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THE LOWELL SUSPECT WHITE DWARFS

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ABSTRACT

A survey of eighty-six suspected white dwarfs in the Lowell GD lists shows that fifty-four are in fact, white dwarfs. These stars have a considerably smaller mean proper motion and a somewhat bluer mean color than the 202 stars observed by Eggen and Greenstein. Otherwise, the GD stars are normal white dwarfs of lower space motion than the EG sample. Line profiles, equivalent widths, and central absorptions are normal. The properties of these degenerate stars of the low-velocity population are shown in graphic form.

Ten hot subdwarfs were found; twenty-two horizontal-branch stars or yellow subdwarfs were also found. A few especially interesting stars are noted, including GD 108, which seems to be of intermediate luminosity, and three very hot, probably helium-rich, O-type subdwarfs, GD 298, 299, and 300.

The GD white dwarfs are largely Population I kinematically, with a tangential velocity of 30 km $\sec^{-1}$; some, therefore, are descended from recently evolved massive stars. The blue high-velocity white dwarfs are all descended from stars near the present turnoff point in the old disk and halo populations, i.e., at most 1.5 $M_\odot$. The newly determined low-velocity white dwarfs, combined with those found by blue color alone, show some interesting differences in distribution of spectral peculiarities. The frequency, corrected for color differences, of the helium-rich DB stars is about triple that in the very high-velocity group. If accretion provides the normal DA star its surface hydrogen, it is odd that the helium characteristic is not suppressed in the GD stars. The carbon-rich, λ4670 stars are rare in the low-velocity group, again an effect opposite in sense to that predicted by stellar evolution, where the more massive stars should produce carbon. However, the number expected is small.

A few GD stars show peculiar line widths suggesting a rotation which, though appreciable, is smaller than expected from contraction of massive Population I stars.

New spectra are given of twenty-two white dwarfs of larger proper motion. Several new suspected red degenerates (EG 254, 256) have been found. A new type of white dwarf with molecular bands may exist in EG 248, which shows broadened CH and possibly C_2 features. The EG list is continued to EG 266.

I. INTRODUCTION

The discovery of new white dwarfs among blue stars of large proper motion is simple, given *UBV* colors; much observational information exists. The space frequency of blue degnerate stars, given a theory of cooling times, provides a guide to the expected number of red and black degenerate stars, for which the observations are still inadequate. An increase in the number of well-investigated hot objects (spectra, colors, space motions) provides a firmer statistical basis. The work of Eggen and Greenstein (1965*a*,*b*, 1967, hereinafter referred to as EG I, II, III) gives data on 202 stars of mixed population types. The stars observed came from the Lowell and Luyten lists, which are largely selections for large space motion. Of these, 65 percent had $\mu > 0''.2$ yr^{-1}, 14 percent had $\mu < 0''.2$ yr^{-1}, and 21 percent were chosen because of their blue color. The space motions derived (EG III, Table 5, Fig. 5) show the very mixed nature of the sample. Tangential velocities, v_T, less than 20 km $\sec^{-1}$ occur for 22 percent of the EG stars, but 24 percent have $v_T > 60$ km $\sec^{-1}$. The mixed-population characteristic may conceal some interesting correlations with spectroscopic peculiarity. From a theoretical point of view, many generations of low-velocity Population I stars have become degenerate and passed through the hot white-dwarf stage. Population I white dwarfs have parent stars of a wide range of masses. The high-velocity and old disk populations, however, now produce

* The observational data were obtained with the Palomar 200-inch telescope, and the analysis was carried out at the Institute for Advanced Study.

hot white dwarfs only from stars slightly more massive than the current turnoff point ($\approx 1.2\ M_\odot$). The pre–white-dwarf evolution times for the numerous Hyades white dwarfs are short ($< 5 \times 10^8$ yr), while that for the high-velocity stars is near 10^{10} yr, when the turnoff mass was near 1.5 $M_\odot$. Accretion of hydrogen may affect white-dwarf evolution, as it does in novae. Accretion will occur in close binaries (which are rare in Population II) and possibly in stars with very low space velocities.

In order to increase the sample size for Population I stars, I have already used spectra of faint stars found by blue color, without regard to proper motion (Greenstein 1966). Eggen (1968) has made extensive photoelectric studies of stars discovered by proper motion, and we may try to isolate the low-velocity objects from his lists. I present here spectroscopic observations of blue stars chosen for small proper motion in the Lowell Observatory proper-motion survey. These are the "Lowell suspect white dwarfs" of the two GD lists (Giclas, Burnham, and Thomas 1965, 1967). Eggen (1968) has studied some of these independently and quoted some of my early spectroscopic results. I chose to obtain spectra of eighty-six stars from the GD lists, of estimated blue color classes (−1 and 0), and of motion classes 1($\approx 0''.075$ yr^{-1}), 2($\approx 0''.150$ yr^{-1}), and 3($\approx 0''.235$ yr^{-1}). The spectra were mostly 190 Å mm^{-1} taken at the 200-inch prime focus, but some were at 90 Å mm^{-1}, and a few were taken with the Cassegrain image-tube spectrograph. Of the eighty-six, twelve stars have already been listed in EG III; a few GD stars were also listed by Luyten (1957, 1961) (from motion) and by Feige (1958) (from color). About 60 percent have *UBV* colors by Eggen, but my selection was independent except for those in EG III. The mean apparent magnitude is near 15.0, with a few as bright as 13.5. Generally, only one spectrum is available per star.

