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DOUBLE DEGENERATES AMONG DA WHITE DWARFS[1]

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ABSTRACT

We report the results of a spectroscopic survey of catalog white dwarfs in search of radial velocity variations indicative of a binary motion. In a sample of 54 DA white dwarfs, we find one Double Degenerate (DD) system with a period of $1\overset{\mathrm{d}}{.}15$ (the shortest period DD system yet discovered). We also find two other excellent and two good DD candidates, and two white dwarf + red dwarf pairs. If all the candidates should be confirmed, this would indicate a frequency of $\sim 13\%$ of interacting binaries in an unbiased sample of evolved stars, with a DD frequency of $\sim 10\%$. These results suggest fairly large values for the common-envelope parameter α, implying that a source of energy other than orbital may be required to eject the envelope during common-envelope events. Finally, in combination with previous evidence our result implies that DDs with WD components of the DA variety are unlikely to be the precursors of Type I supernovae, but we maintain that DDs with non–DA components remain very attractive candidates.

Subject headings: stars: binaries — stars: stellar statistics — stars: supernovae — stars: white dwarfs

I. INTRODUCTION

A major fraction of stars belong to binary or multiple systems, and the majority of stars terminate their evolution as white dwarfs (WD). We would correspondingly expect a rather high formation rate of Double Degenerate (DD) systems in our Galaxy. Particularly interesting are those systems which experience Roch-lobe overflows and leave close DD remnants able to merge in a time comparable to the Hubble time, or shorter. Indeed, thanks to gravitational wave radiation, a DD system will merge in a time (Landau and Lifshitz 1951):

$$t_{\rm GWR}({\rm yr}) = \frac{1.5 \times 10^8 A_{\rm ff}^4}{M_{1\rm R} M_{2\rm R}(M_{1\rm R} + M_{2\rm R})} \simeq \frac{8 \times 10^7 P^{8/3}(M_{1\rm R} + M_{2\rm R})^{1/3}}{M_{1\rm R} M_{2\rm R}} , \qquad (1)$$

where $A_{\rm ff}$ is the separation in $R_\odot$ units, P is the period in hours, and the mass of the two WDs is in $M_\odot$ units. Two major difficulties tend to prevent theory from predicting the frequency of close DDs and the distribution function of their binary parameters (masses and separations). First, our poor knowledge of the distribution function of initial masses and separations (M_1, M_2, A_0), and, second, the uncertainties in mapping them into their final values ($M_{1\rm R}$, $M_{2\rm R}$, $A_{\rm ff}$). This follows from the difficulty of predicting the mass and (specially) angular momentum losses during the Roche-lobe overflow phases which can lead to common-envelope events (CEE). To describe the net outcome of CEEs, Tutukov and Yungelson (1979) introduced the simple parameterization:

$$GM_1^2/A_0 = \alpha G M_{1\rm R} M_2/A_f , \qquad (2)$$

where again M_1 and M_2 are the masses of the two components prior to the first CEE, A_0 is their separation, and $M_{1\rm R}$ and A_f are the corresponding quantities after the CEE. This parameterization can be used to relate the separations before and after any subsequent CEE. Here the dimensionless parameter α is a measure of the effectiveness of the transformation of the orbital energy into work to eject from the system the CE material. For small α ($\ll 1$), the transformation is *inefficient*, and a large orbital shrinkage results; for large α ($\gtrsim 1$), the orbital shrinkage is very modest, and a source other than orbital has to provide the energy needed to drive the CE off (see Iben and Tutukov 1990). Pioneering two-dimensional and three-dimensional hydrodynamical studies suggest small values of α (0.3–0.6; Livio 1989; Taam and Bodenheimer 1989), while Iben (1990) and Iben and Tutukov (1990) explore in detail the $\alpha = 1$ scenario. One rather striking aspect of this parameterization is that $t_{\rm GWR}$ is proportional to an extremely high power of α (actually, $t_{\rm GWR} \propto \alpha^9$; see Iben and Webbink 1989). For example, a system which with $\alpha = 1$ would produce a DD merging in one Hubble time (~ 15 Gyr) would instead give a DD surviving for only $\sim 3 \times 10^5$ yr in the case $\alpha = 0.3$. So, given the factor ~ 3 or more uncertainty in α, theory is unable to predict with any degree of confidence the number, period distribution, and merging rate of DD systems (for $t_{\rm GWR} \lesssim 15$ Gyr, the space density of DDs is roughly proportional to $t_{\rm GRW}$, i.e., to α^9!). However, this very fact implies that—proceeding in the opposite direction—the proper observations may set tight limits on α and therefore on the physics of CEEs.

