# 9. NEW SPECTROSCOPIC RESULTS ON SUBLUMINOUS STARS, V

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**Abstract.** Determination of temperature and surface gravity by colors and hydrogen-line profiles have been carried out for hot halo stars. A narrow horizontal branch is found stretching to above 40000 K; the hot O subdwarfs show a nearly vertical sequence, dropping towards the hot white dwarfs.

Spectra for 285 white dwarf stars have been obtained, and the classification scheme is reviewed. Theoretical problems of these spectra remain, largely, unsolved.

The red subluminous stars found by Eggen were studied spectroscopically; among 68 stars only one new red degenerate star was found. The others are very metal-poor, high-velocity stars with large ultraviolet excess.

## 1. Introduction

I will discuss three separate topics (A) the approach to the white-dwarf stage among the hot-horizontal branch and subdwarf B and O stars, (B) recent data on normal and peculiar white dwarfs, (C) theoretical problems, (D) the suspected red subluminous stars.

### A. THE SPECTROSCOPIC EVIDENCE ON THE PRE-WHITE DWARF STARS

The discovery of interesting varieties of stellar spectra with a goal of determining composition has been successful, among ordinary stars. Interesting composition differences and the effects of nucleosynthesis are thus observed. For the degenerate stars we have not been so optimistic, since pressure broadening, gravitational separation, and unknown opacity sources present as yet unsolved problems when we attempt to deduce the true composition of the star. Since some hot degenerate stars show effects of nucleosynthesis in the form of low-hydrogen content, high-helium and high-carbon content, some core material has been brought to the surface; other cool degenerate stars show weak or no lines i.e., have low-surface metal content. In the pre-white dwarf stage, it was suggested in 1960 that the surface He/H ratio was low; later observations confirmed this, for halo horizontal-branch stars. My recent work on halo blue stars was presented as the Henry Norris Russell Lecture of the American Astronomical Society, and will be published in detail later. The major relevant features are: (1) The sample of halo stars were selected by blue color only, in the galactic polar caps, not by proper motion. (2) The UBV colors determine effective temperature, $T_e$, moderately well from 12000 K up to 30000 or 35000 K, independent of the surface gravity $g$. (3) The model atmospheres available now predict hydrogen-line profiles as a function of $(T_e, g)$ in the desired range. My spectra (from 18 to 190 Å mm$^{-1}$) yield profiles of sufficient accuracy to determine $g$, given $T_e$.

I selected 170 stars from 9th to 16th mag, with negative B − V colors; the brighter

*Luyten (ed.), White Dwarfs,* 46–60. 

stars are largely uninteresting, in that they seem normal, even though far from the galactic plane. Of course, their existence does present a serious evolutionary question. The fainter stars were 'abnormal' in that they belonged to groups identified by visual spectral classification as (1) 'horizontal branch' (HBA, HBB) recognized by sharp, numerous hydrogen lines i.e., low $g$ and weak or no metallic lines; (2) subdwarfs (sdB, sdO) with broader shallower H lines, distinguished by very weak or no He I in the sdB, and very shallow H lines in sdO, which might be accompanied by He II lines; (3) white dwarfs with very broad hydrogen lines (DA), helium lines (DB), or no detectable lines (DC). A few peculiar spectra will be discussed later. The visual classification of some of these stars was published in Greenstein (1966) and some luminosity estimates in Greenstein and Eggen (1966). Quantitative analyses by use of UBV (or other) colors and H$\gamma$ profiles have been carried out by Searle and Rodgers (1966), Sargent and Searle (1968) and Newell (1969). In this investigation fainter stars were studied and often at higher dispersion. A few general remarks about the new results may be interesting. The 'normal' stars amounted to 20%, but had a bright mean apparent magnitude 10.4. The HBA and HBB stars accounted for 22%; the sdB 16%; the sdO 13%, and were faint, $\langle m = 14.1\rangle$. Twenty-two stars had composite colors and spectra (i.e., unresolved binaries), showing that the percentage of binaries is not very low in the halo. Fifteen percent of the halo stars were white dwarfs found by color i.e., not selected for motion. Selection effects do exist, in that I observed the bluest stars first, and a very large number of HBA stars near B $-$ V $=$ 0.0 were not observed. Thus, the fraction of very hot stars is too large. The frequencies per volume of space for the different groups are obviously quite different, and the 'normal' stars suffer from the density decrease with $z$-coordinate. A preliminary solution indicates a luminosity function such that the true number per unit volume increases as exp $(0.65\, M_V)$ from $M_v = -4$ to $+5$. This will be recomputed on a $M_b$ scale.

The value of $g$ found depends on the assumed mass; since all the stars may be assumed to be highly evolved, it seems best to adopt a constant mass. Some sdO stars may become planetary nebulae, to lose excess mass, and a few have associated planetaries of low-surface brightness. The mass assumed in Table I was 1 $m_\odot$ in the relation

$$M_b = 2.5 \log g + 10 \log \theta - 2.5 \log (m/m_\odot) - 5.82\,. \tag{1}$$

Therefore $M_b$ should be increased by $+0.75$ if $m = 0.5\, m_\odot$. The accidental errors are of the same order, except for the very hot stars. Since the colors have errors $\pm 0.03$, the value of the reddening-free color parameter $Q$ has errors $\pm 0.042$,

$$Q = (\mathrm{U} - \mathrm{B}) - 0.72\,(\mathrm{B} - \mathrm{V})\,, \tag{2}$$

and that of $\theta \pm 0.021$. Then at $\theta = 0.12$, the highest temperature used, $M_b$ has errors $\pm 0.9$ mag. In addition, the $g$ from line profiles have errors, since the line strength depends on both $\theta$ and $g$.

Table I provides temperatures and luminosities determined spectroscopically for a selection of three types of objects from our larger catalog of results. The bolometric luminosities are plotted in Figure 1. The cooler horizontal-branch stars, near B $-$ V $=$ 0.0 have colors which may depend on $g$, so we show only stars with $T > 10\,000$ K.

