11. EFFECTIVE TEMPERATURES OF WHITE DWARFS

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1. Introduction

White dwarf stars are among the most challenging and interesting objects which can be studied. Because they represent the interiors of highly-evolved stars, the chemical composition can be enormously variable from object to object. Furthermore, because of the very large gravities, the composition of the atmosphere may be very different from that in the interior. The theory of the degenerate interior provides a relation among mass, radius and chemical composition. Since temperatures, effective gravities, and redshifts can, for certain stars, provide further relations between mass and radius, one can hope to make checks on the theory which are not possible with ordinary stars.

Two parameters which are required, if the maximum possible information is to be obtained from white dwarfs, are effective temperature and gravity. These parameters are obtained for normal stars by matching absolute spectral energy distributions with fluxes computed from model atmospheres. In the case of white dwarfs, until a few years ago neither spectral energy distributions nor good model atmospheres existed. Effective temperatures had to be inferred from UBV photometry and interpolation between the main-sequence stars and black bodies. Further information was obtained from hydrogen-line profiles and rather simple model atmospheres (Weidemann, 1963).

2. Observations

It became evident two or three years ago that excellent model atmospheres would become available, and a program was launched to obtain spectral energy distributions of selected white dwarfs. The initial observations were made with the prime-focus scanner attached to the 200-inch Hale telescope. The practical magnitude limit was approximately 13, so only a few white dwarfs could be observed. With the completion of the 32-channel spectrometer two years ago (Oke, 1969) almost any known white dwarf could be observed. Consequently, the program was expanded to include several examples of the many different types of white dwarfs.

The spectral energy distributions cover the spectral range from 3200 Å to 10000 Å. Below 5600 Å the resolution is usually 80 Å; above 5600 Å is is 160 Å. The resolution is adequate to define the continuum and to measure equivalent widths of some features, but is not sufficient to measure profiles. A few scans have been made with higher

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Luyten (ed.), White Dwarfs, 67–76.

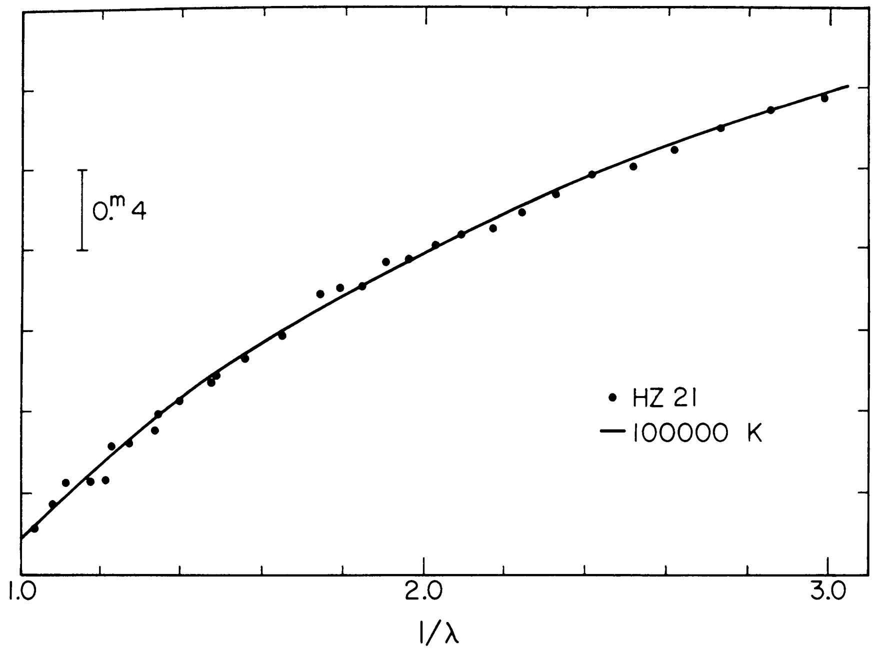

Fig. 1. *HZ 21*. This star has lines of H, HeI, HeII (Eggen and Greenstein, 1965). The continuum matches a black body with $T = 100000$ K. The absolute flux in magnitudes, as defined in Equation (3), is plotted against $1/\lambda(\mu)$.

