MASSES, RADII, TEMPERATURES, LUMINOSITIES AND SURFACE COMPOSITIONS OF WHITE DWARFS

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My title is so inclusive that it is not possible to find signifi-cant subject matter not in direct conflict with the specialists' talks scheduled throughout this Colloquium. I intend, however, to emphasize areas where it is probable that much remains to be done. From the Kiel group come printouts for a large family of models, first for hydrogen and recently for helium-dominated atmospheres, which D. Koester has kindly made available. Hydrogen atmospheres for a wide variety of temperatures by Shipman and McGraw and Shipman exist also in computer printout form. Models of mixed He/H composition are less available, but are being prepared. Some hydrogen-deficient stars are the richest in metals, so that models for a variety of metal/helium ratios will need to be computed, and synthetic spectra. Clearly, further models with differing C/He ratios are needed. The successful observations in the ultraviolet with the IUE also demand computations of Lyman-α pro-files using modern broadening theory, and a few now exist (Koester 1979). Present observational capabilities require quite detailed pre-dicted fluxes and He II, He I line profiles.

The Kiel group (Koester, Schulz, and Weidemann 1979) and Shipman (1979), Shipman and collaborators (preprint) have used existing colors or my multichannel energy distributions to compute radii from luminos-ities and temperatures to obtain masses from the theoretical carbon-core mass-radius relation. As these will be discussed, I need only say that radii for stars of known parallax, and masses, together with their variance, now exist. Shipman (1979) has discussed selection effects in a magnitude-limited sample. The most severely magnitude-limited sample, however, is that selection – the apparently brightest stars (most luminous, i.e., lowest masses) – observed for gravitational redshift by Wegner, and by myself and collaborators. Yet a slight discrepancy now exists in that the observed mean redshift is slightly too large for the mean radius and mass otherwise derived. The mass, as derived from the radius, is sensitive to the effective temperature and appears to be most commonly in the range 0.5 to 0.7 $M_\odot$ for DA's. The distance, d, enters from $L \propto d^2 f$; f is the integrated flux, de-termined if possible, from wide-range energy distributions. A mono-chromatic flux predicted from a model, H, may be used, with less cer-tainty. In either case, $R/d \propto T^{-2}$; fractional errors are $\Delta R/R = -2\Delta T/T + \Delta d/d$. The enormous improvement in the parallaxes made possible by the U. S. Naval Observatory program, initiated by Kaj Strand, must

be gratefully acknowledged. But as an observer of extremes, I must still ask for more parallaxes of the hottest and intrinsically brightest objects, which will have small parallaxes, but are astrophysically most important. Since $M \approx R^{-1}$ over the middle of the known range of white dwarf masses, the predicted gravitational redshift, $M/R \propto 4\Delta T/T - 2\Delta d/d$. Thus, the temperature and parallax, both poorly determined at the hot end, enter critically into the expected redshift.

I should mention that in single white dwarfs those few bright DA stars observed by Boksenberg and myself (first by Peterson and myself), have small rotation. Unpublished preliminary work on DB stars also suggests small rotation. The single magnetic stars, also, have slower rotation than suggested by conserving angular momentum during evolution. Apparently we need not expect substantial deviations from the classical M-R relation to be caused by rotation, and it is probable that meridional circulation is also slow. See Greenstein et al. (1977).

THE TEMPERATURE SCALE

Given the improvements of knowledge of the absolute energy distribution represented by the work of Hayes, Latham, Oke, Schild and others, wide-range scans of white dwarfs have been particularly useful for comparison with models; although Strömgen photometry is very precise, it is subject to systematic differences between observers, for each photometer and filter set. The optical limited spectral coverage from scans resulted in two parameters being useful--the slope on the high-frequency side of the Paschen limit, and the drop beyond the Balmer limit in DA stars. Strömgren photometry measures these parameters also, and both methods have been extensively used recently to give a large number of temperatures and gravities (with less certainty). About 200 DA stars have Strömgren or multichannel photometry. Since the various models now give essentially similar predicted fluxes, the temperature scale seems well defined, except for the hottest stars. Limited by our atmosphere, one cannot expect colors to determine high temperatures well. In Greenstein (1979), I conclude that either from two multichannel colors $m_{2.12} - m_{1.44}$ (called G-R), and $m_{2.80} - m_{1.85}$ (called U-V), or from fitting the entire multichannel energy distribution to a model gives the same result, and up to 30,000 K quite reliably. Examining 45 DA stars in common to Shipman (1979) and myself, $\log T_S - \log T_G = +0.002\pm0.004$, with $\sigma = \pm0.028$ for one determination. The temperatures range from 7000 K to 30,000 K; I used Koester's $\log g = 8$ models, while Shipman used his own models. These LTE, blanketed models compare quite well, and also fit observations such as the MCSP data in Greenstein (1976b).