TABLE I

Sample data for hot horizontal-branch and subdwarfs

| FB No. | Name | V | B − V | U − B | $\theta$ | log $g$ | $M_b$ | W(Å) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | He I λ4388 | He I λ4471 | He II λ4686 |
| | | | | Subdwarf O | | | | | | |
| 3 | TS 144 | 12.9 | −0.17 | −1.18 | < 0.12 | 5.0: | < −2.5 | 1.14 | 2.46 | 2.77 |
| 13 | TS 201 | 13.2 | −0.24 | −1.04 | 0.17 | 5.8 | +1.0 | < 0.12 | 0.30 | 0.74 |
| 26 | HZ 3 | 12.9 | −0.14 | −1.10 | 0.12 | < 6.0: | < 0.0 | 0.96 | 1.94 | 2.52 |
| 42 | Abell 31 | 15.5 | −0.31 | −1.28 | < 0.12 | > 5.5 | −1.2 | < 0.20 | < 0.20 | 1.17 |
| 45 | GD 299 | 12.1 | −0.28 | −1.15 | 0.14 | 5.4: | −0.9 | 0.37 | 1.20 | 1.93 |
| 48 | GD 300 | 12.8 | −0.33 | −1.19 | 0.14 | 5.2: | −1.4 | 0.29 | 1.38 | 2.22 |
| 51 | F 34 | 11.2 | −0.30 | −1.35 | < 0.12 | 5.9 | −0.3 | < 0.03 | < 0.03 | 2.47 |
| 62 | F 46 | 13.2 | −0.25 | −1.16 | 0.13 | 6.9: | +2.6 | 1.81 | 3.09 | 1.28 |
| 89 | F 67 | 11.8 | −0.33 | −1.21 | 0.13 | 5.2: | −1.7 | < 0.12 | < 0.12 | 1.31 |
| 102 | HZ 38 | 14.2 | −0.27 | −1.16 | 0.13 | 7.2 | +3.3 | 1.67 | 3.13 | 1.17 |
| 115 | HZ 44 | 11.7 | −0.29 | −1.19 | 0.13 | 5.7 | −0.4 | 1.68 | 2.99 | 2.32 |
| 167 | F 110 | 12.5 | −0.30 | −1.20 | 0.13 | 6.5 | +1.6 | 0.24 | 0.43 | 1.43 |
| | | | | Subdwarf B | | | | | | |
| 1 | TS 135 | 13.2 | −0.18 | −0.80 | 0.25 | 5.0 | +0.6 | < 0.12 | < 0.12 | < 0.12 |
| 10 | TS 183 | 12.6 | −0.24 | −1.05 | 0.17 | 5.5 | +0.2 | < 0.09 | < 0.09 | < 0.09 |
| 11 | F 11 | 12.1 | −0.26 | −1.02 | 0.19 | 5.3 | +0.2 | < 0.12 | $p$ | < 0.20 |
| 47 | GD 104 | 15.9 | −0.35 | −1.23 | 0.13 | 5.6 | −0.4 | < 0.20 | < 0.20 | < 0.20 |
| 49 | GD 108 | 13.6 | −0.21 | −0.91 | 0.22 | 5.3 | +0.8 | < 0.05 | < 0.05 | < 0.05 |
| 56 | F 38 | 13.0 | −0.23 | −1.00 | 0.18 | 5.6 | +0.7 | < 0.20 | 0.39: | < 0.20 |
| 66 | F 55 | 13.6 | −0.38 | −1.25 | 0.13 | 5.9: | +0.1 | < 0.12 | < 0.12 | < 0.12 |
| 67 | HZ 17 | 15.5 | −0.22 | −1.00 | 0.18 | 5.5 | +0.5 | < 0.20 | < 0.20 | < 0.20 |
| 69 | HZ 19 | 15.6 | −0.22 | −1.09 | 0.15 | > 6.6: | > +2.4 | 0.20: | 0.88 | < 0.20 |
| 84 | F 65 | 12.0 | −0.23 | −0.99 | 0.19 | 5.1 | −0.3 | < 0.03 | 0.46 | < 0.03 |
| 86 | F 66 | 10.5 | −0.32 | −1.06 | 0.19 | 5.3 | +0.2 | 0.20 | 1.06 | < 0.03 |
| 106 | HZ 39 | 15.4 | −0.32 | −1.16 | 0.14 | 6.5: | +1.9 | < 0.20 | < 0.20 | < 0.20 |
| 109 | HZ 40 | 14.6 | −0.24 | −1.02 | 0.18 | 5.6 | +0.7 | < 0.20 | 0.47 | < 0.20 |
| 110 | F 75 | 14.5 | −0.21 | −0.93 | 0.21 | 5.0 | −0.1 | < 0.12 | < 0.12 | < 0.12 |
| 117 | F 81 | 13.5 | −0.22 | −1.02 | 0.18 | 5.6 | +0.7 | < 0.20 | 0.45 | < 0.20 |
| 127 | F 91 | 13.4 | −0.28 | −1.07 | 0.17 | 5.5 | +0.2 | < 0.20 | 0.55 | < 0.20 |
| 143 | TN 788 | 13.2 | −0.18 | −1.00 | 0.17 | 5.5 | +0.2 | 0.35 | 1.20 | < 0.12 |
| 146 | TN 245 | 13.9 | −0.24 | −0.90 | 0.23 | 5.0 | +0.3 | < 0.12 | < 0.12 | < 0.12 |
| 165 | F 108 | 12.2 | −0.28 | −1.06 | 0.18 | 5.1 | −0.5 | < 0.12 | < 0.12 | < 0.12 |
| | | | | Hot Horizontal Branch B − V ⩽ −0.05 | | | | | | |
| 20 | F 23 | 11.9 | −0.11 | −0.44 | 0.38 | 4.0 | +0.7 | < 0.20 | < 0.20 | < 0.20 |
| 50 | GD 113 | 11.6 | −0.09 | −0.49 | 0.34 | 3.8 | −0.3 | < 0.05 | < 0.05 | < 0.05 |
| 52 | +40°449-34 | 11.3 | −0.12 | −0.48 | 0.35 | 3.7 | −0.4 | 0.29 | 0.67 | – |
| 63 | F 48 | 13.3 | −0.17 | −0.68 | 0.29 | 3.8 | −1.0 | < 0.20 | < 0.20 | < 0.20 |
| 70 | +36°2242 | 10.0 | −0.08 | −0.26 | 0.43 | 3.5 | 0.0 | < 0.05 | < 0.05 | < 0.05 |
| 75 | F 59 | 11.6 | −0.06 | −0.10 | 0.49 | 3.1 | −0.5 | < 0.05 | < 0.05 | – |
| 78 | HZ 24 | 11.9 | −0.05 | −0.15 | 0.47 | 3.7 | +0.9 | < 0.05 | < 0.05 | < 0.05 |
| 79 | +49°2137 | 10.7 | −0.14 | −0.60 | 0.31 | 3.8 | −0.7 | $p$ | 0.25 | < 0.03 |
| 82 | HZ 26 | 13.8 | −0.06 | −0.30 | 0.41 | 3.6 | 0.0 | < 0.20 | < 0.20 | < 0.20 |
| 85 | HZ 30 | 13.6 | −0.14 | −0.62 | 0.31 | 3.7 | −1.0 | < 0.20 | 0.33 | < 0.20 |
| 103 | HZ 47 | 15.3 | −0.13 | −0.74 | 0.26 | 4.6 | +0.5 | – | 0.50 | < 0.20 |
| 105 | HZ 37 | 12.5 | −0.08 | −0.18 | 0.46 | 3.4 | 0.0 | < 0.05 | < 0.05 | – |
| 107 | F 74 | 12.0 | −0.10 | −0.32 | 0.41 | 3.0 | −1.5 | < 0.09 | 0.40: | < 0.09 |

