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SPECTROPHOTOMETRY OF STARS NEAR THE COOL END OF THE WHITE DWARF SEQUENCE

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SUMMARY

The spectra of five stars near the cool end of the white dwarf sequence are described. Two of these, GH7-21 and W489, have CH bands and relatively weak C_2, metal hydride, and metal line features in their spectra and thus appear hydrogen rich and metal deficient. It is suggested that they are examples of cooled down DA stars. The stars GH7-22 and L97-12 seem to have nearly continuous spectra with weak lines of Ca I and Ca II, but other weak molecular features appear present as well. This would be consistent with them being both metal and hydrogen deficient. The spectrum of LFT 526 shows strong molecular bands, notably of MgH, and metal lines, the most important being due to Ca I, Ca II and Na I. From the reduced proper motion, this star is probably intermediate between the Main Sequence and classical white dwarfs. It could therefore be either a low mass degenerate or a sdM star. From the spectra of the five stars, a few hypotheses are made regarding the appearances of the spectra of cool white dwarfs and their evolution.

1. INTRODUCTION

Cool degenerate stars are important for understanding the evolution of the white dwarfs. The existence of two abundance subclasses has led to the suggestion that the white dwarfs' envelope compositions evolve due to the onset of convective mixing and perhaps accretion of interstellar matter as they cool down (*cf.* Strittmatter & Wickramasinghe 1971; Shipman 1972; Baglin & Vauclair 1973). The very coolest degenerates should have relatively deep outer convection zones and evidently, molecular features will become increasingly important at lower effective temperatures, the dominant molecules depending on the relative atmospheric abundances. Ultimately, such stars could give information on possible processes such as mixing in white dwarf envelopes which are important for understanding their cooling history.

However, this is not so easy to do, for Greenstein's (1971) study has indicated that it is difficult to find true degenerates cooler than the Sun. This may be a real physical effect or due to the lack of very faint stars being studied. No matter what the reason may be, the spectra of few stars near the cool end of the white dwarf sequence have been described up to the present and this is an attempt to take first steps in that direction.

2. OBSERVATIONS

The basic astronomical data for the stars in this paper are given in Table I. The *UBV* data are taken from Eggen & Greenstein (1965) and Eggen (1969),

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TABLE I

The observed stars

Star	α_{1950}	δ_{1950}	m_V (mag)	$B-V$ (mag)	$U-B$ (mag)	π (″)	M_V (mag)	Notes
GH7-21	$03^h 47^m \cdot 2$	$+09° 12'$	(13·7)	+0·6:	−0·4:	—	—	1
GH7-22	$03^h 47^m \cdot 2$	$+13° 16'$	14·94	+0·75	−0·04	—	11·9	2
LFT 526	$07^h 22^m \cdot 2$	$-39° 13'$	13·66	+1·34	+1·04	—	—	—
L97-12	$07^h 52^m \cdot 8$	$-67° 38'$	14·09	+0·66	−0·17	+0·173	15·25	3
W489	$13^h 35^m \cdot 3$	$+03° 52'$	14·68	+0·96	+0·37	+0·124	15·2	4

Notes to Table I:

(1) A possible Hyad. The colours are estimated from the electronographic spectra.
(2) A possible Hyad. M_V from Eggen (1969).
(3) Trigonometric parallax from Jenkins (1963).
(4) Parallax discussed in Wegner (1972).

except for the star GH7-21 where the colours could be estimated roughly from the electronographic spectra. Where available, parallaxes and the resulting absolute magnitudes are also given.

The spectroscopic observations were made using four different telescopes and are summarized in Table II. Three of these instruments (Kitt Peak, Mount Stromlo and Radcliffe) employ Carnegie-type image-tubes and Eastman Kodak IIa-O photographic plates. These spectra have comparable resolutions with reciprocal dispersions between 100 Å mm^{-1} and 140 Å mm^{-1} and have instrumental profiles with half widths in the range of 2·8 and 5·0 Å, respectively. A detailed description will not be repeated and relevant references are given in Table II. The spectra obtained with the 98-in. (2·5-m) Isaac Newton telescope were obtained with a Spectracon image-tube and Ilford G5 and XM electronographic emulsions on a mylar film backing. These spectra have a reciprocal dispersion of about 210 Å mm^{-1} and cover the approximate wavelength interval 3500–6000 Å. Descriptions of the Spectracon, emulsions and spectrograph used on the 2·5-m telescope are given by Kahan & Cohen (1969) and Palmer & Milsom (1972).