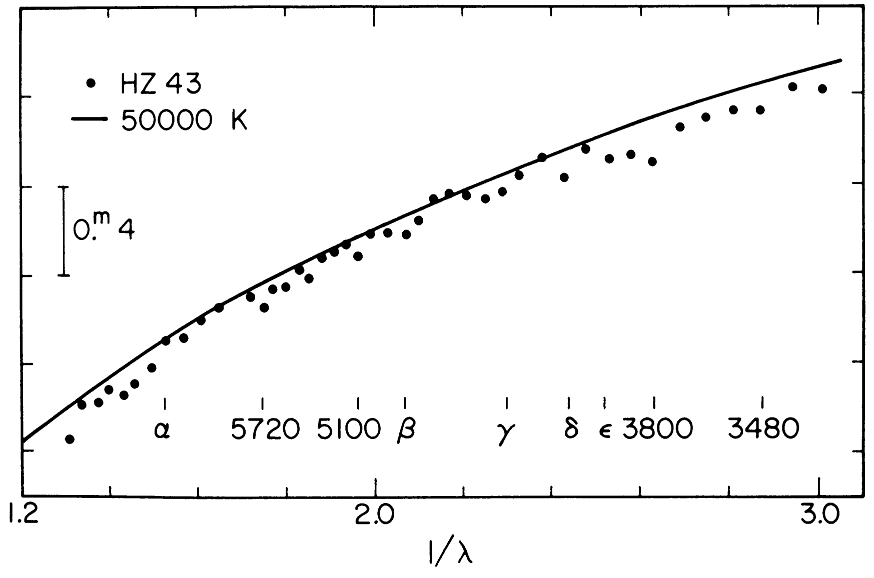

Fig. 2. *HZ 43*. This star has a faint red companion at a distance of 3″ which may contaminate the energy distribution slightly. The black body temperature is 50000 K. Hydrogen lines are weak (Eggen and Greenstein, 1965).

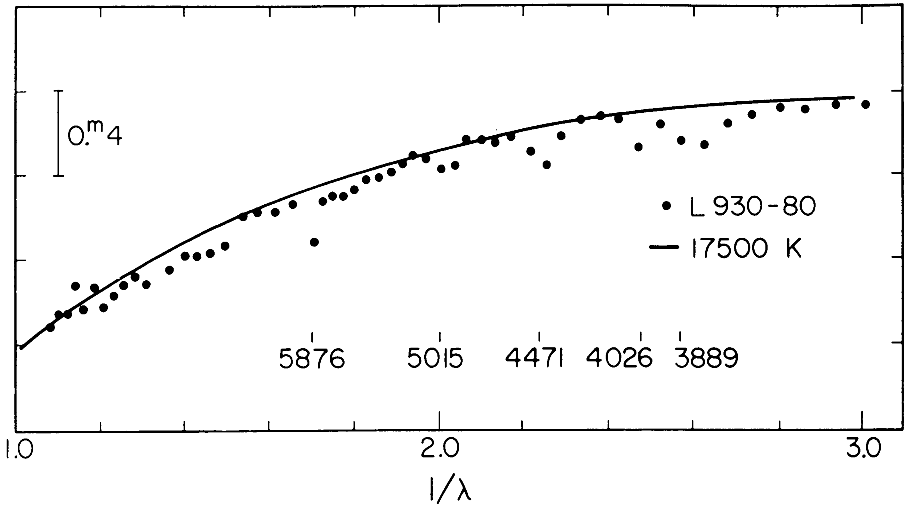

Fig. 3. *L 930-80* is of type DB and has strong Helium lines. The curve is a black body.