*Table I (continued)*

| FB No. | Name | V | B − V | U − B | θ | log *g* | $M_b$ | W(Å) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | He I | | He II |
| | | | | Hot Horizontal Branch B − V ⩽ −0.05 | | | | λ4388 | λ4471 | λ4686 |
| 108 | HZ 42 | 14.6 | −0.14 | −0.54 | 0.33 | 3.8 | −0.4 | <0.12 | <0.12 | <0.12 |
| 112 | F 76 | 15.2 | −0.12 | −0.65 | 0.29 | 4.0 | −0.5 | <0.20 | <0.20 | <0.20 |
| 116 | HZ 45 | 12.8 | −0.15 | −0.57 | 0.33 | 3.8 | −0.4 | <0.05 | <0.05 | – |
| 121 | F 86 | 10.1 | −0.15 | −0.66 | 0.30 | 3.5 | −1.6 | 0.15: | 0.50 | <0.05 |
| 128 | F 92 | 11.5 | −0.13 | −0.61 | 0.31 | 3.8 | −0.7 | *p* | 0.50: | – |
| 160 | PHL 25 | 12.0 | −0.14 | −0.68 | 0.28 | 4.4 | +0.3 | 0.93 | 1.25 | <0.12 |

(A large number of apparently normal, main-sequence stars are not plotted.) Two globular cluster B stars are shown, with $M_V$ as directly determined and with bolometric corrections from Mihalas (1965). Considering the errors of observation, the H-R diagram is surprisingly clean, showing a horizontal branch centered near $M_b = 0$, from 10000 to 50000 K, with a very small scatter. The branch is continuous with that found for $T < 10000$ K, and through the RR Lyrae variables. No present theoretical model of horizontal-branch evolution can explain this long and narrow track. The observed major difference from globular clusters is that the branch in clusters terminates at

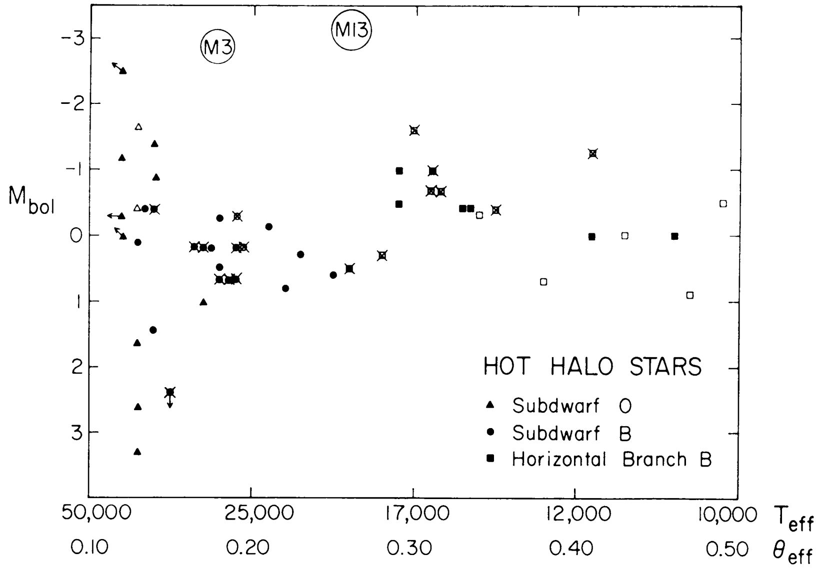



Fig. 1. Spectroscopically deduced bolometric magnitudes and temperatures of the hot halo stars. Open symbols are bright nearby stars ($m < 12$). The symbol M 3 represents the globular cluster O star in M 3, and M 13 the B star in M 13. Arrows indicate direction of possible errors. All sdO stars (triangles) have He II and sometimes He I; sdB (circles) and HBB (squares) do not show He I unless an × is added.

about $T \leqslant 17000$ K. The halo stars do not all have the same age and mass, as do stars in a cluster. Above 30000 K the present H – R diagram shows an abrupt change, with larger scatter caused by errors of $\theta$ and $g$. But the spread in $M_b$ is almost certainly real; some stars in Table I are nearly white dwarfs spectroscopically. It is known that hotter and brighter subdwarfs are found as nuclei of classical planetary nebulae, and fainter ones in old novae and other binaries. Since my temperature discrimination is poor at small $\theta$, it is possible that some sdO stars are evolving upwards and to the left, while others are dropping vertically downwards towards the white dwarf. The sdO star in M 3 (Strom, 1970) and the B star in M 13 (Stoeckly and Greenstein, 1968) lie well above and to the right of these stars, and represent a different and probably earlier stage of evolution.

## B. THE SPECTRA OF THE WHITE DWARFS

A series of 3 papers with Eggen (EG I-II-III) a fourth (GR IV Greenstein, 1969a) and this report give spectra of approximately 265 white dwarfs for most of which colors and motions are known. New data on 18 more have been published (GR VI Greenstein, 1970) with added observations of EG stars (numbers less than EG 266), using a series number labelled GR, starting with EG 267. For some of these photoelectric data is missing; since only a few binaries are included, no attempt is made to give absolute magnitudes and space motions as was done before. My classification system for 285 white dwarfs is described below and has been used previously; white dwarfs differ in temperature, surface gravity and composition and therefore require a complex classification scheme. The UBV colors are not sufficient to determine the spectrum, although they correlate with dominant features over certain ranges. J. Graham (unpublished) has made considerable progress with Strömgren-type color systems. The following paragraphs attempt to describe the major type of white dwarfs as now recognizable at about 200 Å $\text{mm}^{-1}$.