Others eventually must compare the results for helium stars; since I had no grid of model atmospheres for work on stars with helium atmospheres (1976a). Shipman (1979) gives data on 28 cooler, probably helium-rich stars, including magnetic and carbon types 6000 to 17,000 K. Koester (1979) has supplied predicted colors on the baseline $m_{2.08} - m_{1.36}$ (called G'-R'), and U-V which indicate that DB stars showing He I reach 30,000 K; He I lines disappear at my resolution below 12,000 K. The numerous yellow DC stars have colors which form a natural extension of helium atmosphere colors to much lower temperatures. Here again,

more models are needed. Koester has analyzed the multichannel data on helium degenerates and derives a lower mean log g and mass (1979). Metals appear in many helium-atmosphere stars in this cooler range, with varying intensities, and in GD 40 (Shipman, Greenstein, and Boksenberg 1977) Ca II is seen at 15,200 K. A very interesting group of stars bluer than established DB's have been found colorimetrically by R. Green (in progress). They have strong He I lines; little is known about their proper motions or their luminosities; the line broadening is not sufficient alone to establish by inspection whether they are DB's hotter than 30,000 K, or hydrogen-poor cooler relatives of the sdO group with intermediate log g values. Some intermediate composition stars may exist, types DBA or DAB; in addition to sdO stars with little He II, or little H, or with both.

In late stages of the evolution of helium-carbon cores, the helium degenerate core of minimum mass (0.54 $M_\odot$, say) may grow, during shell burning, to larger masses either in helium- or hydrogen-envelope stars. A mass as low as 0.5 $M_\odot$ has an expected Einstein shift 24 km s^{-1}; at 0.7 $M_\odot$ this is 40 km s^{-1} and at 0.9 $M_\odot$, 65 km s^{-1}. If the final mass depends on details of late evolutionary stages, it should be determinable from gravitational redshift measures, perhaps as well as from determinations of log g (which ranges theoretically from 7.9 to 8.5 for the above mass range).

I have a private doubt concerning the nature of very high-temperature white dwarfs. It is of the greatest theoretical importance to know how hot a degenerate star can be, because of the still uncertain final evolutionary connection between either nuclei of planetary nebulae, horizontal branch, sdB, or hot sdO stars, and the hottest fully degenerate star. Many of the hottest known DA white dwarfs are in binary systems; Feige 24 is a much closer spectroscopic binary, with some interaction. One must wonder whether this is an accident or whether there is a causal connection. In PG 1413+015, Schmidt and Green ascribe 50,000 K temperature to their eight hour eclipsing binary containing a dM, 10^{11} cm from a white dwarf. Wray, Parsons, and Henize (1979) add another, unusual He II-rich object, HD 149499B, which they observed with the IUE. Its spectrum resembles some sdO's. They ascribe a temperature near 85,000 K. At 2 arcseconds distance from a KOV primary, the separation is 9 x 10^{14} cm; the degenerate star subtends so small an angle that it would intercept geometrically only 10^{-13} of any stellar wind from the primary. At a mass-loss rate of 10^{-9} $M_\odot$ yr^{-1}, and neglecting any focussing or radiation-pressure effects on the capture rate, the white dwarf receives so small a mass that, at the velocity of infall, this $\dot{m}$ yields only 2 x 10^{21} erg s^{-1}. But the white-dwarf radiation may force more rapid mass loss, or magnetic-field funneling reduces the enormous dilution of the stellar wind. Possible mechanisms of heating in binaries need some thought. The spectrum of a hot model atmosphere differs greatly from that of an accretion disk, so that it is not likely that these high T are only apparent. Table I gives a list of these hottest stars, with rough linear separations. The frequency of binaries is high, possibly even too high, for chance.