With this kind of scientific background, in 1984 we started a systematic survey of WDs in search for DD systems and aimed at determining (1) the fraction of close DDs among cataloged WDs, (2) their periods and orbital parameters, and (3) their merging rate. One main driving force for the project was the perspective of checking the idea that systems able to merge in less than one Hubble time— and exceeding the Chandrasekhar limit— could be the precursors of Type I supernovae (Iben and Tutukov 1984; Webbink 1984; Paczyński 1985). A similar

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search has been completed by Robinson and Shafter (1987) on a sample of 44 WDs, with a null result. Their technique was able to detect only very short period systems ($P \lesssim 3$ hr), which according to equation (1) should have formed less than ~ 0.5 Gyr ago, therefore sampling only a minor fraction ($\sim 3\%$) of Galactic history. In the meantime, a DD system (L870-2) with $P \simeq 1^{\mathrm{d}}.6$ has been discovered by Saffer, Liebert, and Olzewski (1988), thus proving that fairly short period DD systems do actually exist. The DD nature of this object was anticipated by Greenstein (1983) from its exceptionally high luminosity for its temperature. In this *Letter* we present the main results of our survey of 54 DA WDs and attempt a first interpretation of them. The presentation of the full data set, and an extended discussion of the results, will appear in subsequent papers.

II. OBSERVATIONS

Our observational strategy differs substantially from that of the quoted investigations, first because it allows the discovery of binary WDs with periods much longer than 3 hr, and second because it is not biased to WDs with special characteristics. The main selection criterion for our target WDs has been just the apparent luminosity, so as to minimize exposure times, maximize the number of surveyed WDs, and maintain a good phase resolution for short-period systems. Moreover, both known pulsating or magnetic WDs have been avoided, and in case of nearly equal luminosity we have preferred hotter (therefore younger) WDs, so as to expect (in case of binarity) spectral line shifts rather than line profile changes which would have been more difficult to diagnose. No other bias was introduced in selecting the target WDs, and we have first concentrated on WDs of the DA variety about which we report in this *Letter*. Table 1 lists the 54 DAs in our survey.

For the observations, we have used the ESO 3.6 m telescope + EFOSC for the survey and occasionally the ESO 1.5 m telescope + Boller & Chivens spectrograph for the follow-up of interesting objects. The data set has been obtained in the course of five observing runs from 1985 September to 1990 January for a total of 17 nights at the 3.6 m telescope and three nights at the 1.5 m telescope. For each target WD we have obtained two to four low-resolution (~ 5 Å) spectra of fairly high quality (S/N ~ 100) using the B150 grism (spectral range 3600–5590 Å) with short exposure times (typically $t_{\mathrm{exp}} \sim 10$ minutes). For each target WD, the spectra have been taken 3–24 hr apart, and wavelength-calibration lamps have been taken before or after each exposure with the same telescope attitude.

The radial velocity changes (Δv_r) have been obtained cross-correlating each WD spectrum with another of the same star taken as template. The cross-correlation algorithm was optimized to work on the very broad Balmer lines typical of DA WDs. For each program WD the largest Δv_r obtained in this way is given in Table 1, together with the number N of spectra taken for each star (including few red spectra for the confirmed close binaries). Also given in Table 1 is the WD mass M_g as derived from surface gravity (see note). The estimated radial velocity variations are affected by a typical 1 σ error of ~ 40 km s^{-1}, although for some stars the accuracy is up to a factor of 2 better. Correspondingly, our survey should be able to detect DD systems with periods from about 0.5 hr to several days. The values of Δv_r from first-run data are affected by larger errors ($\sigma \simeq 100$ km s^{-1}) as fewer calibration lamps were taken. Clearly, this method works only if in a DD system the spectra of the two WDs are not too similar; otherwise, there is little or no line shift but rather a change in line profile, such as in the DD L870-2. In such a case, the cross-correlation algorithm would give a vanishingly small Δv_r. To check also for variations of the line profile, we have visually inspected the count ratios of all the pairs of spectra available for each program WD.