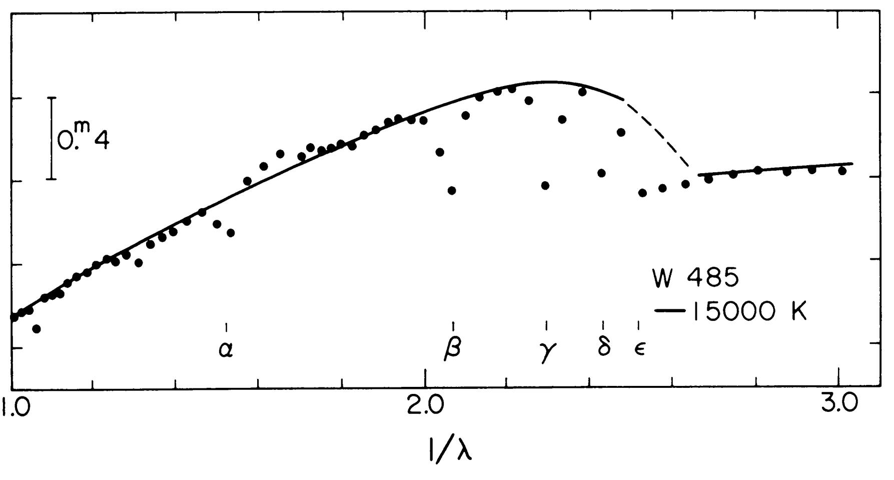

Fig. 4. *W 485* is a typical DA. The model is from Terashita and Matsushima (1969).

resolution and these can be used for profile measurements. Observations have been completed for approximately 35 white dwarfs. These include 13 of type DA, 7 of type DB, 4 of types DF and DG. The remainder are peculiar objects.

All of the objects studied here have been observed with a slit spectrograph by Greenstein (1958, 1960) and Eggen and Greenstein (1965, 1967), and these spectra can be used for line profiles and equivalent width measurements.

In Figures 1–5 are shown a few typical examples of observed energy distributions and the fitted model atmosphere fluxes (see below). In some cases, the fitted curves

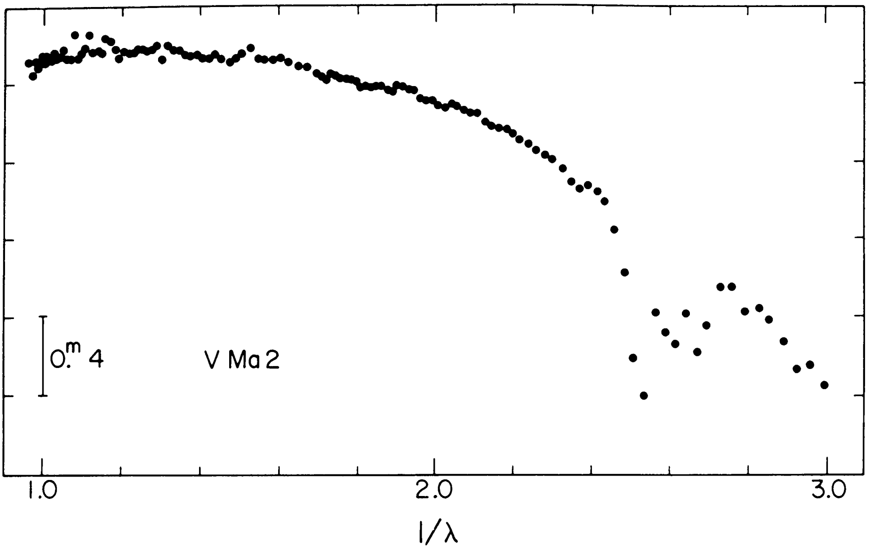

Fig. 5. *V Ma 2.* The best-known DG star. The effective temperature is probably less than 5000 K. The star has strong metal lines in the ultraviolet in addition to H and K of Ca II (Eggen and Greenstein, 1965).

are black-body curves. The results so far obtained from all the available stars are as follows:

(a) The DA stars have effective temperatures ranging from 13000 K to 50000 K.

(b) DB stars range from 15000 K to 25000 K.

(c) There are two stars with $T_e = 100000$ K.