TABLE II

The spectroscopic observations

Star	Plate No.	Date (UT)	Exposure (m)	Telescope	Remarks
GH7-21	647·4	1973 Sept. 22	150	2·5-m Isaac Newton	G5
	654·2	1973 Oct. 4	70	2·5-m Isaac Newton	G5
	658·1	1973 Oct. 6	30	2·5-m Isaac Newton	XM
GH7-22	657·5	1973 Oct. 5	48	2·5-m Isaac Newton	XM
	974·1	1974 Oct. 22	46	2·5-m Isaac Newton	XM
LFT 526	Cx 1002 C1	1974 Mar. 2	60	1·9-m Radcliffe	
L97-12	2355	1972 Mar. 21	40	1·9-m Mount Stromlo	
	2364	1972 Apr. 4	63	1·9-m Mount Stromlo	1 mm wide
W489	Cl 1600a	1970 May 2	52	2·2-m Kitt Peak	
	Cl 1600b	1970 May 2	50	2·2-m Kitt Peak	
	Cl 1605	1970 May 3	58	2·2-m Kitt Peak	
	Cl 1610a	1970 May 4	50	2·2-m Kitt Peak	

Particulars regarding the instrumentation employed can be found in earlier papers, For the Kitt Peak, Mount Stromlo and Radcliffe observations see Wegner (1972, 1973. 1975), respectively. The Isaac Newton telescope observations are described in the text.

Intensity tracings of the spectra were made in Oxford using the Moll-type microphotometer, except for those of W489 which were traced in Pretoria with the Joyce–Loebl microphotometer of the Radcliffe Observatory. The spectra on photographic plates were converted to intensity using standard procedures, while for the electronographic spectra, a linear relation between density and intensity was assumed.

3. DESCRIPTIONS OF THE SPECTRA

3.1 *GH7-21*

This is a possible Hyad according to Giclas, Burnham & Thomas (1962) and Luyten (1971); but because of its brightness, may be a foreground star with the motions of the Hyades. The estimated broadband colours in Table I would place it near the blackbody line in the two-colour diagram and the intensity registration of the star's spectrum in Fig. 1(a) further indicates that it is degenerate because of the large pressure broadening. The strongest spectral features correspond to the CH band heads listed by Pearse & Gaydon (1963). The strength and sharpness of the CH band head near λ 4300 is particularly remarkable and also is present in the spectrum of W489. The weak depressions near λλ 4700 and 5165 could be C_2 while Ca I and Ca II may be present.

One star, the magnetic white dwarf G99-37 (=EG248), has a somewhat similar spectrum and broadband colours ($B–V = +0{\cdot}46$). It has been described