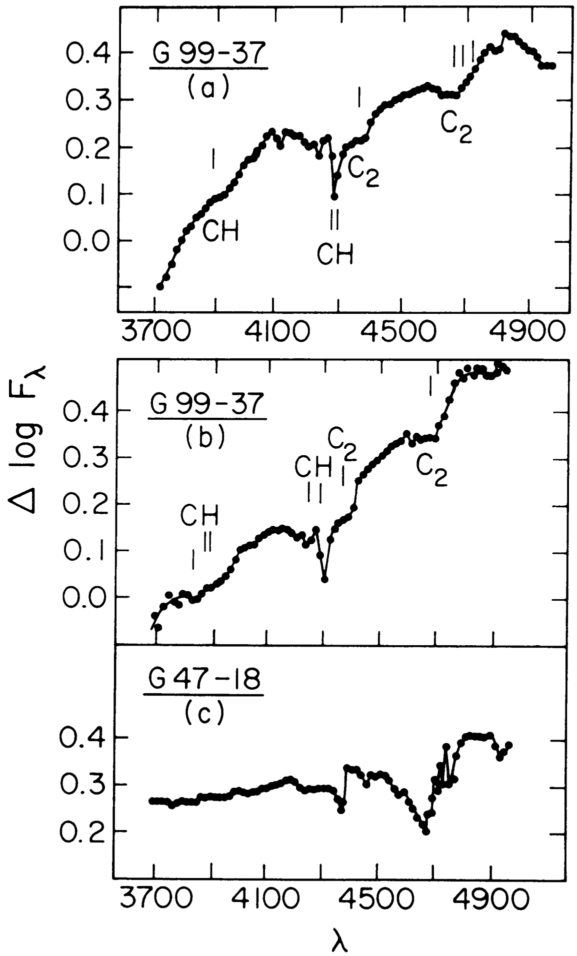
*DA*: Hydrogen lines of various strengths and half widths are seen, with a maximum equivalent width ($W = 40$ Å) at $U - V = -0.55$ mag, and a width at half-central absorption $w_{0.5} = 55$ Å. Some DA stars have weak H lines for their color, are called DAwk, but DAwk occurs at both color extremes ($U - V = -1.6$ and $-0.2$ mag) of the DA group. Sharp-lined stars DAs appear, and especially for $U - V > -0.3$, dominate. Line blanketing and new opacity sources affect the models. Balmer lines perturb the $B - V$ colors. In none are lines detectable beyond H 10 or H 11. Near $U - V = -0.2$ lines become very sharp and weak, but the Stark or pressure broadening persists, since the cooler DAs stars do not show even H 8, although H$\gamma$ is sharp. A new temperature scale for DA is being prepared by Oke. Most lie below the blackbody line in UBV.

*DB*: Over a limited range of color, near $U - V = -1.0$, a considerable fraction show only lines of He I, without any trace of He II or H. The $W(\text{H}\gamma)$ is reduced by a factor of at least five to ten. Theoretical analysis indicates very high He/H ratio; they lie near the blackbody line.

*DO*: A few very blue, hot stars (50000 to 100000 K) show He II, sometimes He I, and weakly H. These have high bolometric luminosity, but are below the hot sdO stars of Figure 1. Note that at 57000 and 0.01 $R_\odot$, we have $L = L_\odot$ i.e., $M_b = +4.7$. Oke believes that EG 86 (HZ 21) has $T_{\text{eff}} = 100000$. DO, DAwk, hot sdO, all lie close together and near the blackbody line.

*DC*: Many stars are found with no detectable lines; in the best observed cases, the central absorption $<0.05$ i.e., no line has $W > 1.2$ Å. These are found with U − V colors from −0.7 to +1.8; however, at a given B − V, DC stars may have different U − B colors. Therefore, some may have appreciably different line absorptions e.g., blended, broad invisible lines.

*DA, F; DG, DK*: So few cooler degenerate stars are bright enough for detailed study that only a rough classification exists based on metallic lines. The first appearance of Ca II in stars with sharp H lines marks DA, F. The DG stars have Ca II, and a few metallic lines e.g., Fe I and Mg I blends in the ultraviolet. DK stars are redder and have




(2a)

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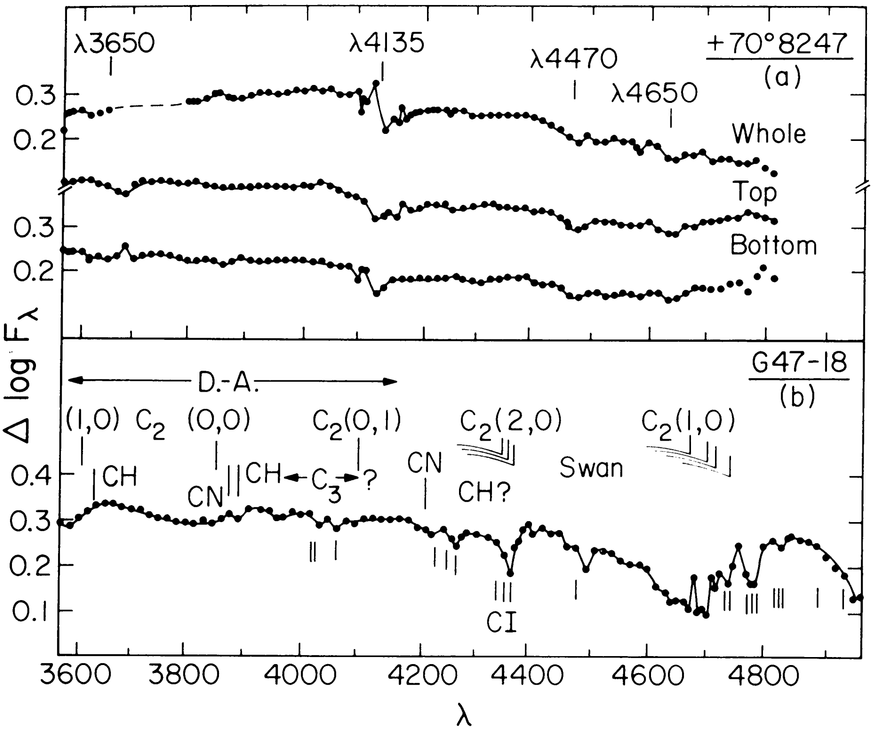


(2b)

Fig. 2a. Intensity tracings (unsmoothed) of peculiar white dwarfs; $\Delta \log F_\lambda$ is given with respect to a DC star EG 78. Broad bands of molecular carbon, $C_2$, and CH are seen (a, b) in G99-37 (EG248); $C_2$ and C I are seen in G47-18 (EG 182) (c), and at higher dispersion (b), in Figure 2b. The $\lambda$4135 band dominates 3 tracings of different parts of the same 90 Å $mm^{-1}$ plate of +70°8247 (EG 129) (a) in Figure 2b. Weak bands at $\lambda\lambda$3660, 4480, 4650 are also present.

Ca II and Ca I (weak). Metallic lines vary greatly, appearing first at U−V = −0.5, and still appear in the reddest, which have U−V = +1.9.

*DM*: All candidates for DM are faint (17th mag photographic). The lines seen are Ca II, Ca I, a broad depression at $\lambda$>4227 which may be $Ca_2$ (quasi-molecule, suggested in late dM stars) or a blend of metallic lines, and blurred weak bands of TiO in the green. The properties of metal-poor sdM stars are poorly known. They have weak TiO, but usually strong MgH, and very sharp metallic lines; at adequate resolution they should be distinguishable from DM. The colors of DM stars must be affected by blurred atomic or molecular line blanketing. The colors show changes of 0.5 to 0.8 mag in U−B at a fixed B−V from near the main sequence to above the blackbody line.