TABLE 1

PROGRAM WHITE DWARFS AND RESULTS

WD	M_g ($M_\odot$)	N	$\lvert\Delta v_r^{\max}\rvert$ (km s^{-1})	Notes
0031−274......	0.28	2	5.5	sHe I, He II
0034−211......	0.17:	7	55.6	WD+RD
0047−524......	0.42	2	90.7	DD??
0048−202......	0.15	2	4.8	
0050−332......	0.87	2	(43.6)	
0109−264......	0.13	2	162.7	wHe I, DD?
0255−705......	0.49	2	18.3	
0310−688......	0.32	2	18.4	
0343−007......	0.17:	2	56.2	
0346−011......	0.58	4	88.5	DD??
0419−487......	0.28	20	352.2	WD+RD, $P \approx 0^{\mathrm{d}}.5$
0446−789......	0.58:	3	31.4	
0549+168......	0.79	2	45.7	
0612+177......	0.32	3	23.9	
0651−020......	1.17	2	35.4	
0701−587......	0.46	3	45.9	
0732−427......	0.54	2	60.0	
0740−570......	0.51	2	21.0	
0839−327......	0.41	4	54.6	DD?
0850−617......	0.73	2	14.7	
0940+068......	0.24	2	90.2	DD?
0950−572......	0.43	2	13.5	
0954−710......	0.43	8	104.5:	
0957−666......	0.16	30	279.7	DD, $P \simeq 1^{\mathrm{d}}.15$
1022+050......	0.18	2	82.9	DD?
1042−690......	0.60	2	7.8	
1052+273......	0.54	2	40.9	
1053−550......	0.54	3	26.9	
1223−659......	0.38	2	42.9	
1236−492......	0.85	2	36.6	
1257−723......	0.42	2	29.8	
1323−514......	0.49	2	28.8	
1407−475......	0.59	3	38.0	
1422+095......	0.57	2	70.5:	
1451+006......	0.24	3	29.8	
1524−749......	0.49	2	1.6	
1555−089......	0.37	2	43.7	WD+MS
1615−154......	0.69	2	1.0	
1620−391......	0.32	4	20.5	WD+MS
1709−575......	0.36	2	8.1	
1824+040......	0.24	2	51.8	
1834−781......	0.29	2	4.6	
1845+019......	0.17:	2	19.0	
1953−011......	0.63	3	(140.0)	
2007−219......	0.29	3	(188.4)	
2007−303......	0.58:	3	(41.9)	
2039−682......	0.65	2	24.7	
2115−560......	0.46	3	(179.5)	
2149+021......	0.53	2	4.9	
2232−575......	0.69	2	23.2	
2309+105......	0.83	2	48.2	
2329−291......	...	3	(133.4)	sHe I
2337−760......	0.58:	2	30.1	
2359−434......	0.41	2	(24.8)	

NOTES.—M_g from Guseinov *et al.* 1983; if not available the Koester *et al.* 1979 value is given; the mass of WD 0346−011 is from McMahan 1989. For a few WDs without published values of the mass, M_g is estimated from $(U-B)$ and $(B-V)$ as in Koester *et al.* 1979. DD = confirmed DD; DD? = suspect DD; DD?? = suspect but less likely DD; WD+RD = white dwarf+red dwarf pair; WD+MS = WD with a visual MS companion; wHe = weak He lines; sHe = strong He lines. Values of $\lvert\Delta v_r^{\max}\rvert$ within parentheses refer to objects observed only during the first run, for which the errors may be considerably larger than average.