(d) The DC star L 1363-3, which shows no features has a temperature in the neighborhood of 10000 K.

(e) DF and DG stars have a wide temperature range, at least from 4500 K to 9000 K.

3. White Dwarfs with Carbon Bands

It has been noted by Eggen and Greenstein (1967) that the white dwarf G 47-18 has both atomic C I lines and molecular bands of C_2. The energy distribution is shown in Figure 6 where the many C_2 bands are conspicuous. Another recently-discovered white dwarf, G 99-37, (Greenstein, private communication) clearly shows the same C_2 bands as G 47–18, but with different relative intensities. In addition, G 99-37 appears to have bands of CH. The difference in the band strengths and the presence of CH in one of the two stars may be a result of the obviously very different effective temperatures of the two stars.

4. Model Atmospheres

The model atmospheres used in this investigation were constructed using the program

https://doi.org/10.1017/S0074180900097102 Published online by Cambridge University Press

ATLAS, written by R. Kurucz of the Harvard and the Smithsonian Observatories (cf. Strom and Avrett, 1964, 1965; Kurucz, 1969a, 1969b). Opacity sources included H I (continuous and line opacity), H^-, H_2^+, He I, He II, He^-, Si, Mg, C, N, O, Ne in appropriate stages of ionization, and electron and Rayleigh scattering. For these models, H was the only important opacity source. The chemical composition was taken

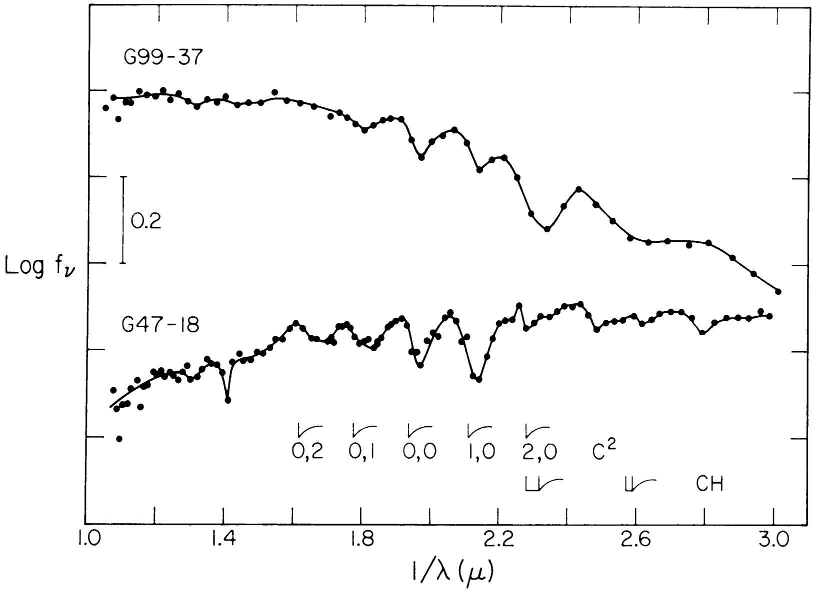

Fig. 6. Spectral energy distributions of G 47-18 and G 99-37. Various C_2 and CH molecular bands are indicated.

to be that of population I (He = 0.1, H = 0.9, metals = solar); although (see below) the chemical composition of DA atmospheres is actually almost pure H, the near-complete ionization of H and the dominance of H as an opacity source makes the metal abundance completely unimportant in its effect on the atmospheric structure. The effect of changing the He abundance to zero merely increases the surface gravity corresponding to a given model by 0.12 in the logarithm (cf. Terashita and Matsushima, 1969).

Model atmospheres were constructed for $T_{\rm eff} = 12000$, 16000, 20000, and 25000 K and $\log g = 7$ and 8. One model with $T_{\rm eff} = 16000$ K, $\log g = 7.5$ demonstrated that for the interpretation of the hydrogen-line strengths, linear interpolation over $\log g$ is satisfactory.