*$\lambda$4670, $\lambda$4670p*: The wavelength of the shallow-broad feature detected for these carbon-rich stars is shortward of the (1.0) head of $C_2$. The (0, 0) head was also seen, and is strong. In one hot carbon star, EG 182 (G47-18) the C I lines are also strong.

One single, and very puzzling example, EG 248 (G99-37) has CH strong and blurred, and strong $C_2$ bands as well.

*λ4135*: One star of this type is known, EG129, (Greenwich +70°8247). This most exciting object has a band-like feature, deepest at *λ4135*, degraded to the red, and weak features at *λλ4475, 3910, 3650* (Greenstein and Matthews, 1957). It has just been established by Kemp and Kemp *et al.* (1969, 1970) that this star shows several percent of circular polarization and must have a magnetic field near $10^7$ G, (Figure 3).

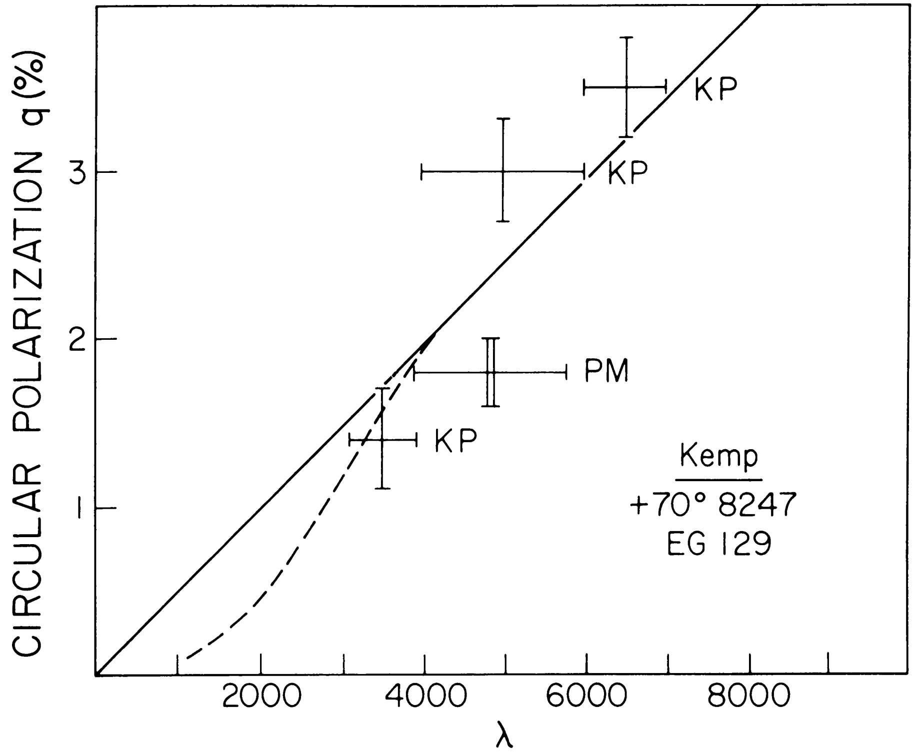


Fig. 3. Circular polarization in EG 129, +70°8247, as a function of wavelength (from Kemp *et al.*, 1970b).

## C. NEW THEORETICAL ASPECTS ON WHITE DWARF SPECTRA

The explanation of the spectroscopic features by model atmospheres is most advanced for the DA stars. Here, Terashita and Matsushima (1969) and currently, D. Peterson, H. Shipman, and J. B. Oke (at Caltech) have constructed model atmospheres with all known opacity sources. The models have gradually improved in their ability to represent both the continuum flux and the Balmer lines. Line blanketing has severe effects on the ultraviolet continuum, and must be included. Since metals may have abnormally low abundance, cool models involve some uncertainty; convection may appear and alter the temperature gradient. The helium stars have lower opacity (Weidemann, Bues) and a very high He/H ratio is required in DB stars to prevent H lines from appearing. However, the broadening theory is much less complete for He I lines, the He I continua are complex and non-hydrogenic, and the helium-star models need much further study. The possibility that very rapid rotation stabilizes a star of mass greater than Chandrasekhar's limit was explored by Ostriker and Bodenheimer (1968) and the effect on the DA spectrum recently studied by Wickramasinghe and Strittmatter (1970) (following a suggestion by Sobolev). They find that rapid rotation cannot wipe out the Balmer lines and produce a DC white dwarf. Gravity darkening at the limb reduces the flux from the high-velocity equatorial regions.

Observations of details of the continuum spectrum, and interpretation by model atmospheres, together with H-line profiles should permit establishment of a white-dwarf temperature scale, and determination of surface gravity. At present the single-channel spectrophotometric scans are being improved on by use of a multi-channel spectrometer at Palomar, by Oke. A brief report of his work will be given later. Tentative surface gravities are lower than expected, nearer $\log g = 7$ than 8 (expected for He interiors, 0.7 $m_\odot$).

A recent study of the detectability of magnetic fields in DA stars by Preston (1970) involves quadratic Zeeman effect on the Balmer lines. Lines are both shifted to shorter wavelengths and broadened,

$$\langle \Delta\lambda \rangle = -7.5 \times 10^{-23} \lambda^2 n^4 H^2 , \tag{3}$$

where $\lambda$ is in Å, and $H$ in G. The run with principal quantum number, $n$, is such that at $10^6$ G, the apparent velocity ranges from $-11$ km sec$^{-1}$ at H$\alpha$, to $-61$ at H$\gamma$, to $-213$ at H$\varepsilon$. These negative means are contradicted by observation, as is the trend with $n$. Note that if magnetic flux is conserved while a star contracts, $H$ is proportional to $R^{-2}$, so the shift varies as the luminosity $L^{-2}$. In a typical DA with $L = 10^{-3}$ $L_\odot$, the field is increased by $10^6$ i.e., the initial field should be less than 1 G, or observable quadratic Zeeman effects would occur.

Kemp (1970a, b) has developed a theory of blackbody emission in a strong magnetic field, and predicts a circular polarization

$$q(\omega) \approx -eHm^{-1}\omega^{-1} . \tag{4}$$

This would be about 0.1% at $10^6$ G. Laboratory experiments on metals showed the effect, insulators did not, and the carbon flame gave an opposite sign, ascribed to $C_2$ (Kemp *et al.*, 1970a). Kemp found the circular polarization in EG 129 which is, approximately 1 to 4% in the visible, and larger in the infrared. The process remains obscure; The Zeeman components of any frequency are unequal in strength in an optically thin gas. Angel and Landstreet (1970) found no linear polarization in several DA stars. Kemp claims a projected field strength of $10^7$ G is present; extensive observations of EG 129 are underway.