To demonstrate the nature of the sample, Figure 1 compares the frequency distribution of tangential velocities (uncorrected for solar motion). The top three histograms are given for samples out of EG I–III; proper motions and colors give v_T (on the assumption that the stars are all on our "upper sequence," when no other parallax source exists). Figure 1, *a* includes proper-motion stars of large angular motion; Figure 1, *b*, proper-motion stars of smaller motion. Figure 1, *c* contains stars first selected for observation by blue color; Figure 1, *d*, the GD stars ($\mu < 0''.27$) for which v_T can be computed. Note how similar the bottom three groups are in their median velocity, about 30 km sec^{-1}. The stars of large proper motion have a median velocity near 70 km sec^{-1}, and include a few with $v_T > 200$ km sec^{-1}.

II. RESULTS

Table 1 contains the available data on stars in the first GD list, many of which Eggen (1968) has observed; Table 2 is from the second GD list, and is in order of GD number and lacks photoelectric colors. The stars in Table 1 are ordered by right ascension. I have continued to extend the EG numbering system for convenience (EG I–III contain stars up to EG 202). The photoelectric colors, a newly defined quantity H' related to the reduced proper motion H, the spectral type, and remarks follow. Note that the normal definition of H differs by 5 log 4.74 from H'. Finally, three columns describe the Hγ line profile, with W the equivalent width in angstroms, A_c the central absorption depth, and w the width in angstroms at half-central depth. A cross in the W column indicates that Hγ is present but that the plate is too poor to measure; parentheses indicate uncertain values. In the "Remarks" column, n is the quantum number of the last hydrogen line seen. GD 104 was noted at Lowell as blue, with no detectable motion. The GD motions are only estimated, and where Luyten (1957, 1961) gives μ, it has been used in computing H'; otherwise, the mean μ for the Lowell motion classes was used. This accounts for some of the spread in v_T shown in Figure 1, *d*. The use of H' simplifies equation (2). The absolute magnitude M is related to H':

$$H' \equiv m + 8.38 + 5 \log \mu \,, \tag{1}$$

$$M = H' - 5 \log v_T \,. \tag{2}$$

Stars of a wide variety of spectra were found in the eighty-six GD stars classified spectroscopically. All fifty-four white dwarfs were of early type, because of the color selection. Among the thirty-two stars that are not white dwarfs, twenty-two are horizontal-branch stars or yellow subdwarfs which presumably appear blue on Lowell photographs because of their large ultraviolet excess. There are ten halo B and A stars and hot subdwarfs; GD 298 is one of the brightest sdO stars known, and deserves detailed spectroscopic analysis. Among the fifty-four white dwarfs, forty-four have only hydrogen lines (DA); nine have He I lines of various widths (DB); one seems to have a continuous spectrum (DC). In this rough first analysis, the very blue stars with broad, shallow

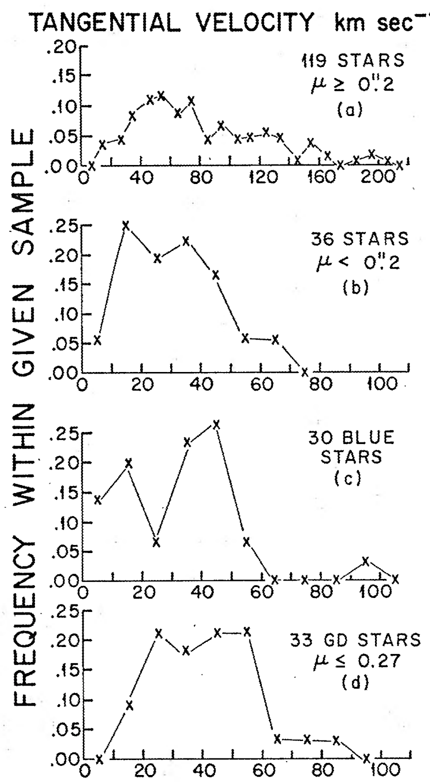

FIG. 1.—Histograms of the frequency distribution of space motions of white dwarfs within various samples with known spectra. The first three (*a*, *b*, *c*) show the stars in EG I–III, excluding the GD objects; the bottom (*d*) is the GD sample here studied. Sample (*a*), stars of large proper motion, plotted on a smaller scale; (*b*), stars found first by blue color. There are essentially no Population II stars in (*b*), (*c*), or (*d*).

lines are arbitrarily included in the DAwk class, although some could be hot subdwarfs with low helium content. The later-type stars found in the two GD lists are largely weak-line G and K stars and will be described in a forthcoming paper on the search for red degenerate stars. There are twenty-two of these, and to prevent unnecessary observations, I merely list their GD numbers: 103, 105, 118, 177, 181, 211, 213, 214, 217, 228, 239, 242, 252, 318, 334, 338, 345, 346, 350, 361, 367, 373.

In Figure 2 are plotted the photoelectric colors, the main sequence, the blackbody locus, and the usual boundary (from EG III) within which the DA stars fall. All the GD, DA, and DB stars fall in the normal region; the DC is on the blackbody line. The DB are clustered, as usual, near $B - V = -0.10$ mag, at which color Hγ has $W \approx 25$ Å normally in a DA star. Only one DB, EG 146 = GD 233 = L1002−62 has a deviant color, as previously noted. The crosses mark the G and K subdwarfs in the GD list.

