as private communication in Holberg *et al.* 1985) would give a radius of $\log R/R_\odot = -1.84$ and mass $M = 0.87\ M_\odot$, slightly outside the errors of our results, where the photometric radius was used.

c) DB Stars

The situation is much less fortunate for the DB stars with pure He spectra. As was already noted by Greenstein and Trimble (1967), the shifts are different from line to line, and at least some are even negative. This indicates that pressure shifts caused by the quadratic Stark effect are not negligible and may even dominate the shifts as shown by BPM 18164 and LDS 649B. Laboratory measurements and theoretical predictions (see, e.g., the compilation by Konjevic and Roberts 1976) often disagree on the magnitude and sometimes even on the sign of the shift—for $\lambda\lambda$4713 and 4388 both give positive shifts. With the present state of the theory it is thus not possible to evaluate the DB data in terms of gravitational redshifts.

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