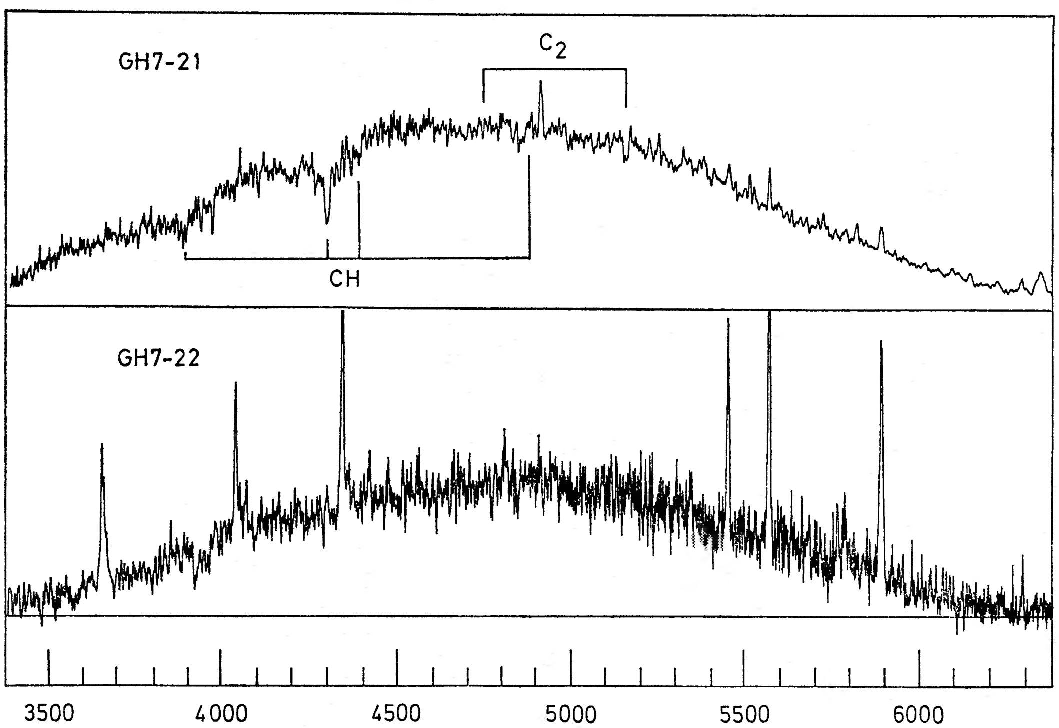

FIG. 1. *Intensity registrations of the spectra of two Hyades suspects observed with the 2·5-m Isaac Newton telescope, original reciprocal dispersion about 210 Å mm⁻¹. The zero intensity levels are located at the bottom of each panel. (a) GH7-21 from spectrum No. 647·4 with Ilford G5 film. The strongest observed spectral features and their possible identifications with molecular bands are indicated. (b) GH7-22 from spectrum No. 974 using Ilford XM emulsion. The feature near λ 3950 is attributed to Ca* II.

by Greenstein *et al.* (1971) and Angel & Landstreet (1974) find a value of $3 \cdot 6 \times 10^6$ G for the magnetic field from the variation of polarization across the CH band. From a model atmosphere analysis, Grenfell (1974) found that for $T_{\text{eff}} = 6300$ K and $\log g = 8$, the C and O abundances are nearly equal and about 0·1 per cent, other metals are strongly depleted, and $N_{\text{CH}} \approx 13 N_{\text{C}_2}$ which indicates a hydrogen abundance considerably higher than for helium-rich white dwarfs like vMa2. Bues (1973) reached similar conclusions from a study of the continuum energy distribution of the star.

While GH7-21 and G99-37 both show C_2 and CH band heads, they differ in that the CH bands appear to be stronger in the spectrum of GH7-21 with respect to the C_2 bands than they do in G99-37, so it is possible that GH7-21 has an even higher H abundance. If GH7-21 is a Hyad, it is tempting to identify it as a cooled down star which was previously a H-rich and metal-poor DA. Unfortunately, any interpretation must await further observations and a trigonometric parallax.

3.2 *GH7-22*

Like GH7-21, this star is a possible Hyad. Eggen (1969) gave *UBV* photometry and discussed the luminosity. The spectrum, as can be seen from Fig. 1(b), is nearly featureless, except for weak H and K lines of Ca II. Thus it resembles several of the stars classed by Wegner (1973) as DF, on the basis of only weak H and K lines being visible, which have similar *UBV* colours. If a CH band as strong as the λ 4300 feature in GH7-21 existed in this star, it would be detectable with the present data. Additional weak molecular features might exist in the spectrum as is hinted by possible discontinuities in the slope of the spectrum near $\lambda\lambda$ 4700 and 5100.

3.3 *LFT 526*

The interesting spectrum of this cool star has been described briefly in Wegner (1975) where it was originally considered to be a white dwarf suspect on the basis of its proper motions fitting the W219 group convergent point. No parallax is available but published *UBV* colours and the reduced proper motion,

$$H = m + 5 \log \mu + 5,$$

combined with Jones' (1972) discussion would suggest that LFT 526 lies between the white dwarf and Main Sequences. Little is known about the spectra of sub-luminous stars this red. Greenstein (1971) has described a number of metal-poor sdM stars. Generally, they have weak TiO and strong MgH bands. These characteristics can be seen in Fig. 2 where several of the strongest depressions can be attributed to MgH. If TiO is present, it is very weak.