TABLE 1

OBSERVATIONS OF WHITE DWARFS AND OTHER FAINT BLUE STARS IN THE LOWELL SUSPECT FIRST LIST

EG	GD	$B-V$ (mag)	$U-B$ (mag)	H'*	TYPE	REMARKS	Hγ W	A_c	w
203	2	−0.29	−1.21	16.6	DAwk		7	0.18	38
...	3	...	...	15.8	A	$n=15$	×	...	...
204	8	−0.22	−1.20	17.5	DAwk	Shallow lines	(6)	(0.14)	(27)
179	11	−0.23	−1.05	19.5	DAs	Poor plate	×	...	...
205	13	...	...	16.8	DA		30	0.48	32
206	20	...	...	17.3	DA	Feige 17; poor plate	(35)	(0.43)	(65)
207	31	+0.21	−0.68	19.4	DA	PHL 1358	41	0.58	54
208	45	+0.08	−0.68	19.4	DAs	BPM 85584	35	0.54	48
209	64	+0.23	−0.61	16.5	DA		43	0.64	54
210	71	−0.25	−1.16	18.3	DAwk	LTT 11733	14	0.31	33
211	72	0.00	−0.82	19.8	DA		31	0.47	55
212	77	+0.13	−0.64	20.0	DA		43	0.48	(70)
213	80	−0.21	−1.19	19.1	DAwk		17	0.27	52
214	83	+0.19	−0.52	20.5	DAs		23	0.53	27
215	84	+0.08	−0.79	20.4	DC	Possible weak lines	...	...	...
216	85	−0.11	−0.99	19.2	DBs	Relatively sharp	...	...	...
...	87	+0.22	+0.02	17.0	A	$n=16$	×	...	...
217	91	+0.20	−0.52	20.0	DAs	LTT 12215	×	...	...
218	98	−0.13	−0.94	19.2	DA		23	0.42	35
219	99	+0.19	−0.59	19.8	DA	Slightly sharp	33	0.57	36
...	104	−0.35	−1.23	...	sdOp	Zero motion	(4)	0.17	(22)
...	108	−0.21	−0.91	16.4	sdB	No He; $n=10$; nearly DAwks	9	0.37	18
...	113	−0.09	−0.49	14.4	Bp	LB 566; $n=17$ Halo. Weak He I, Si II	10	0.46	14
220	117	+0.33	−0.63	21.0	DAwk	Poor plate. Sharp lines	×	...	...
221	125	−0.08	−0.98	18.4	DAn	Ton 556	23	0.41	42
184	140	−0.06	−0.98	16.8	DA		30	0.47	48
186	148	+0.06	−0.68	19.7	DA		47	0.64	60
187	153	−0.25	−1.18	18.3	DAwk	LTT 13724. Very weak H	(13)	(0.23)	(27)
...	159	+0.20	−0.02	15.6	HBA	$n=16$; very weak Ca II	×	...	...
189	163	+0.03	−0.81	19.5	DA	LTT 14141	34	0.50	49
222	165	+0.14	−0.59	19.7	DA	LTT 14236	×	...	...
190	175	+0.40	−0.42	20.2	DAwk	Poor plate	×	...	...
191	178	+0.09	−0.65	18.4	DA		37	0.49	57
192	185	0.00	−0.81	18.0	DA	BPM 77964	32	0.48	47
223	189	+0.25	−0.55	19.5	DA		×	...	...
193	190	−0.10	−1.00	17.5	DB		...	...	...
194	198	−0.11	−0.94	18.3	DB		...	...	...
224	205	−0.09	−0.98	19.2	DBn	BPM 92077	...	...	...
...	210†	+0.43	+0.12	...	sdA–F	BPM 79017. Very weak Ca II; $W(K)=50$ mÅ	13	0.48	15
225	215	+0.25	−0.62	19.0	DAss	Poor plate	(23)	(0.61)	(21)
201	219	+0.06	−0.66	16.1	DA	BPM 94172	38	0.53	56
226	222	−0.12	−0.88	17.4	DA	BPM 94484	×	...	...
146	233	−0.05	−0.73	19.8	DB	L1002−62= LTT 8579	...	...	...
227	234	−0.04	−0.83	18.8	DA		30	0.46	52
228	236	...	...	20.7	DA		34	0.52	47
229	240	...	...	21.2	DAwk	PHL 380, Feige 106. Very hot	(6)	(0.17)	(30)
230	243	...	...	18.3	DBn		...	...	...
231	244	...	...	21.2	DA		35	0.53	52
232	245	...	...	17.8	DA		26	0.49	36
233	246†	−0.32	−1.23	18.0	DAwk	BPM 97859. Very hot. No He II	(7)	(0.13)	(40)

* H' is defined by equation (1) and is related to the reduced proper motion, H.

† Stars listed in Table 4 of EG III.

Note that they lie where red degenerate stars would be found, and are a serious source of error in estimating the space density of red degenerates.

The star GD 108 occupies an unusual location in Figure 2, at the extreme boundary of the normal, hydrogen-line-blanketed, DA colors; its spectrum is unusual, shows wide Balmer lines to $n = 10$, and is nearly a sharp-line DAwk; it may be that rare type, a subluminous B star; sdO stars are more easily found. The halo star, GD 113, is classified as

TABLE 2

OBSERVATIONS OF WHITE DWARFS AND OTHER FAINT BLUE STARS IN THE LOWELL SUSPECT SECOND LIST

EG	GD	Color Class	H'	Type	Remarks	$H\gamma$ W	$H\gamma$ A_c	$H\gamma$ w
...	298	0	13.8	sdO	4686=4471>4340	?	...	...
...	299	−1	14.8	sdO	4686=4340>4471	×	...	...
...	300	−1	16.8	sdO	4471>4686>4340	?	...	...
234......	322	−1	17.8	DA	LB 2520	×	...	...
235......	323	−1	18.8	DBp	He I very weak; LB 2539	?	...	...
236......	336	−1	18.8	DA		×	...	...
237......	344	−1	19.3	DA		×	...	...
238......	357	−1	20.2	DA	BPM 91679	36	0.56	46
239......	358	−1	18.3	DB		×	...	...
240......	363	−1	19.3	DA		(42)	(0.60)	(33)
241......	375	−1	19.3	DA	BPM 92960	×	...	...
242......	378	−1	18.3	DB		...	...	...
243......	391	−1	17.8	DA		26	0.41	42
244......	394	−1	17.3	DAwk		17	0.28	32