Two white dwarfs vary quasi-periodically in brightness in roughly $10^3$ sec; HL Tau 76, EG 165 was claimed to have a variable spectrum, but from several spectra seems to be a simple DA; G44-32, EG 72, is 17th mag, but one spectrum seems to be that of a DC. Recent spectra of some unusual white dwarfs are shown in Figure 3, from microphotometer tracings on an intensity scale. They have to be normalized for the sensitivity of the system, but are sufficient to locate features of these unusual types of stars.

### D. RED SUBLUMINOUS STARS

In an extensive series of papers Eggen (1968, 1969, 1970) has shown that G-K-M stars of high ultraviolet excess, or suspected very high space motion, may include genuinely subluminous stars. Some parallaxes are available and some have common proper motion main-sequence stars. The red 'subdwarfs' are an extension of the well-known sdF and SdG stars of very low-metal content, but (1) seem to have excessively large $\delta$(U – B) and (2) when calibrated by R – I (in which line-blocking should be relatively small) they fall below the Hyades $M_I$, R – I sequence. At first it seemed plausible that these were red degenerate stars. By 1968, I already found that the yield of classical red white dwarfs was very low, and that the number of newly discovered

TABLE II

Southern LTT stars, f, g, k, Eggen

(A) Greenstein, Published Kumar's *Low-Luminosity Stars*, 20 Stars
Types sdG-sdM; $\langle T \rangle = 520$ km sec$^{-1}$; $\langle \delta(\mathrm{U}-\mathrm{B}) \rangle = 0.31$ mag;
Two degenerate stars found, both bluer than the sun

| LTT | B – V | U – B | $\delta$(U – B) | $T$ | Type | Remarks |
|---|---|---|---|---|---|---|
| 375 | 0.65 | – 0.32 | 0.50 | 1800 | DC | EG 246 (new) |
| 7983 | 0.23 | – 0.61 | 0.71 | 1100 | DA | EG 137 (old) |
| (B) Other LTT stars, large $T$ or $\delta$(U – B) | | | | | | |
| 2066 | 0.57 | – 0.21 | 0.31 | 500 | sdG | Extr. wk. CH |
| 2981 | 0.66 | – 0.18 | 0.38 | 3300 | DC | L97-12 = EG 56 (old) |
| 5454 | 0.68 | – 0.16 | 0.38 | 350 | sdG | Extr. wk. CH stg., vel. = + 223 |
| 5560 | 0.73 | – 0.09 | 0.39 | 350: | sdG | Extr. wk. CH stg., vel. = – 216 |
| 5852 | 0.62 | – 0.20 | 0.36 | 280 | sdG | Extr. wk., vel. = – 35 |
| 6079 | 0.56 | – 0.23 | 0.32 | WD, 690 | sdG | Extr. wk. |
| 6194 | 0.52 | – 0.13 | 0.16 | 710 | sdF | Extr. wk. |
| 6307 | 0.84 | + 0.10 | 0.43 | 200: | sdG | Extr. wk. |
| 7132 | 0.72 | – 0.13 | 0.41 | 230 | sdG | Extr. wk. CH stg. LPM 661, vel. = – 216 |
| 7238 | 1.04 | + 0.53 | 0.39 | 200: | idK | CH stg. |
| 7381 | 1.36 | + 1.25 | 0.00 | 700: | sdM | MgH stg. Metals wk. |
| 12560 | 0.41 | – 0.23 | 0.24 | 400 | sdF | Ross 889, vel. = – 59 |
| 13746 | 0.64 | – 0.09 | 0.27 | 4500 | DC | EG 95 (old) |
| 14272 | 0.86 | + 0.27 | 0.27 | 300: | sdK | |
| (C) Lowell stars, large $T$ or $\delta$ (U – B) | | | | | | |
| G39-27 | 0.65 | – 0.06 | 0.06 | 1200 | DC | EG 40 (old) |
| G99-44 | 1.06 | + 0.81 | 0.18 | 2800 | DK | EG 45 (old) |
| G113-40 | 0.93 | + 0.51 | 0.19 | 500 | sdK | CH, Mg I stg. LTT 3144 |
| G128-7 | 0.67 | – 0.16 | 0.37 | 3600 | DAss | GR 284 (new) |
| G134-22 | 0.73 | + 0.02 | 0.28 | 3600 | DC | EG 16 (old) |

$\langle T \rangle = 420$ km sec$^{-1}$; $\langle \delta(\mathrm{U}-\mathrm{B}) \rangle = 0.30$; $\langle m \rangle = 13.0$

*Totals*, old and new: non-degenerate 33 stars; degenerate 8; new degenerate 2.

stars like Wolf 489 was zero (Greenstein, 1969b). Table II, III, IV herewith show the type of evidence, and the spectroscopic results.

What do we expect to see? First, if stars have $\log g = +7.4$, (as do low mass DA stars) i.e., $R = 0.03\ R_{\odot}$, and have a temperature near that of the sun $M_v \approx +12$. They have very low opacity atmospheres; and unless the metal abundance is high, Rayleigh scattering will dominate. Then we expect an ultraviolet deficiency, not an excess. Next, if there are some metals, and $H^-$ dominates, various degrees of line-blocking by broad invisible lines might occur, probably resulting in an approach to the black-body line. If $\log g$ is even lower and the atmosphere has a low pressure region containing metals, individual lines might be seen.

Opacity and line broadening vary with composition, electron and gas pressure; cool stars would be expected, near the main sequence, to show effects of both the metal/hydrogen ratio and $g$ (roughly as the square root). Although a variety of simple formulas have been derived which depend on the fractional ionization of the metals, and the opacity dependence on electron or gas pressure, these would not be profitable here. Over a modest range of $g$, we expect strong lines to show larger pressure broadening; if the metals are very deficient and the opacity low, this would be easily detected. In case Rayleigh scattering or molecules contribute to the opacity, $g$ would hardly affect the lines. We do not even know whether Eggen's red subluminous stars have high $g$, since it is conceivable that they have low mass.