The present grid of models is quite similar to that presented by Terashita and Matsushima (1969). (Hereafter these authors will be referred to as TM).

The principal difference is that we have taken pressure ionization into account in computing the ionization equilibrium, white TM do not (cf. TM, 1966). This changes the electron densities at $\tau_{5000} \approx 1$ by a factor of about 2. The continuous energy distributions are unaffected by taking this factor into account, but the hydrogen-line strengths for a given model are *increased* over the earlier ones and consequently our surface gravities (and hence masses) are lower than those deduced by TM. The expression we used to compute the lowering of the ionization potential is

$$\Delta E = \frac{e^2}{\lambda_D}; \quad \lambda_D = \left[\frac{kT}{4\pi e^2 (n_e + n_i)}\right]^{1/2}.$$

Where λ_D is the Debye length; $(n_e + n_i)$ is the total charge density. At a temperature of 20000 K, this corresponds to

$$6 \log n = 21.64 - \log n_e$$

where n is the highest bound level of H. This is in reasonably good agreement with the results of Schatzman (1958) and Kolesov (1964), and agrees with the equation used by TM (1966) to compute the continuous energy distributions. A sample fit of the continuum is shown in Figure 4.

5. Procedure for Comparing Observations and Models

The scans described above for DA stars were fitted to the model atmospheres to determine the effective temperature. The deduced effective temperatures are plotted against the (U − V) color (from Eggen and Greenstein, 1965) in Figure 7. It is apparent that for DA stars cooler than $T_{eff} = 25000$ K, U − V is an unequivocal indicator of effective temperature. The difference between our temperature scale and that of Terashita and Matsushima is due to the difference in calibration. Our scale is based on a direct comparison of the stellar energy distributions and the models. Terashita and Matsushima folded the model energy distributions with the rather poorly-known UBV filter and sensitivity functions. The zero points of the UBV system, especially of the U filter, are not particularly well known.

Gravities were determined in two ways. From the scans, it was possible to measure the equivalent width of Hβ. A computer program was written to determine the equivalent width of Hβ from the models in the same way as it was measured from the scans, that is, by fixing the 'continuum' as the monochromatic intensity in a certain scanner band (usually ~200 Å from line center), folding the model flux distribution with a rectangular instrumental profile (80 or 40 Å wide), and integrating the resulting instrumentally-broadened profile. This procedure insured that models and observations were treated in a self-consistent manner and insured that systematic errors, particularly in the matter of continuum placement, were minimized. Such a procedure is necessary to avoid the ambiguity of defining what is meant by 'the continuum' in stars where most of the Balmer lines overlap.

Equivalent widths can be measured this way to an accuracy of 15%, leading to a random error in the derived value of $\log g$ of about 0.3.

We also determined surface gravities from the profiles determined by Greenstein

https://doi.org/10.1017/S0074180900097102 Published online by Cambridge University Press

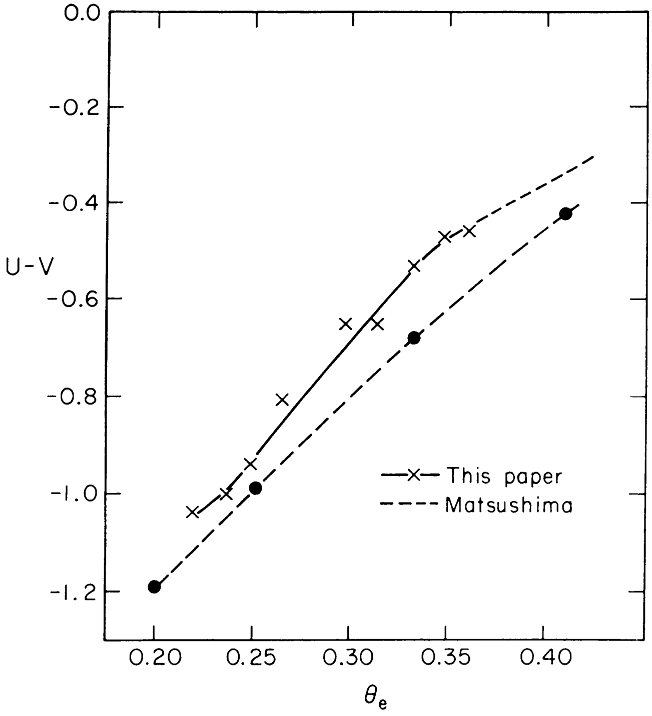

Fig. 7. A plot of the U − V color versus the derived effective temperature $\theta_e = 5040/T_e$ for DA stars.