3.4 *L97-12* (also known as EG56)

Bell & Rodgers (1964) were the first to obtain a spectrogram of L97-12 and classed it as spectral type DC. They noticed that this star has a large proper motion and considered it a W219 group member. On the basis of the broad shallow feature in the star's spectrum in the wavelength region λ 4900 to λ 5300 being present, it was classed earlier as a C_2 white dwarf (Wegner 1973). However, other possible contributors could include MgH and Mg I. Also neither the spectrum nor the colours are like other C_2 white dwarfs, so this classification should probably be revised. Recently, Greenstein (1974) showed that such a shallow depression is characteristic of the cool magnetic white dwarfs.

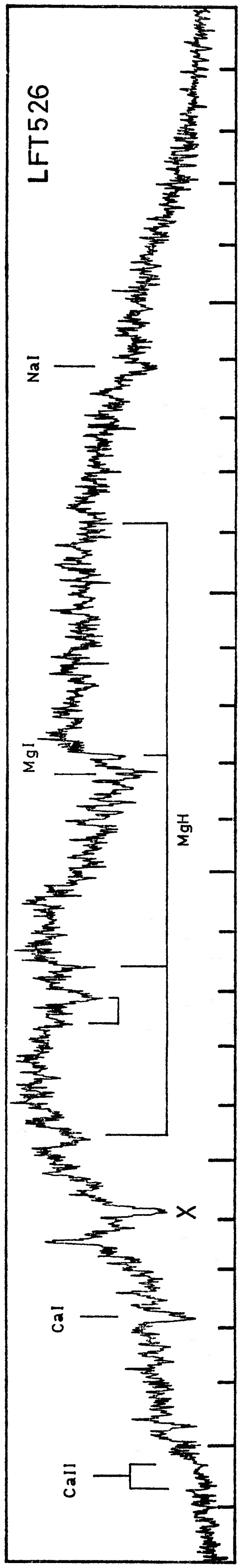

FIG. 2. *Intensity scan of the spectrum of LFT 526 from Radcliffe 1·9-m telescope No. Cx 1002 C1, observed by T. Lloyd-Evans. The original reciprocal dispersion is 146 Å mm^{-1}. The strongest features and their possible identifications are indicated. The depression marked by 'X' near λ 4400 is an image-tube defect. The zero intensity level is located at the bottom of the panel.*