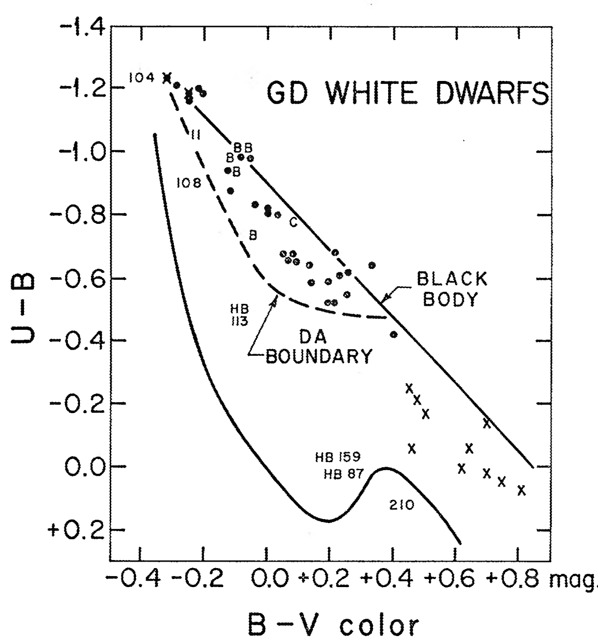

FIG. 2.—*UBV* colors of GD stars; dots are white dwarfs of type DA; *B* and *C* are DB and DC types Dots with crosses are hot, weak-lined (DAwk). Individual interesting stars are identified by GD number HB means possible horizontal-branch star; crosses are weak-line G or K subdwarfs. The GD white dwarfs fall in the same region of the *UBV* plane as do ordinary white dwarfs.

Bp and plotted with the symbol HB; the peculiar colors of GD 87 (classified A, probably HBA) and of GD 159 (HBA) go with their spectra. They may be "blue stragglers." GD 210 has a particularly strange color and spectrum.

III. SPACE MOTION OF THE DA STARS

Since most of the GD stars are single, lack parallax measures, and have only estimates of μ, v_T can be derived only roughly. The DB stars will be treated separately; they would increase the $\langle v_T \rangle$ here obtained. An obvious concern may arise that many stars of intermediate luminosity might exist. If the GD stars were intrinsically brighter than white dwarfs, the v_T determined from absolute magnitudes derived from colors (under the assumption of the white-dwarf C-M relation) would be very small. Let us estimate M by methods used in EG I; for $(U - V) < -0.9$, stars are on the "upper sequence," with

$$M_u = 11.65 + 0.85(U - V) . \tag{3}$$

Stars with $-0.9 < (U - V) < 0.0$ can be on the "upper" or "lower" sequence with

$$M_l = M_u + 1.5 . \tag{4}$$

However, to obtain the worst answer, we will always use M_l for these yellow stars. There are eleven DAwk stars with $(U - V) < -0.9$; we use equation (3) to obtain their $\langle M_u \rangle$, derive $\langle H' \rangle$, and find $\langle \log v_T \rangle = 1.54$ or $\langle v_T \rangle = 35$ km sec^{-1} (if statistical corrections are neglected). The nineteen DA and DC stars with $(U - V) > -0.9$ have $\langle \log v_T \rangle = 1.30$, $\langle v_T \rangle = 20$ km sec^{-1}. The entire sample gives $\langle \log v_T \rangle = 1.46$ or $\langle v_T \rangle = 29$ km sec^{-1}. These numbers differ slightly from the median velocities near 30 km sec^{-1} given from Figure 1; the systematic difference arises since we assumed here that the yellower stars are on the lower sequence. No plausible argument can make the GD stars fit on the horizontal branch, which would multiply the space motions by 100 and also give incorrect *UBV* colors. If they are considered subdwarfs near $M = +6$, the motions are increased by 10 to $\langle v_T \rangle = 290$ km sec^{-1}, just within the possible range. However, for reasonable mass, the surface gravity would then be 10^6 rather than 10^8 cm sec^{-2}, and the Stark-broadened hydrogen lines would be weakened by about $(10^{-2})^{2/5}$, or a factor of 6. The spectrophotometric results will show this to be impossible.

Without correction for solar motion, or for the stellar radial velocity, the tangential motions are those of either a relatively young group of stars or a group containing more than half Population I and the rest old disk stars. A less probable hypothesis is that the GD white dwarfs and the white dwarfs found by blue color are, in fact, descended from a pure Population I sample, but from an old one. For example, it has been suggested that encounters between stars and gas clouds gradually increase the velocity dispersion from the 8–15 km sec^{-1} characteristic of B stars to the 30 km sec^{-1} typical of the G and K stars. However, since the mean luminosity of the GD stars is near +11, their cooling times are short ($<2 \times 10^9$ yr), and the transfer of kinetic energy should be small in this short interval.