TABLE I

THE HOTTEST DEGENERATES

Object	Ref.	Type	T_3	Pair	Dist. cm	Comments
HD 149499B	1	DO	85:	Vis.,2",KO	10^{15}	Might be He high-g subdwarf.
HZ 43	2	DAwk	60+	Vis.,3",dMe	2×10^{15}	EUV source; EG 98.
Feige 24	3	DAwk	60	Spect.,dMe	10^{11}	Interacting binary; EG 20; P = 4 days.
G191B2B	–	DAwk	50-60	Vis.,sdK	5×10^{16}	EG 247
HZ 21	4	DO	48	Single	...	He/H$\approx$10; EG 86.
PG1413+015	5	DC:	>50	Eclipsing Binary	10^{11}	Late M, not seen. P = 8 hours.
HZ 34	4	DAB	50	Single	...	EG 93
GD 561	–	DAvwk	50	Single	...	Gr 304. Motion small, possible subdwarf.

The list contains all those known to Shipman or myself, T > 50,000.
Many dM+DA pairs known with low DA luminosity and T. Results[6] of ANS
photometry included.

1 – Wray, J. D., Parsons, S. B., and Henize, K. G. 1979, Ap. J. (Letters), in press. In this, IUE spectrum is atypical, showing high members of λ4686 series.

2 – Auer, L. H., and Shipman, H. L. 1977, Ap. J. (Letters), 211, L103. Temperature depends on low He/H ratio.

3 – Margon, B., Lampton, M., Bowyers, S., Stern, R., and Paresce, F. 1976, Ap. J. (Letters), 210, L79; Thorstensen, J. R., Charles, P. A., Margon, B., and Bowyer, S. 1978, Ap. J., 223, 260.

4 – Koester, D., Liebert, J., and Hege, E. K. 1979, Astr. Ap., 71, 163.

5 – Green, R. F., Richstone, D. O., and Schmidt, M. 1978, Ap. J., 224, 892.

6 – Wesselius, D. R., and Koester, D. 1979, Astr. Ap., 70, 745.

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New data on the ultraviolet spectra of white dwarfs gives new information that might have revolutionized our views. We have an un-paralled opportunity in being able first to observe a number of such spectra with the IUE. This remarkable instrument gave Oke and myself (1979) a glimpse of the spectrophotometric properties of 3 DA's and one DO star, with Lyα profiles of useful quality. The results were that the ultraviolet gave the same temperatures and (probably) surface gravities, when fitted to available model atmospheres, as had been obtained from the ground, using the multichannel spectrophotometer (Shipman 1979; Greenstein 1979). Oke will illustrate the DA spectra later in this con-ference. Table II compares the results at present available for a mix-ture of magnetic, hydrogen and helium atmosphere white dwarfs. The IUE temperature determinations must be viewed as preliminary, since the spectrophotometric stability is only moderate and a new error in cali-bration has been discovered, especially for faint stars measured in the presence of a radiation background. A further problem was the absence of suitable model-atmosphere predicted fluxes for those stars containing helium. Nevertheless, these further results are indeed exciting; the observations by Oke and myself will appear soon in detail. A further fact should be emphasized, that no evidence for any ultraviolet metallic lines has been so far found in any DA star.

The hydrogen-atmosphere DA's, of which 8 have been observed, range in temperature from 7000 to above 60,000 K; if all have similar radii, this corresponds to a range of 9.3 in bolometric magnitude. Comparison between ground-based and IUE temperatures is shown in Table II, with individual DA stars listed; since this grid of models is the most com-plete, errors are small, and the systematic agreement excellent. Models giving ultraviolet fluxes are from Koester, D. H. Peterson, McGraw and Shipman or Shipman computer printouts. One ZZ Ceti variable, G29-38 (EG 159), is plotted. Its temperature is 11,500 K from IUE, and 12,000 K from Shipman or Greenstein using the normal spectral region. Vari-ability apparently does not affect the ultraviolet flux.