TABLE III

Eggen's suspected red degenerate stars; four Lowell fields, color class + 1

| Star | B − V | $\delta$(U − B) | $T$(km sec$^{-1}$) | Type | Remarks |
|---|---|---|---|---|---|
| G138-4 | 0.48 | 0.19 | 530 | sdG | CH stg. H 14 |
| -6 | 0.40 | 0.26 | 790 | sdG | Extr. wk. H 13, vel. = − 258 |
| -16 | 0.83 | 0.23 | 920: | sdG | CH stg. |
| -21 | 1.11 | 0.16 | 440: | sdMp | TiO wk. |
| -38 | 0.97 | 0.06 | 630: | idK | CH stg. |
| -53 | 0.93 | 0.30 | 540: | idK | |
| -65 | 0.87 | −0.13 | 800: | idK | CH stg. vel. = + 70 |
| G141-6 | 0.87 | 0.18 | 1000 | sdK | Extr. wk. |
| -15 | 0.52 | 0.20 | 470 | sdG | Extr. wk. H 15, CH wk., vel. = − 290 |
| G181-19 | 0.81 | 0.34 | WD, 310: | sdK | Extr. wk. CH stg., vel. = − 172 |
| -45 | 0.74 | 0.36 | WD, 180: | sdK | |
| G178-9 | 0.83 | 0.41 | WD, 230: | sdK | Vel. = − 170 |
| -30 | 0.86 | 0.27 | WD, 130 | sdK | |
| -41 | 0.48 | 0.24 | 470 | sdG | Extr. wk. CH wk. H 13 |
| -49 | 0.98 | 0.31 | WD, 200: | idK | Vel. = − 194 |

$\langle m \rangle = 13.5$

15 Stars: none degenerate

$\langle T \rangle = 510$ km sec$^{-1}$ $\langle \delta(\mathrm{U-B}) \rangle = 0.23$

Total, Tables II, III: 48 non-degenerate, 8 degenerate; 6 are rediscoveries; 2 new degenerate stars. $\langle T \rangle = 450$ km sec$^{-1}$ $\langle \delta(\mathrm{U-B}) \rangle = 0.28$

*Degenerates*: $\langle T \rangle = 2750$ km sec$^{-1}$; $\langle \delta(\mathrm{U-B}) \rangle = 0.34$

TABLE IV

New possible red degenerate stars

$T > 200$ km sec$^{-1}$, Large $\delta(U-B)$, or $\delta(U-B) > 0.20$ at $(B-V) > 0.70$

| Star | B − V | δ(U − B) | T | Type | Remarks |
|---|---|---|---|---|---|
| G71-53 | 0.77 | 0.36 | 290 | idK | Eggen 530; CH stg. |
| VA 216 | 0.96 | 0.03 | 340 | dM | Suggested DM in Hyades; TiO, metals seen. |
| VA 391 | 0.70 | 0.17 | 290 | sdF | Suggested DK in Hyades; Ca II sharp. |
| G47-48 | 0.57 | 0.02 | 900 | dK | |
| GD 103 | 0.75 | 0.29 | 190 | sdK | |
| GD 105 | 0.70 | 0.23 | 220 | sdK | Extr. wk., CH stg. |
| GD 118 | 0.45 | 0.25 | 360 | sdG | |
| G119-11 | 1.11 | 0.31 | 900: | sdK | Could be DK. |
| G119-57 | 1.46 | – | 410: | idM | |
| G61-35 | 1.12 | 0.20 | 510: | sdK | |
| G164-61 | 0.59 | 0.19 | 540 | sdG | Extr. wk., CH stg. |
| LTT 6660 | 0.87 | 0.45 | 160: | sdK | Extr. wk. |
| G17-37 | 0.84 | 0.40 | 240: | sdK | Extr. wk., CH stg. |
| GD 211 | 0.64 | 0.24 | 330 | sdK | Extr. wk., CH stg. |
| G155-27 | 1.36 | – | 740: | sdM | Eggen 700; wk. lines; MgH stg. |
| GD 214 | 0.81 | 0.38 | 140: | sdG | Vel. = −67 |
| GD 217 | 0.70 | 0.39 | 80: | sdG | Vel. = +96 |
| GD 224 | 0.88 | 0.23 | 160 | sdK | |
| G125-59 | 1.03 | 0.19 | 400: | sdK | Extr. wk.; Vel. = −277. |
| G18-51 | 1.42 | – | 550: | sdM | CC 1363; MgH present; Vel. = −157. |

Fainter Sample $\langle m_V \rangle = 14.5$
20 Stars $\langle T \rangle = 390$ km sec$^{-1}$; $\langle \delta(U-B) \rangle = 0.25$
17 Non-degenerate, 1 Possible, 2 improbable degenerates.

The clues searched for in the spectra so far obtained have been: (a) presence of extreme line broadening, or enhancement of strong lines with respect to weak ones; (b) presence of abnormal hydrogen lines; (c) presence of abnormal molecular bands; (d) discrepancies between the ionization level and the color; (e) abnormally low excitation level. In general, the tables indicate that the red subluminous and subdwarf stars have: (a) abnormally strong, sharp hydrogen lines for their color; (b) abnormally weak neutral and ionized metallic lines; (c) weak TiO, and very strong MgH bands; (d) very strong CH bands in weak-metal stars.

The statistical results are that the percentage of classical red degenerate stars is nearly zero. The statistics are:

(A) Table II shows 33 non-degenerate; 2 new degenerate of which one is like vMa2, but shows no lines, and one is DA; and rediscovery of 6 EG yellow degenerate stars.

(B) Table III shows 15 non-degenerate stars.

(C) Table IV shows 20 non-degenerate stars.

There are 68 non-degenerate stars, 1 DA, 1 yellow DC found, and 6 old objects rediscovered. No analogs of the intrinsically faint yellow and red stars like vMa2, W 457, W 489 were found. Genuine 'red-white dwarfs', with 0.01 $R_\odot$ are rare in space and make up less than 1% of the proper-motion stars. But these proper-motion