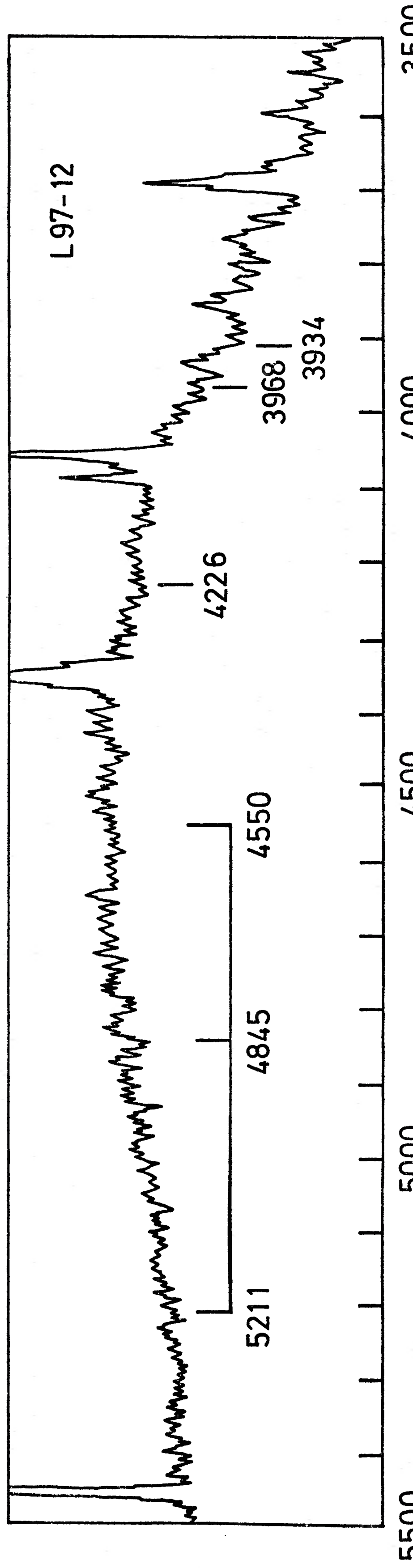

FIG. 3. *The intensity registration of the spectrum of L97-12 obtained by averaging two Mount Stromlo (1·9-m telescope) spectra. The original reciprocal dispersion is 100 Å mm^{-1}. Probable real features in the spectrum are marked. For possible identifications, see the text. The zero intensity level is located at the bottom of the panel.*

In Fig. 3 is shown the intensity registration of the spectrum of L97-12 constructed by averaging two Mount Stromlo spectra. Weak spectral features that are believed to be real are marked. At shorter wavelengths, weak highly pressure broadened lines of Ca I and Ca II seem present. The contribution of the Ca_2 quasi-molecule in the region near λ 4226 (Espenhain, Kusch & Lochte-Holtgreven 1965) should also be considered a possible contributor. Additional weak depressions which reasonably fit with MgH band heads are indicated. An additional feature near λ 4500 which appears very strong in W489 could be due to CaH.

The large trigonometric parallax of L97-12 establishes without a doubt that it is a classical degenerate star. The $(B-V)$ colour would suggest that the star has an effective temperature between that of GH7-21 and W489. The absence of the strong λ 4300 CH feature indicates an atmospheric composition different from these stars.

3.5 *W489* (also known as EG100)

This star is among the coolest of the known degenerate stars whose true nature is definitely established by a large trigonometric parallax. Eggen (1970) gives $(R-I)_K = +0{\cdot}33$. For a blackbody this corresponds to $T_{\text{eff}} \doteqdot 4500$ K, while Wehrse's (1972) solar composition ($\log g = 8$) white dwarf models yield $T_{\text{eff}} \doteqdot 5100$ K. From the standpoint of its colours, Weidemann (1966) and Wehrse (1972) have suggested that this star is a cool hydrogen-rich white dwarf. Eggen & Greenstein (1965) called the star a DK, having weak H and K lines of Ca II. Wegner (1972) suggested the spectral classification DC.

The spectra of Wegner (1972) have been re-examined. In this investigation, tracings were made at a low dispersion to bring out the presence of very broad shallow spectral features which had been missed earlier. In Fig. 4 is the registration