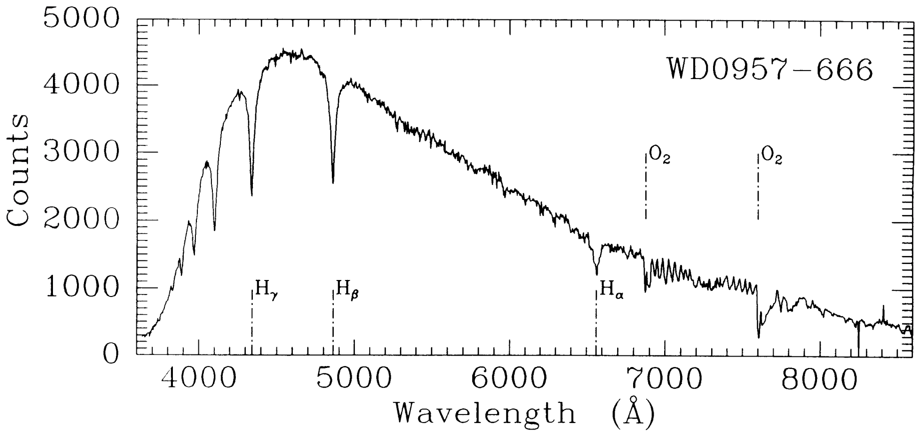

FIG. 1.—The composite spectrum of the double degenerate system WD 0957−666 obtained by combining the EFOSC observations with the grisms B150 (λ = 3600–5500 Å), O150 (λ = 5000–7000 Å), and R150 (λ = 6700–8600 Å). In the red side of the spectrum only terrestrial features are noticeable.

III. RESULTS

The object WD 0957−666 (first observed in 1988 January) soon showed sizable radial velocity changes ($\sim$200 km s^{-1}) and was reobserved in all subsequent runs. A composite spectrum covering the range 3600–8600 Å is shown in Figure 1. No sign of a red dwarf (RD) companion is visible at long wavelengths, and we conclude that the radial velocity changes are due to the presence of a degenerate companion, i.e., the object is a DD system. The period $P = 1^{\rm d}.15$ is the one which gives the best account of all the Δv_r's derived from the 28 blue spectra of this object. For the projected semiamplitude, we obtain $K \sin i = 104 \pm 20$ km s^{-1}. The radial velocity curve is shown in Figure 2. WD 0957−666 appears to be the shortest period DD system yet discovered.

The object WD 0419−487 is a WD + RD pair, as previously indicated by infrared photometry (Probst and O'Connell 1982), but its inclusion in our survey is unbiased and we can speak of an independent spectroscopic rediscovery. It shows fairly large radial velocity changes in both the WD Balmer lines and the RD TiO bands. The best-fit orbital elements are $P = 0^{\rm d}.54$, $K_{\rm WD} \sin i = 160 \pm 30$ km s^{-1}, $K_{\rm RD} \sin i \simeq 300$ km s^{-1}, somewhat more uncertain than $K_{\rm WD}$, and E = HJD 2,447,501.820. There is a modest Hα emission.

Also, WD 0034−211 is a WD + RD pair, and the same considerations about the previous photometric evidence apply. All Balmer lines show an emission core, very strong in Hα which is filled by the light of the RD companion responsible for the prominent TiO bands longward of $\sim$5000 Å (see Bragaglia *et al.* 1988). No detectable changes in radial velocity or line profile have yet been noticed (see Table 1).

In Figure 3 we plot the mass M_g of the program WDs versus the $B-V$ color. Individual masses are rather uncertain, with typical 1 σ errors of $\sim$0.1 $M_\odot$, occasionally even more, and possibly affected by a systematic underestimate (McMahan 1989). In spite of these uncertainties, we consider rather significant the fact that all the three binary WDs have a mass definitely below the minimum mass for helium ignition in a degenerate core ($\sim$0.5 $M_\odot$) and therefore most likely are helium WDs which formed from a low-mass star ($\lesssim 2$ $M_\odot$) having filled its Roche-lobe while first ascending the red giant