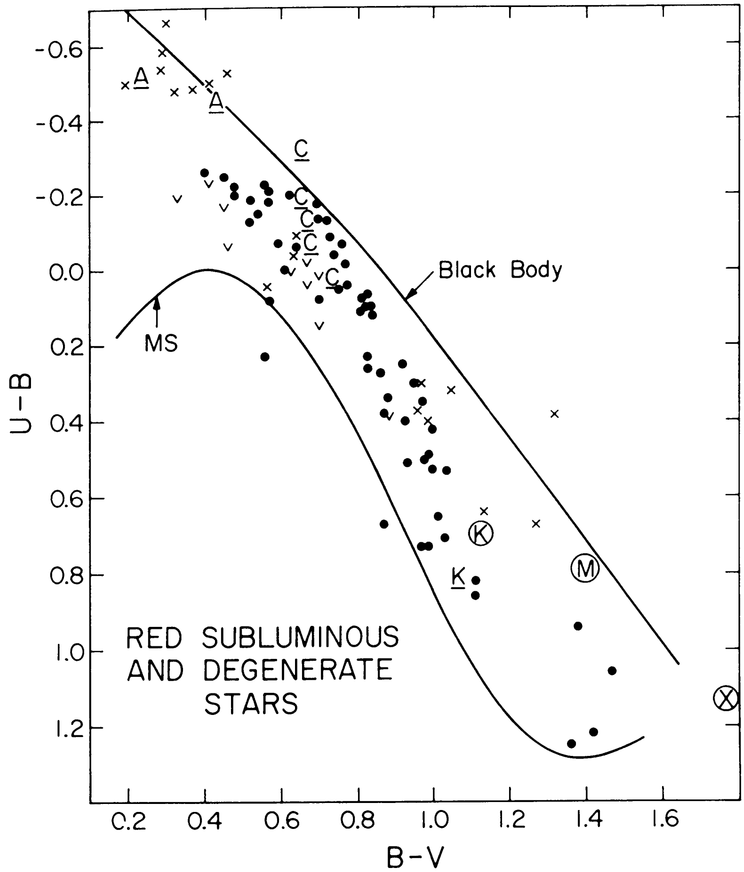


Fig. 4. Results of search for red degenerates among objects of large $\delta(U-B)$ and transverse motion. Failures (checks) are stars with $\delta(U-B) < 0.25$, $T < 300$ km sec$^{-1}$. Dots are extreme subdwarfs (F, G, K, M) above these limits. Degenerate stars are shown by crosses if previously known, underlined, if found in this search, and circled if possibly subdwarf or degenerate. C are DC Stars.

stars, as a group, have luminosities (from UBV) such that the tangential velocity is 450 km sec$^{-1}$ (Tables II, III) or 390 km sec$^{-1}$ (Table IV). Further, the excesses for sdG-sdM stars average $\langle\delta(U-B)\rangle = 0.28$ mag (Tables II, III), and 0.25 (Table IV). The degenerate stars in this sample had $\langle T\rangle = 2750$ km sec$^{-1}$ and $\langle\delta(U-B)\rangle = 0.34$. Thus only stars with very extreme $T \geqslant 1000$ km sec$^{-1}$ derived from UBV photometric parallaxes are likely to be classical yellow or red degenerates.

Figure 4 illustrates these results based largely on Eggen's (1968, 1969) photometry. I have not been able to observe his more recently published stars. The sample is quite large enough to show how few new red degenerate stars are found, but it does concern a relatively bright group of stars (about 14th mag), which are very peculiar. The fainter group (Table IV) is no less peculiar. The large values of $\delta(U-B)$ in cool stars were not originally expected, but persist to sdM type. The very large tangential velocity (over 400 km sec$^{-1}$) is that of extreme halo population II. The radial velocities obtained at 90 or 190 Å $\mathrm{mm}^{-1}$ are of low accuracy, but as tables II–IV show, are very large; for 23 stars $\langle|\varrho|\rangle = 142$ km $\sec^{-1}$, while $\langle\varrho\rangle = -93$ km $\sec^{-1}$. The large negative mean radial component arises from the distribution of the stars over the sky with respect to the direction of galactic rotation. Among 14 stars in Tables II–IV, 11 have large negative radial velocities, and 3 positive. But evaluating the contribution to the $V$-velocity, in the direction of galactic rotation, we find 9 stars have a radial velocity contribution, $\varrho(\partial V/\partial\varrho)$, to $V$ of $-120$, and 5 have $\varrho(\partial V/\partial\varrho) = +30$. Thus, in these stars, the high negative radial velocity is required to keep the stars bound in the galaxy. The radial velocity contribution to the $W$-coordinate, $\varrho(\partial W/\partial\varrho)$ averages 90 km $\sec^{-1}$, so that even with zero proper motion the stars would be halo objects.

The tangential motion for these stars is 400 km $\sec^{-1}$, very large compared to the radial-velocity dispersion; clearly it is possible to reduce it to a reasonable value if the stars are closer to us i.e., have lower luminosity than given by the UBV photometric parallax. Thus, if $\langle|\varrho|\rangle$ is equated to $2/\pi\ \langle T\rangle$, which would be true for stars uniformly distributed over the sky, and with random space motions, we find that $\langle T\rangle$ should be about 220 km $\sec^{-1}$ or about one-half what we observe. Then the stars are 1.5 mag below the Hyades main sequence i.e., half the main sequence radius, or one-quarter the surface gravity. (This was already indicated by Greenstein (1969b).) Quantitative spectroscopic analysis, using H lines, Ca I and Fe I line-broadening theory and models should be sufficient to reveal so large a factor. Thus Eggen's stars seem to be subluminous, but not normal red degenerate stars. They are far above the low-mass DA white dwarfs which might have 0.03 $R_\odot$. The existence of low-mass hydrogen-rich degenerate stars below 0.1 $M_\odot$ has not been established observationally; their radii would be given from non-relativistic partially degenerate models, and might well be greater than 0.10 $R_\odot$. It seems improbable that they would be as large as 0.50 $R_\odot$, and very improbable that they would be as hot as these stars.

The fact that genuine red degenerates have not been found in this study, while several are known close to the sun depends on the high apparent brightness ($\langle V\rangle \approx 14.5$) of the sample. However, it is clear that the red degenerates are, in fact, not very common, and certainly not in proportion to their cooling time based on a simple theory. Solidification and low specific heat are responsible (see Greenstein 1969c) for shortening cooling times at low $T_{\mathrm{eff}}$. Where can red degenerates be found? Luyten (1970) has published an extensive list of 1055 faint stars of large proper motion: he finds that about 70% are of color class k or redder. The reduced proper motion $H$ is related to the tangential motion by

$$H = m + 5 + 5\log\mu = M + 5\log T - 5\log 4.74\,. \tag{5}$$

His scale of apparent magnitudes is photographic, so we must subtract 1.8 mag to obtain the visual luminosity

$$M_v \approx H_{pg} + 1.6 - 5\log T\,. \tag{6}$$

Stars near $m_{pg} = 20$ exist with $\mu = 1''\ \mathrm{yr}^{-1}$, and many m stars have $H_{pg} \gtrsim 22$. If $T = 75$ km $\sec^{-1}$, as Luyten adopts, (valid for old disk stars and moderately high-velocity stars) $M_v \gtrsim +14$ i.e., these faint objects can be either main sequence or red degenerates.

For $T = 400$ km sec$^{-1}$, however, as in the sample discussed in this paper, $M_v \gtrsim +11$, the stars can be M dwarfs, but *not* red degenerates. For statistical purposes, radial-velocity dispersions of red stars of large $H$ might provide a clue as to the fraction of degenerate stars. Color discriminants might be found from a combination of B, V, R, I and further infrared photometry. Differences between known red degenerates and main-sequence stars, if recognizable, would enormously simplify spectroscopic search for the faint end of both groups of objects.

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