When we attempt to do the same fitting of the few helium stars, DB (GD 190) or DBM (GD 40, Shipman, Greenstein, and Boksenberg), and HZ 21 (DO; Koester, Liebert, and Hege 1978) we were in a much worse situation, lacking at the time a grid of helium models. Considering the coarseness of the grid, the accidental and systematic errors seem satisfactory, the worst error being HZ 21. The most interesting case is Ross 640, a helium atmosphere (with some hydrogen), rich in metals, and far too cool to show He I. An analysis by P. Cottrell is in pro-gress, by the method of spectrum synthesis. He used the helium-model atmosphere at 8800 K that Liebert (1977) had used to fit the optical region, with the result that what continuum is visible, given the strong metallic lines, provides, in fact, a good fit. Therefore, the UV determination of temperature agrees moderately well with the (8500 K) of Liebert (1977). We will return to this star when we discuss compos-itions. A single, weak carbon band degenerate, L1363-3 needs a helium-model somewhat cooler than the least-squares blackbody given.

Data on two magnetic stars observed will be discussed by Greenstein and Oke (1979; in preparation) in detail. Feige 7, which shows both H

TABLE II

COMPARISON OF EFFECTIVE TEMPERATURES DETERMINED FROM GROUND BASED AND
SPACE OBSERVATIONS

| Name | EG,GR | log T_{eff} | | | Type |
		Shipman	JLG	IUE	
DA, Hydrogen Atmospheres					
L870-2	11	3.86	3.86	3.85	DA
Feige 24	20	4.78	(4.78)	<4.84	DA[a]
40 Eri B	33	4.23	4.21	4.22	DA
HZ 43	98	4.80	...	(4.78)	DAwk
Wolf 1346	139	4.33	4.33	4.34	DA
+73°8031	144	4.19	4.20	4.18	DA
G29-38	159	4.08	4.08	4.06	DAV
G191B2B	247	4.79	4.75	4.78	DAwk
Helium Atmospheres					
HZ 21	86	(4.70)[b]	4.68KLH	4.60W	DO
Ross 640	119	3.93H[c]	3.89L	3.94	DFp
L1363-3	148	3.93	...	(3.98)BB	DC_2wk
GD 190	193	(4.26)[b]	4.34	4.36	DB^2
GD 40	384	4.15(SGB) ...		<4.18	DBM
Magnetic					
Grw +70°8247	129	4.14	(4.13)	4.18(BB)	DXP
Feige 7	267	...	4.34(GB)	4.36(W)	DABP

References: BB = blackbody; GB = Greenstein and Boksenberg, MNRAS, 185, 823,

1978; SGB = Shipman, Greenstein, and Boksenberg, A. J., 82, 480, 1977;

(W)=Wickramasinghe, Mem. R.A.S., 76, 129, 1972; L = Liebert, Astr. Ap.,

60, 101, 1977; KLH - Koester, Liebert, and Hege, Astr. Ap., 21, 163,

1979; W = Wesemael, unpublished model.

[a]Composite, red companion affects MCSP.

[b]Shipman Thesis.

[c]Hammond Thesis.

and He I Zeeman-resolved lines can be analyzed using Wickramasinghe's (1972) DB models, since, fortunately, he had allowed the H/He ratio to be 10^{-4}. As a result, although no Balmer jump is seen, a Lyα line is, and his model gives a reasonable fit to line and continuum. In fact, the many Zeeman lines depress the optical region extensively, so that the temperature is equally poorly (or well) determined in both portions of the spectrum. For Grw +70°8247, the ultraviolet spectrum is so highly distorted that only a blackbody fit is possible, at a temperature differing by 12 percent from that determined in the relatively smooth optical region (Greenstein 1979) from the color-color properties of that star. The most striking result, however, is the integrated low flux of this star, which in the observed wavelengths covered is 3.3×10^{-10} erg cm^{-2} s^{-1}, probably 3.6×10^{-10} erg cm^{-2} s^{-1}, with reasonable allowance for the far infrared and ultraviolet. From an accurate parallax, the luminosity is 7.1×10^{30} erg s^{-1}; within the range of effective temperatures 10,000 to 16,000 K, the radius varies from 0.0135 to 0.0053 R$_\odot$; however, the IUE flux in the ultraviolet is not consistent with T < 14,000 K (where there is a large ultraviolet excess). The minimum of the residuals, i.e., the "least squares" fit to a blackbody curve is at 16,000 K where the radius is 0.054 R$_\odot$. This would be much the smallest known white dwarf radius, corresponding to 1.23 M$_\odot$ (for a helium-core, zero-temperature degenerate configuration). Even the lowest plausible temperature gives a mass 1.03 M$_\odot$. It would be important to obtain a parallax also for Feige 7, where the temperature is better determined. The magnetic, polarized white dwarf (DXP type) LP44-113 = G240-72 (Gr 372) had been noted to have a remarkably low luminosity M_v = 15.22 by the USNO parallax observers (Dahn et al. 1976).