IV. SPECTROSCOPIC PECULIARITIES AND STELLAR EVOLUTION

The most obvious way in which the GD white dwarfs differ from those with large proper motion is in the higher frequency of DB, or helium-rich stars. While the DB stars occur only in a narrow range of color, the EG I–III white dwarfs include this color range (see EG I, Fig. 6), although they also include many cooler degenerates which are absent in the blue GD stars. The statistics of the occurrence of DB stars are given in Table 3; N is their number and S is the sample size. Selection of stars for the sample was based on various criteria, as described. The ratio N/S is very high for the GD stars and the stars found by blue color alone (Greenstein 1966), and lowest for the stars of large proper motion in EG I–III. There is one obvious systematic error arising from the narrow range of colors within which DB-type spectra may appear. We may correct for this in an approximate fashion. Order the $U - V$ colors in intervals 0.20 mag wide and count the number n of white dwarfs of known color ($n < N$) within the DB color range. From the observations, the DB range is $-1.40 < (U - V) < -0.61$. The size of the sample is s; let us normalize other samples to the distribution of colors found for sample A (the GD stars), where $(n/s)_A = 17/36$. The numbers of stars are small, and I combined samples B and E. The corrected fraction of DB stars in sample i is

$$(N/S)'_i = (N/S)_i (n/s)_A (n/s)_i^{-1} . \quad (5)$$

While the numbers N are small, the results seem significant. These correction factors reach 40 percent, but do not change the behavior already indicated by N/S in Table 3. There is little doubt that the ordering of the samples in Table 3 is one of decreasing frequency of DB stars. Thus, Population I white dwarfs have a much higher probability of showing surface helium (within the proper range of color, and probably of effective temperature) than do degenerate stars of large proper motion in the old disk or halo population. The suggestion that accretion will provide the surface hydrogen so common in DA hot white dwarfs meets the immediate difficulty that accretion should be most effective in Population I, because of the low space motion, and it is in Population I that

TABLE 3

FREQUENCY OF DB STARS

Sample	Criterion	N	S	N/S	$(N/S)'$
A..........	This paper, blue GD stars, $\mu < 0\overset{''}{.}27$	9	54	0.17	0.17
B..........	Found by blue color (Greenstein 1966)	3	25	0.12	0.12
C..........	All EG I–III	11	202	0.05	0.07
D..........	EG I–III, omitting blue and GD stars	7	177	0.04	0.06
E..........	EG I–III, $U-V$ known, $\mu<0\overset{''}{.}2$	3	58	0.05	0.05
F..........	EG I–III, $U-V$ known, $\mu>0\overset{''}{.}2$	3	110	0.03	0.04

the helium-rich surface is observed. Over fifteen white dwarfs are observed in the Hyades and Pleiades, mostly of type DA; with the N/S of sample A we might expect two DB stars but find none. Possibly clusters are particularly favorable to hydrogen accretion, if the red-giant stellar winds are decelerated so that the gas remains bound in the cluster. No strong 21-cm H I emission is associated with clusters. Mass exchange in close binaries would also favor hydrogen accretion and conceal the helium. Such binaries are most common in Population I, which seems to have the larger number of DB stars. The results of Table 3 are therefore quite unexpected. The novae, pre-white-dwarf binaries of type DA (e.g., WZ Sge) are members of the old disk population; their hydrogen, however, comes from the companion.

We must not generalize so rapidly from the large fraction of DB among the GD stars that we conclude that they are absent at high velocity. In Figure 5 of EG III, it was noted that some DB stars had high velocity and a peculiar distribution in the (U,V)-plane. Table 4 contains the DB stars from EG I–III (some of which were first found from color surveys). The v_T is derived from $(U^2 + V^2 + W^2)^{1/2}$, and if the DB stars were merely helium-rich subdwarfs, then at $M = +5$ the v_T would be intolerably high.[1] The $\langle v_T \rangle$ from Table 4 is 60 km sec^{-1}. Four of the nine DB stars in the new GD list lack colors. We adopt $\langle M \rangle = +11.0$ and find $\langle \log v_T \rangle = +1.52$ or 33 km sec^{-1}, half the EG value. If $\langle M \rangle$ is different, the line profiles might show different broadening in GD stars and those of Table 4. But, for the moment, we may say that DB stars exist in both main populations.

[1] Two binaries, EG 63 and EG 145, provide reliable luminosities.

The production of helium in the cores of all stars is followed by carbon production only in stars of appreciably higher mass than the Sun. Helium white dwarfs may have cores of carbon or heavier elements, and therefore cool more rapidly than white dwarfs with a hydrogen surface and a helium core (descended from stars of 1 $M_\odot$). Greenstein, Truran, and Cameron (1967) have suggested that gravitational diffusion of H with respect to He may occur in stars otherwise stabilized against convection. If the diffusion time scale is comparable to that of cooling through the DB luminosity and temperature range, interesting differences in He/H at the surface will occur, from star to star. A hot DB at $M_V = +11$ will have a cooling time of $2 \times 10^9\ A_i^{-1}$ yr, where A_i is the mean molecular weight of the interior. If the envelope composition differs, the heavy-element content Z affects the opacity, and the lifetime is also proportional to the envelope value $Z^{2/7}$. If this opacity effect is neglected, the difference in lifetime between a helium and a neon core is 4×10^8 yr. This exceeds the lifetime of the horizontal-branch stage, where gravitational diffusion has been invoked; the gravitational field is also larger in the white dwarf.

The carbon-abundance anomaly of the λ4670 stars is worth further discussion with regard to population differences. The λ4670 stars are rare, only six being known in the

TABLE 4

SPACE MOTIONS OF DB STARS IN EG I–III

EG	Name	v_T (km sec^{-1})	Remarks
3......	LB 433	10	Found by color; μ small
63......	LDS 235 B	60	
77......	Ton 573	95	Found by color
133......	L1573–31	50	
145......	LDS 749 B	110	
146......	L1002–62	20	= GD 233; μ=0″.27
149......	L930–80	65	
153......	LDS 785 A	60	

266 EG stars; the band is detectable only on excellent spectra, and a few possible λ4670 stars are listed in Table 6. Four are in the high-velocity Wolf 219 group, and the two others are in the binary systems G87–28/29 and HD 77408/G47–18. Thus, excess surface carbon seems to depend on group membership or duplicity, while excess helium goes with low space motion. The cooling time to the λ4670 mean luminosity is large ($\langle M_V \rangle = +13.1$), about $2.5 \times 10^{10}\ A_i^{-1}$ yr, or about 2×10^9 yr for a carbon core, and the parent star is therefore more massive than stars at the present turnoff point for the old population. Since the Wolf 219 group has high velocity, the suggested age is large, possibly nearly that of the globular clusters. A mass for the parent stars much larger than 1.5 $M_\odot$ seems implausible. We thus require carbon production at a rather low mass to explain the λ4670 peculiarity. Alternatively, the effect of duplicity or cluster membership will have to be invoked; the two binaries are physically wide pairs, however.