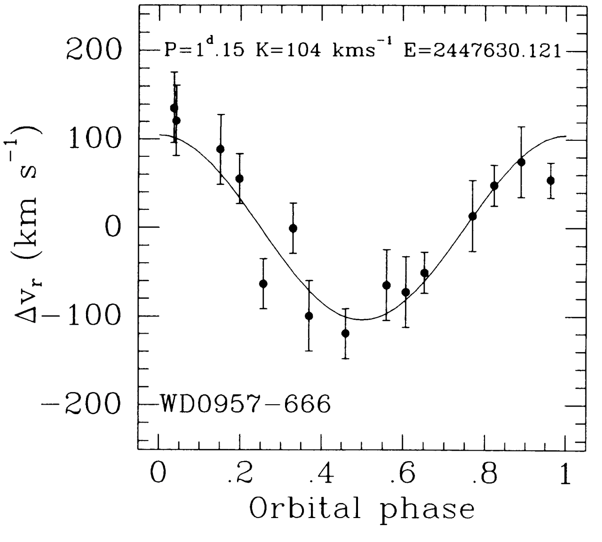

FIG. 2.—The radial velocity curve of WD 0957−666. The Δv_r values have been averaged within phase bins $\Delta\phi$ = 0.05. The sinusoidal best fit with the indicated orbital elements is also shown, and the epoch E of the ascending node is given.

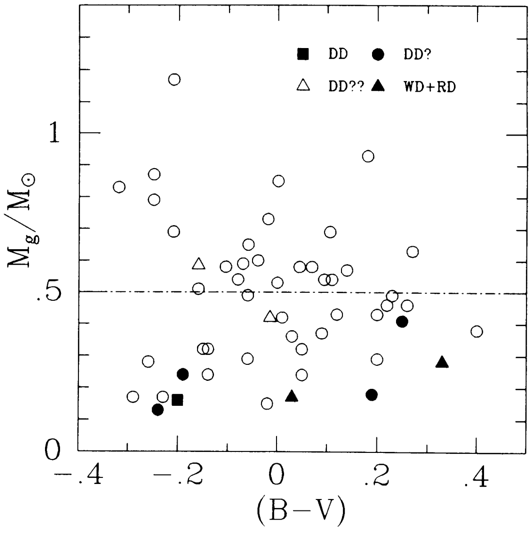

FIG. 3.—The surface gravity–derived mass of the program WDs (from Table 1) vs. their ($B-V$) color. With different symbols are shown the DD system, the two WD + RD pairs, the four best DD candidates, and the two less likely DD candidates.

branch. In Figure 3, different symbols are used for the WDs exhibiting maximum Δv_r values above 2 σ. It is clear that the mass of these WDs is systematically smaller than the average, in all but one case smaller than 0.5 $M_\odot$, suggesting a DD nature for at least some of them, and here we comment on individual objects.

WD 0047−524.—We have only two spectra, and their Δv_r is just above 2 σ. Given also its mass (< 0.5 $M_\odot$, but close to the mode of the sample), there is only a modest chance for this object to be a DD system.

WD 0109−264.—The spectra indicate a 4 σ radial velocity difference. Given also the very small mass, we regard this system as an excellent DD candidate.

WD 0346−011.—Of the four spectra, only one gives a Δv_r some 2 σ away from the other three. We do not consider it a likely DD system.

WD 0839−327.—The cross-correlation algorithm does not give significant radial velocity changes, but with the method of spectral count ratios, we consistently detect line profile variations in all accessible Balmer lines. The object is likely to be a DD system similar to L870-2, perhaps with a somewhat larger velocity amplitude.

WD 0940+068 and WD 1022+050.—Given also their small mass, we regard these WDs as good DD candidates.

Worth comment also is WD 0954−710, for which at an early stage we had one fairly large Δv_r, but which later did not show appreciable radial velocity discrepancies. We incline to dismiss this object from the list of DD candidates. Finally, we note in passing that some of the program DA WDs definitely exhibit helium lines (see Table 1).