BRIEF COMMENTS ON COMPOSITION

Few or no hydrogen degenerates show metallic lines. The upper limits to the metal abundances in DA's are of little practical usefulness, and a spectrum that shows H and Ca II, like that of Ross 627 (EG 79), has been interpreted as a mixed helium-hydrogen atmosphere in which metals do appear. The usual breakdown of degenerate stars into DA or non-DA is actually a separation between nearly pure H or pure He (with some metals). It is to be hoped that a more physically meaningful spectral classification will soon be adopted. The He/H ratio in DA's is at most 10^{-3}; in HZ 43, rocket observations with a spectrometer developed by Malina (1979) show an apparent He II photoionization continuum at $\lambda228$ corresponding to He/H 10^{-4} or 10^{-5}. In the DB's, He/H $\geq 10^{5}$, with some mixed DBA atmospheres near He/H = 3 to 10×10^3. Cool DB's show no He I lines, are classified as DC's. The transparency of helium occasionally results in the appearance of some metals. Several magnetic stars are mixed, DBA stars. In cool DBA's, Hα has been detected, in one magnetic star, CH. The "carbon" degenerates are a limited group of He-dominated atmospheres, with about the solar C/He ratio, and no metals. The few DO stars are quite hot and have intermediate He/H ratios; only one has been quantitatively analyzed. Very blue stars, far above the 30,000 K limit of DB stars have been found in Green's Palomar survey, many apparently of mixed composition, and will require further study. The sdO stars have a variety of He/H and probably of metal-to-helium ratios. Recent non-LTE quantitative analysis by Simon et al. (1979) of a sdO in a binary system, HD 49798 gives He/H $\approx$ 1. My

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own impression from Greenstein and Sargent (1974) is that some sdO's
show essentially only H, some only He II and He I, and others H, He II
and He I. Oke, in this conference, will show IUE observations of sdO's;
some seem to be losing mass; some are very helium rich. In their atmos-
pheres the usual highly-ionized elements, C, N, Si, are seen.

But for this I confine myself to the evidence on metal abundances
in degenerate stars with dominantly helium atmospheres. Advances in
the theory of gravitational settling, diffusion, convection and accre-
tion have been substantial; a review of the observations (see also,
Vauclair, Vauclair, and Greenstein 1979) displays the variety of metal
abundances found. In most cases, data is taken from the published re-
sults, using the adopted temperatures, except for G165-7, for which I am
indebted to R. Wehrse (in press), and Ross 640, where P. Cottrell is
analyzing my IUE data by spectral synthesis. Table III shows the re-
sults for stars hotter than vMa2, and includes upper limits for a DC.
Note that the spectral classifications used must be viewed as on an out-
moded system, and should soon be replaced by a more rational one which
separates helium from hydrogen stars, gives a temperature indicator, and
then indicates the presence of metals. The star GD 40, called DBM, has
both He I and Ca II lines; it shows Mg II $\lambda2800$ in its IUE spectrum.
G111-54 is slightly cooler, and really very similar, but at present can
only be called DF. In the table, T_3 is the effective temperature in
10^3 K, and all abundances are log $n(M)/n(He) \equiv -N$. In the abundance
column P means present, but no quantitative results yet available. In
the fifth column W(K) gives an approximate strength of H and K, if blend-
ed, or K alone. Note that if any general trend exists, it is that the
cooler strong-lined stars have, in fact, relatively lower abundances of
metals to helium than do the few hot stars that show Ca II. If the Fe/
Ca ratio is preserved, then the hot stars should have very strong ultra-
violet resonance multiplets of Fe II, worth searching for with the IUE.
The solar abundances, at the bottom, are standard values, log M/H; were
all hydrogen processed into He, then log(M/H+He) should be these values
plus 0.5. Even the most metal-rich star so far analyzed is strongly
metal deficient, except possibly GD 40. If that star fits the same
model as Ross 640, then if $N \propto W^{1/2}$, then $-N_1 = 7.8$, i.e., still metal-
deficient. Most upper limits to metal abundances derived from the ab-
sence of lines in the optical regions are 10^{-10} to 10^{-11}. The data can-
not establish any preferential abundance enhancement or deficiency as
yet, although Ca II when present seems to have the lowest deficiencies.
The most promising avenue for future exploration of this question with
the IUE or Space Telescope, is the Fe II or Mg II ratio to Ca II.