V. SPECTROPHOTOMETRY: INDIVIDUAL STARS AND ROTATION

In EG I, Figure 8 showed the correlations between color, Hγ equivalent widths W, and half-widths w. These mean relations are replotted in the present Figure 3, together with the present measurements for the GD stars. The accuracy is low, since only one plate is used and systematic differences in setting the level of the continuum enter quadratically. The central depth, A_c, is more accurate and is shown in Figure 4; the dashed curve for eleven normal white dwarfs is obtained from spectra of the same dis-

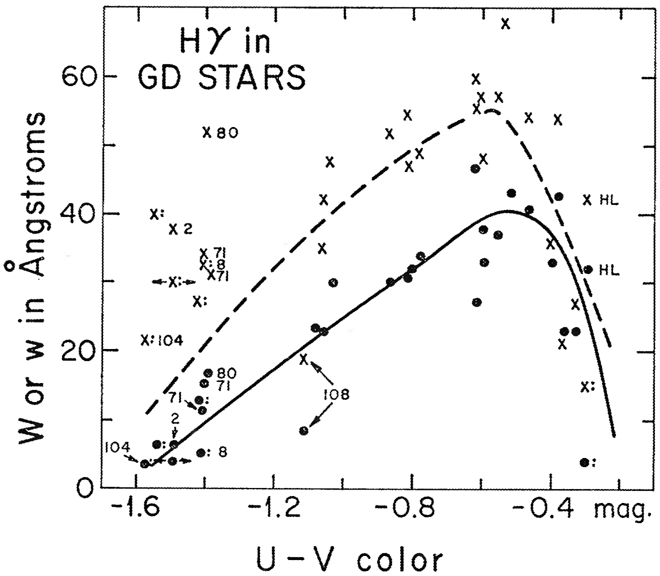

FIG. 3.—Parameters of the observed Hγ profile as a function of photoelectric color. Dashed line gives width at half-central depth *w;* solid line, equivalent width *W*, for the white dwarfs in EG I. *Crosses,* half-widths *w; dots,* equivalent widths for the GD stars. Individually interesting stars are indicated by GD numbers; colons indicate poor measures. The star HL is EG 265.

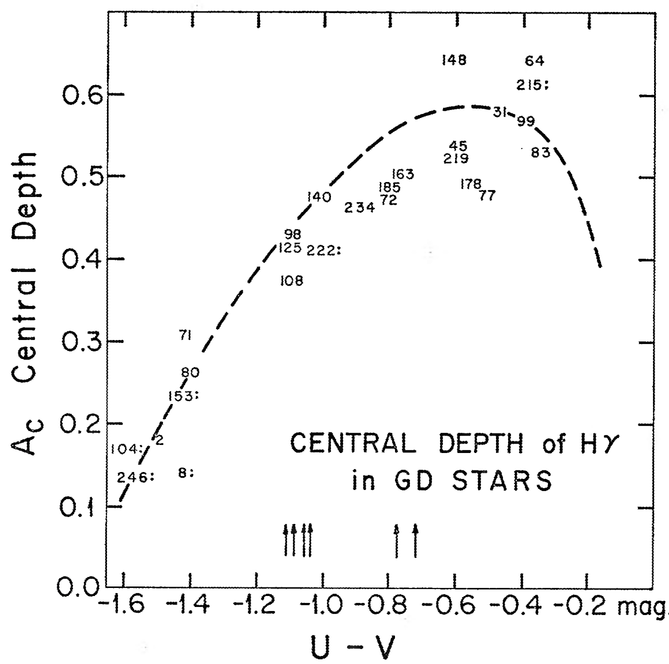

FIG. 4.—Central absorption depth, A_c, as a function of color. Dashed curve is based on older and more accurate measures in Greenstein (1960); numbers are individual GD stars; colons indicate poor measures. The DB and DC star colors are marked with vertical arrows; for them $A_c < 0.1$.

persion, more accurately measured in Greenstein (1960). There is no significant difference between the GD stars and other white dwarfs, except for a few objects marked. When $(U - V) < -1.20$, the DAwk stars have W slightly, and w markedly, larger than expected. The excess W can be explained if some of the Feige and Humason-Zwicky hot stars used to calibrate the relationship in EG I were, in fact, hot subdwarfs with low surface-helium content. Since the resolution is near 5 Å, the observed value of A_c is near the true one for $W > 20$ Å, or for very wide lines. The drop in A_c indicated by Figure 4 near $(U - V) = -0.30$ probably arises from corrections caused by the instrumental profile. Then deviations from the curve near $(U - V) = -0.30$ are meaningless because of the extremely steep decrease of W with color.