(1960). Again, in order to treat models and observations in a self-consistent way, the profiles were normalized to zero residual intensity at $\Delta\lambda = 80$ Å. While this procedure neglects the far wings of the line, which certainly extend beyond $\Delta\lambda = 80$ Å, again the ambiguity of continuum placement is eliminated. We estimate the error in surface gravities derived from the Greenstein profiles to be about 0.2 in the logarithm. Both of the above methods give reasonably consistent surface gravities.

For stars with known distances, the radii can be determined from monochromatic magnitudes. From the models, we obtain the relation

$$\log H_{5556} = 1.52 \log (T_e/10^4) - 4.254, \qquad (1)$$

where H_{5556}, the flux at 5556 Å, is correct in the range of the models to within 2%. (H_{5556} is normalized so that $\int_0^\infty H_\nu \, d\nu = \sigma T_e^4/4\pi$). From Equation (1) and the calibration of the absolute flux of Vega by Oke and Schild (1970), we derive

$$\log R/R_\odot = - 0.76 \log (T_e/10^4) - \log \pi - 0.2 m_{5556} - 0.50 \qquad (2)$$

where m_{5556} is the monochromatic magnitude per unit frequency and π is the parallax. m_{5556} is defined by

$$m_{5556} = - 2.5 \log f_\nu - 48.60 \qquad (3)$$

where f_ν is the flux at the frequency corresponding to $\lambda = 5556$ Å in units of ergs sec^{-1} cm^{-2} Hz^{-1}. The above method avoids the uncertainties inherent in the use of bolometric corrections.

6. Helium Abundance

We have calculated He I λ4471 profiles for the models using a procedure described earlier (Shipman and Strom, 1970). The model for W 1346 predicts for the 4471 line, $W = 4.7$ Å for a helium abundance of 10% by number and $W = 2.5$ Å for a helium aboundance of 3%. Since λ4471 has not been observed in medium-dispersion spectra of W 1346 [Greenstein (private communication) cites an upper limit of 0.6 Å], it is apparent that the atmosphere of W 1346 contains little or no He. We have thus increased all values of $\log g$ deduced from the 10% helium models by 0.12 to correspond to zero helium atmosphere (cf. Matsushima and Terashita, 1969).

7. Masses and Radii

The five stars scanned which have known distances have masses and radii tabulated in Table I. Their position on the mass-radius diagram is shown in Figure 8. It is apparent that the large masses derived by Matsushima and Terashita (1969) were due to too-high surface gravities deduced from too-low electron densities in these models, due to the neglect of pressure ionization in the computation of the ionization equilibrium. The mass-radius curves in Figure 8 are from Hamada and Salpeter (1961). The large uncertainties in the radii are mostly due to the uncertain parallaxes, rather than uncertain temperatures.

Most of the stars seem to have interiors composed of Fe, although the possibility of systematic errors (especially in $\log g$) make this conclusion quite tentative. One star, L1512-34B, which is on the lower sequence, as discussed by Eggen and Greenstein (1965), seems to have a neutron core. In order for this star to fall along the Fe track in the mass-radius diagram, the surface gravity would have to be at least 8.2 even if the radius were as large as the error bars allow. We feel that this can probably be ruled out by the observations. More work is needed on the small-radius white dwarfs of the lower sequence.