Ross 640 is a particularly well-studied object in which Liebert
(1977) found a weak $H\alpha$, corresponding to a quite low hydrogen abundance.
Cottrell's synthetic spectra were based on Liebert's model, for which
we are grateful. The IUE spectrum is well represented, except that the
core and wings of $\lambda2800$ of Mg II are not well-fitted simultaneously,
abundance differences by a factor of three being required. The
multiplets of Fe II used in synthesis went up to 1 eV excitation (UVMT,
#1-6, 32-36, 60-64) and give $n(Fe)/n(He) = 2 \times 10^{-9}$, while Liebert had
set an upper limit from the optical region at $< 2.5 \times 10^{-9}$; similarly,
the ultraviolet gives $n(Si)/n(He) = 3 \times 10^{-8}$, while Liebert's value was
$< 10^{-7}$. The most significant datum is the Mg/Fe ratio which seems well

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TABLE III

SUMMARY METAL ABUNDANCES IN HELIUM ATMOSPHERE DEGENERATES

Star	EG Gr	Type	T_3	$W(\overset{\circ}{A})$ Ca II	$-N_1 = \log n(M_1)/n(He)$ Mg	Si	Ca	Fe	Ref.
GD 40	384	DBM	15	4B	...	...	7.5	...	SGB
G111–54	346	DF	12	18	...	...	P	...	G1
GD 401	451	DFp	9.5	170	...	...	>7.0	...	G2
Ross 640	119	DFp	8.8	36	6.4	6.7	8.3	8.5	G3,Cott.
L745–46A	54	DF	7.8	7	>9.4	> 9	10.4	>9.4	Weg.,G3
G165–7	391	DG	7.5	BL	4.9	4.9	6.6	5.5	WL
Ross 627	79	DA,F	7.2	1	...	...	10	...	Ship.
Stein 2051B	180	DC	7.0	<1	> 10	...	> 10	> 10	L
G139–13	494	DG	6.6	105	...	...	P	...	G1
v Ma2	5	DG	5.5	BL	9.4	> 9	10.7	9.7	Weg.
Solar	...	...	...	...	3.7	3.7	4.9	4.3	–

Notes:

In this Table uncertainties arise from the comparison of metal abundances with He rather than H and in the solar abundances adopted.

B: K = 3, H blended Hε; BL Ca II badly blended, strong;

G1: Greenstein unpublished; G111–54 observed with Boksenberg. G139–13 must have high Ca, in range 7 to 10.

G2: Greenstein, J. L. 1976, Ap. J., 210, 524. Abundance estimate based on comparison with Ross 640.

G3: Greenstein, J. L. 1960, Stellar Astronomy, ed. J. L. Greenstein (Chicago: University of Chicago Press).

L: Liebert, J. 1976, Ap. J., 210, 715.

Ship.: Shipman, H. L. 1972, Ap. J., 177, 723. Estimate only; since he used H-atmosphere, < 10.

SGB: Shipman, H. L., Greenstein, J. L, and Boksenberg, A. 1977, A. J., 82, 7.

Weg.: Wegner, G. 1972, Ap. J., 172, 451.

WL: Wehrse, R., and Liebert, J. unpublished. Their conclusion, "metals $\approx 4 \times 10^{-5}$ solar, except for Ca down by factor three."

above the solar value. Attempts to observe v Ma2 with the IUE have failed, so far, presumably because the near ultraviolet is very strongly depressed by line blanketing.

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