The excessively weak lines of GD 108 are most peculiar. If a star has sufficiently high He/H, $W(\mathrm{H}\gamma)$ begins to decrease before visible He I lines are produced; probably w would be normal for the color. Given the low resolution, the observed low value of w might be acceptable. Note that the $U - V$ color is close to that at which DB stars are found. The color might be grossly wrong, by 0.3 mag, but the star lies on the normal $(A_c, U - V)$ relation in Figure 4. Finally, the surface gravity might be lower than in a white dwarf, with a value between 10^6 and 10^7 cm sec^{-2}, i.e., $M \approx +7$, a faint hot subdwarf. The variability in the surface He/H ratio must be very large. Thus EG 86 has small space motion, $U - V = -1.61$, and is of type DO, showing He II. But GD 246 at $U - V = -1.55$ has only shallow Balmer lines. The excessively large values of w occurring for GD 2, 71 (poor plate), and GD 80 are interesting, if they are confirmed. Rotation would produce this effect, although no reduction of A_c is seen in Figure 4. The dashed curve in Figure 3 gives a normal value of 20 Å for w; their observed $\langle w \rangle = 40$ Å. For a damping Voigt profile, the half-widths add linearly, so the rotational width is also 20 Å or the projected velocity, $v = 1400$ km sec^{-1}. The ratio of kinetic to potential energy at the surface is Rv^2/GM. Perturbations of figure of the star would be small, and would be insufficient to stabilize a massive white dwarf as discussed by Ostriker and Bodenheimer (1968), in which $v \approx 3000$–7000 km sec^{-1}. Undeformed objects with normal temperature distribution at such high rotational velocities would produce lines about 100 Å wide. For constant W, A_c would be reduced by a factor of 5, i.e., to about 5–10 percent. Such lines might be visible on photographic spectra and certainly could be detected by a spectrophotometric scanner. If angular momentum were conserved in evolution from a B star of Population I, the expected rotation of a white dwarf would be even larger than above. If rotational braking of convective main-sequence stars is common, so that rotation is confined to the cores, the shrinkage in radius to the white-dwarf stage is less extreme. Nevertheless, loss of angular momentum through stellar winds and magnetic fields must occur to explain the generally low rotation of the white dwarfs of all populations, and certainly of the GD stars. The late-type DAs stars near $U - V = -0.4$ have quite sharp line cores and cannot be rapidly rotating.

VI. OTHER TYPES OF STARS

The nondegenerate stars in Tables 1 and 2 deserve attention, especially the strange group of very hot O subdwarfs GD 298, 299, 300. To isolate the most interesting, Table 5 provides a résumé of the most peculiar spectra found, including very hot DAwk stars, sdO, and halo stars. The DAwk stars, which should be the youngest white dwarfs, may have recently completed rapid evolution by neutrino emission; they deserve study for short-period light variation such as exists in HZ 29 and in EG 265 (HL Tau 76; see below).

The ten spectroscopically nondegenerate stars of Table 5 differ also in their reduced proper motions. Their $\langle H' \rangle = 16.1$, while the DAwk have $\langle H' \rangle = 17.9$. Since the DAwk fit the spectrophotometric data as bright $(\langle M \rangle \approx +10)$ degenerate stars, we omit them, and consider only the sdO, sdB, HB, and peculiar A or B stars in Table 5. This is a very mixed group. With the velocity dispersion characteristic of the GD degenerate stars,

$\langle \log v_T \rangle = 1.46$, we would derive $\langle M \rangle = +8.8$, which seems quite unreasonable. If instead we assume a mixture of horizontal-branch stars and hot subdwarfs, with $\langle M \rangle = +3.5$, then $\langle \log v_T \rangle = 2.52$, a value corresponding to a very high-velocity halo population. This seems too high, and we may prefer to consider most of the stars to be of lower luminosity, like +28°4211, HZ 44, and the blue components of SS Cyg variables (Eggen 1968, p. 124). In that case, most must be very subluminous and possibly variable. Objects that are clearly subluminous are GD 104 (zero motion), 108, 240, 246, 323, and possibly 394; some resemble nuclei of planetary nebulae, but no He II is visible. Members of the remarkable group of sdO stars, GD 298, 299, and 300, resemble HZ 44, and deserve high-dispersion analysis. At high galactic latitude, and separated by nearly 10 degrees, their spectra are remarkably similar. The proper motions apparently differ too much to permit them to be a moving group (μ respectively: class 2, P.A. 125°; class 1, P.A. 160°; class 2, P.A. 210°). The ratio of He/H seems quite different in the three, as

TABLE 5

THE HOT WHITE DWARFS, SUBDWARFS, AND HALO STARS

GD	EG	Type	Remarks
2......	203	DAwk	Possibly subdwarf, no He
3......	...	A	Normal or horizontal branch
8......	204	DAwk	Shallow lines
71......	210	DAwk	Shallow lines
80......	213	DAwk	Wide lines
87......	...	A	Horizontal branch or blue straggler
104......	...	sdOp	No He. Zero motion
108......	...	sdB	No He. Very broad H, nearly white dwarf
113......	...	Bp	Halo B star, weak He I and Si II
153......	187	DAwk	Possibly subdwarf, no He
159......	...	HBA	Or blue straggler
210......	...	sdA–F	Peculiar A–F, or extreme weak-line subdwarf
240......	229	DAwk	Very hot
246......	233	DAwk	Very hot
298......	...	sdO	He rich?
299......	...	sdO	He rich?
300......	...	sdO	He rich?
323......	234	DBp	Sharp lines of He I
394......	244	DAwk	Possibly sharp cores

does the line broadening and ionization. The tangential velocities are dominantly southward but differ considerably in size. If we rely on the (unknown) radial velocities to make the space-motion vectors similar, they must be large compared with the U, V, W derived without regard to the radial velocities. For example, at 40 pc distance (luminosities just above the top of the white-dwarf sequence) differences of 20 km sec^{-1} in radial velocity might suffice. If the distance is 200 pc, the luminosities are like that of HZ 44 and the velocity differences should exceed 150 km sec^{-1}.