It is possible to check the accuracy of our reduction procedures with 40 Eri B, which

TABLE I

Masses and Radii of Five White Dwarfs

Star	T_{eff}	100 $R/R_\odot$	log g	$M/M_\odot$
40 Eri B	17000	1.27 ± 0.06	7.85	0.42 ± 0.09
W 485	15100	1.46 ± 0.3	7.35	0.17 (+0.10, −0.07)
L1512-34B	13600	0.81 ± 0.3	7.55	0.085 (+0.08, −0.04)
He 3	21300	1.26 ± 0.3	7.60	0.23 (±0.05)
W 1346	20300	1.26 ± 0.2	7.35	0.125 (+0.08, −0.04)

has a mass of $0.43 \pm 0.04\ M_\odot$ (Popper, 1954) and a gravitational redshift k of 21 ± 4 km sec^{-1}. Our calculations predict $M = 0.42 \pm 0.09\ M_\odot$ and $k = 21 \pm 5$ km sec^{-1}. We regard this agreement as excellent. Our temperature is slightly higher than the 16300 K derived by Matsushima and Terashita (1969) because of the revised calibration of Vega (Oke and Schild, 1970).

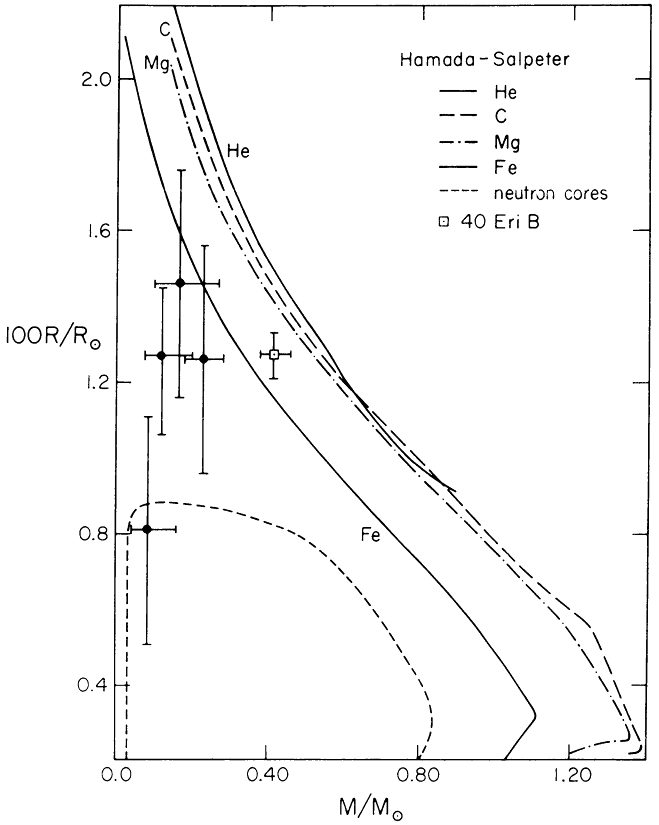

Fig. 8. The mass-radius relation as computed by Hamada and Salpeter (1969). 40 Eri B and several other stars are shown. The error bars reflect mainly the errors in the trigonometric parallaxes.

Furthermore, in deriving the surface gravity of 40 Eri B, we used the photo-electrically-measured Hγ profile of Oke (1963). When normalized to $R_v = 0.0$ at $\Delta\lambda = 80$ Å, the agreement between this profile and that of Greenstein (1960) is quite good. The surface gravities from the Greenstein profile and the Hβ equivalent width are both less by 0.14 in the logarithm than the log$g$ derived from Oke's scan; this is well within the expected error of 0.2 in the logarithm. If, in fact, the surface gravities deduced for the other four stars are slightly small, as this result *might* indicate, the deduced masses will be somewhat greater and the stars will fall nearer the Fe line in the mass-radius diagram.

8. Future Work

Using the $(U-V)-T_e$ relation of Figure 7, we plan to derive masses for as many white dwarfs as we can with known distances. We also plan to scan the Hyades white dwarfs, since their distance is known and their gravitational redshifts have been measured by Greenstein and Trimble (1967).

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