IV. DISCUSSION

In summary, of our 54 WDs, we have one confirmed DD system, two WD+RD pairs, and two excellent and two good DD candidates. All these WDs have a mass considerably below the minimum core mass for the helium flash, which strengthens their interpretation in terms of Roche-lobe overflows during the RGB phase of stars with initial mass less than ~ 2.3 $M_\odot$ (Sweigert, Greggio, and Renzini 1989) and supports the theoretical expectation that all WDs with mass below ~ 0.5 $M_\odot$ are binary-born helium WDs. These findings set a strict lower limit of $\sim 3/54 \simeq 6\%$ to the fraction of interacting binary systems in an unbiased sample of evolved stars, which may increase to $\sim 7/54 \simeq 13\%$ if all the four suspected DDs will be confirmed as such. Even this figure could be regarded as a lower limit, as we may have missed some DDs (because of small sin i, bad phasing, etc.), or some of the program WDs may already be a merged DD (Iben 1990). We consider this result as a very significant, unbiased estimate of the frequency in nature of interacting binaries. Concerning the frequency of DD systems, this result indicates that there may be one such object every ~ 10 WDs, with a very firm lower limit of one every 50. Iben (1990) estimates one (helium) DD system every 23 WDs in the case $\alpha = 1$. This is certainly consistent with our findings, but if all the present candidates will be confirmed as DD systems, then a somewhat larger value of α may be appropriate. Certainly, it would be difficult to reconcile a fraction as large as 10% with $\alpha \lesssim 1$.

Limits on α can also be placed from the orbital elements of the two systems for which we have determined the period. To this end, we use the equations given by Iben and Webbink (1989) and adopt the WD mass from Table 1. Thus, for the WD+RD system WD 0419−487, we adopt $M_{\mathrm{WD}} = 0.28$ $M_\odot$, get $M_{\mathrm{RD}} = 0.15$ $M_\odot$ (the Roche-lobe overflow phase was clearly non-conservative), and finally derive $1.55 \lesssim \alpha \lesssim 6.40$, where the lower and upper limits pertain to the assumptions $M_1 = 1$ and 2 $M_\odot$, respectively. For the single-lined DD system WD 0957−666, the situation is considerably more complicated. For $M_{\mathrm{WD}} = 0.16$ $M_\odot$, very discrepant values of α are implied for the two CEEs. However, the actual mass of the WD may be considerably larger, given its fairly high temperature and then its possible sizable departure from the mass-radius relation for fully degenerate dwarfs. If so, the two values of α come closer to each other but still are very sensitive to the adopted sin i, M_1, and M_2. In practice, no strict limits on α can be placed by the known orbital elements of this system. In any event, as in the case of L870-2 fairly large values of α seem to be preferred (Iben and Webbink 1989).

Finally, we comment on DD systems as possible SN I precursors. Robinson and Shafter (1987) found no DD systems with $P < 3$ hr among 44 WDs and concluded that at the 90% confidence level the space density of such DDs is lower than that required to account for the SN I rate in the Galaxy. Of their WDs, 40 were DAs and four were non–DAs. By coadding our sample, we get a total 90 DAs, none of which is likely to be a DD with $P < 3$ hr, and therefore the space density of such DDs at the $\sim 99\%$ level is lower than the one estimated by Robinson and Shafter to be the minimum required to account for SN I's. The confirmed and suspect DDs found in our survey are most likely helium WD pairs, with a combined mass far below the Chandrasekhar limit, and the small Δv_r's suggest merging times much longer than the Hubble time. So, none of these objects qualifies as a SN I progenitor. Should we conclude that DD systems cannot be the precursors of type I SNs? We believe that this would be a premature conclusion, as such statement cannot apply to non–DA WDs, which remain basically unsurveyed; e.g., Robinson and Shafter observed only four non–DAs, and therefore no statistics were available. Actually, evolutionary arguments suggest that close binary evolution can favor the formation of carbon-oxygen WDs totally deprived of their hydrogen-rich envelope, therefore showing a non–DA spectral type (Bragaglia *et al.* 1990). Future surveys should therefore concentrate on this less-studied WD variety. Until now, we have observed 10 such objects, finding one excellent DD candidate. We will report about the non–DA survey as soon as we will have accumulated a sufficient data base.

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