VII. OTHER NEWLY OBSERVED WHITE-DWARF SPECTRA

Table 6 contains white dwarfs confirmed spectroscopically in my continuing survey of the Lowell, Luyten, and other lists. Spectra and some colors are available; many have large proper motions and are of high velocity (EG 249, 250, 254, 256, 258, 259). A few faint blue stars of small motion are included, as are yellow and red degenerates found in the course of a special search for cool white dwarfs. The red objects EG 254, 256, for which better spectra are needed, are important for the theory of cooling times (Greenstein 1969). Further progress in this search may require image-tube spectra of much fainter stars, since the percentage of successful discovery has been very low compared with the ratio of successes in blue stars. Table 6 contains seven white dwarfs in binary systems; EG 247 is still a doubtful, possibly intermediate object discussed in EG III. No special statistical treatment of the objects in Table 6 is required. They are far less blue than the GD stars, have larger $\langle\mu\rangle$, and must resemble stars in EG I–III.

Among the blue stars of special interest is EG 265, which may vary in brightness (Landolt 1968) in a rough 12.5-minute cycle. It was found superposed on the Taurus dark nebula by Haro and Luyten (1961), and is sometimes referred to as HL Tau 76. Landolt claims that his image-tube spectra show the Ca II K-line superposed on a DA spectrum, but I do not find it on a good prime-focus spectrogram. Note that in the

TABLE 6

NEW SPECTRA AND COLORS OF WHITE DWARFS FOUND FROM OTHER LISTS

EG	Name	μ	V	$B-V$	$U-B$	Type	Remarks
245....	G218–8	0.32	14.1	0	...	DC	LTT 17144; cpm
246....	LTT 375	0.60	14.53	+0.62	−0.14	DC	
247....	G191 B2B	0.10	11.8	−0.32	−1.20	DAwk	cpm; possibly subdwarfs
248....	G99–37	0.27	14.58	+0.46	−0.53	DGp	New type; bands at λλ4300, 4380, 4680
249....	G51–16	0.64	15.7	+0.35	−0.54	DAs	
250....	G195–19	1.56	13.79	+0.30	−0.66	DC	Possible shallow H lines
251....	G195–42	0.30	15.3	0	....	DC	Possible λ4670
252....	G42–33	0.34	15.37	+0.36	−0.49	DC	Possible λ4670
253....	G53–38	0.55	15.33	+0.32	−0.48	DA	LB 577
254....	G119–11	0.59	15.59	+1.11	+0.68	DK	Poor plate; possibly sdK
255....	G198 B6B	0.10	16.0	−1	...	DA	cpm
256....	LP 495–171	0.25	16.38	+1.27	+0.67	DMp	+14°2513B, could be sdMp; cpm
257....	Feige 91	0.06	13.38	−0.28	−1.07	DAs	Hot
258....	G225–68	1.61	15.7	+1	...	DC	LP 101–16; cpm dM5e
259....	G138–47	0.27	16.9	+0.41	−0.50	DC	Poor plate; cpm
260....	LTT 7873	0.36	15.0	+0.18	−0.52	DA	Light variation suspected
261....	G210–36	0.27	13.4	0	...	DA	LTT 16093
262....	G187–15	0.50	15.5	−1	...	DC	LTT 16151
263....	G216 B14B	0.07	15.5	−1	...	DA	cpm sdK8
264....	LTT 9491	0.26	14.4	a	...	DC	PHL 459
			Not Proper-Motion Stars				
265....	HL Tau 76	...	15.2	+0.20	−0.50	DA	Light variable; spectrum changed?
266....	LB 378	...	15.5	0	...	DB	

spectrum reproduced by Landolt the sharp feature is not at the K-line wavelength (as measured on the print) and is far too strong to be interstellar. The modulus from equation (3) gives a distance of 60 pc, so the star is not physically immersed in the Taurus dark nebula. The star should be followed spectroscopically for possible variation.

The most interesting spectrum is that of EG 248 (=G99–37). Only one 400 Å mm^{-1} spectrum exists; it shows a strong, broad absorption with a core near λ4300, and weaker broad features near λλ4380, 4680. The most plausible interpretation is that both the λ4300 G-band of CH and the Swan bands of C_2 are present, highly pressure-broadened, and that EG 248 is a carbon-rich star like the λ4670 objects. The color is slightly above the blackbody line, a circumstance possible if the B-magnitude is increased by about 0.10 by blanketing. Such a correction to the blackbody line would give $(B - V)_0 = +0.36$ and $(U - B)_0 = -0.43$, values corresponding to a temperature of about 7600° K, and close to other cool λ4670 stars (which lie below the blackbody line). If the λ4300 feature is CH and the others are C_2, the molecular equilibria cannot be dominated by the formation of CO. Then, not only are the C/H and C/O ratios higher than normal (consistent with ^{12}C formation by helium burning) but the star's envelope must have retained (or accreted) hydrogen. The luminosity can be estimated from the proper motion; if the space motion is typical of the stars in EG I–III, for which the median $v_T =$ 33 km sec^{-1}, $M = +12.5$. The uncorrected colors predict $M_u = +11.6$ or $M_l = +13.1$. If the star were an unusual Population II subdwarf, with low metal and high carbon content, the color predicts $M \approx +5.5$. The v_T derived, 800 km sec^{-1}, makes this hypothesis implausible. White dwarfs with blurred molecular features now include the λ4670 carbon type with C_2 bands in both hot and cool objects, EG 248 with a CH band, the cool DM stars with weak TiO, and EG 129 with its still unidentified λ4135 band. Thus, most of the common stellar bands have been recognized in degenerate stars, with the interesting exception of CN. Whether the metallic hydrides exist, whose bands are strongest in the yellow and red, is still unknown.

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