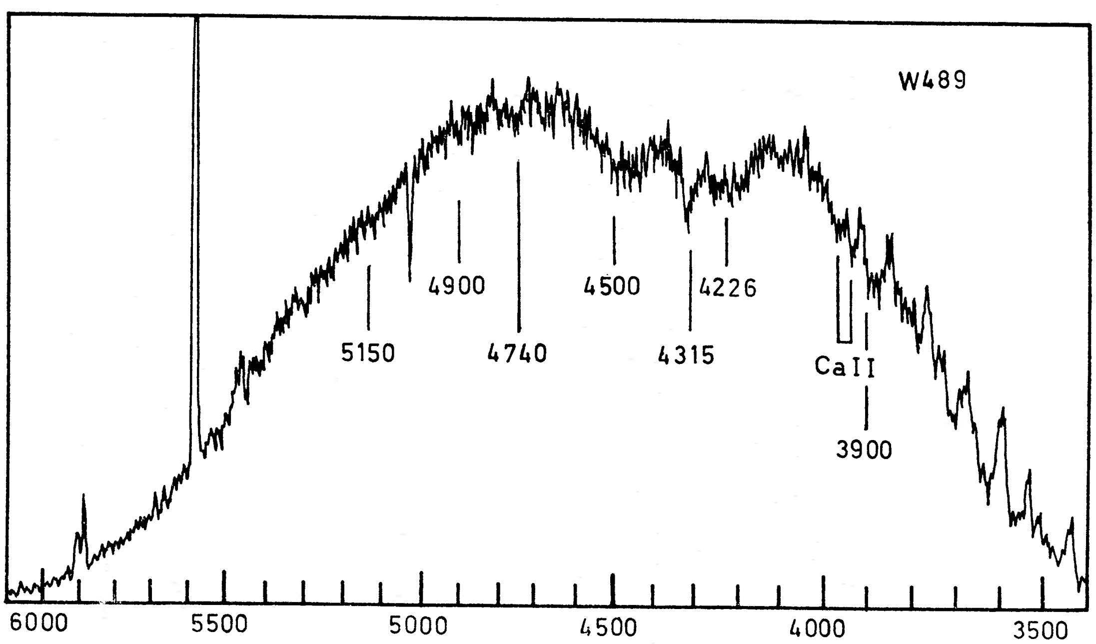

FIG. 4. *Intensity tracing of the spectrum of W489 from Kitt Peak (2·2-m telescope) spectrum No. Cl 1610. Spectral features which appear on all four available spectra are indicated. Original reciprocal dispersion was 124 Å mm⁻¹. Possible identifications are discussed in the text. The sharp depression near λ 5000 is an image-tube defect. The zero intensity level is located at the bottom of the panel.*

of one of the spectra where features seen on all available Kitt Peak spectra are indicated. Highly broadened λ 4226 of Ca I and weak H and K of Ca II seem present. The sharp λ 4315 CH band head and weaker CH band head near λλ 4900 and 3900 are present. The weak depressions near λλ 5150 and 4740 could be due to C_2.

The strong dip near λ 4500 may offer an additional important clue towards understanding the atmospheric abundances in W489 and the other cool white dwarfs. This feature may also be weakly present in the spectra of GH7-21 and L97-12. One possibility is that this is a band head of CaH. To check this identification, observations should be made to see if the stronger λλ 6946 and 6346 band heads of the molecule are present in the star's spectrum. Another possible identification is the λ 4502 system of NH. There seems to be no evidence for TiO in the spectrum of this star.

4. CONCLUSIONS

Detailed interpretation of the spectra of white dwarfs as cool as those reported on here requires appropriate atmospheric models. Wehrse's (1972) solar-like models with $\log g = 8$ show what effects need to be included and provide a framework for the present discussion. From these considerations, it seems clear that none of these stars have solar composition atmospheres and that both H-rich and H-poor stars exist among the cool white dwarfs. For solar-like ($\log g = 8$) models, some very strong spectral features are predicted, for example, near λλ 5180 and 4226, whereas in the star studied here, these features are too weak, suggesting a reduced metal abundance.

The two stars, GH7-21 and W489 seem to be hydrogen-rich in the sense that they have observable bands of CH and weak metal features due to Ca I and Ca II in their spectra. The abundance, N, of Ca in W489 can be estimated very roughly with respect to Wehrse's (1972) 5100 K convective solar composition model which appears to have nearly the same $T_{\rm eff}$. Since the lines will lie on the damping portion of the curve of growth,

$$\Delta \log N \doteq 2\Delta \log W - \Delta \log \alpha,$$

where W and α are the line's equivalent width and the damping parameter, respectively. From the tracings, $\Delta\alpha \doteq 0$ and for Ca I and Ca II, W(W489) : W(model) = 6·5 : 64 and 4 : 120, respectively, where W is in Å. These values are highly sensitive to the location of the continuum, but indicate that $\Delta \log N = -2$ to -3 for Ca. Apparently, even larger reductions would be required for GH7-21.

This estimate of $\Delta \log N$ is not valid if it is assumed that the atmospheres are not hydrogen-rich, but a hydrogen-rich atmosphere with low metal abundances would be consistent with these stars being cooled down DA stars, which Weidemann (1966) suggested for W489. From the absence of metal lines in the spectra of the hot DA stars (*cf.* Strittmatter & Wickramasinghe 1971), it appears that the metal abundances are reduced in the H-rich white dwarfs. The results of Shipman (1972) for one cool DA-F star, which shows a weak Ca II line suggest that the metals are reduced to about 1 per cent, similar to the above value for W489.

Two more of these stars, L97-12 and GH7-22, however, seem to be both hydrogen- and metal-poor since their spectra are nearly continuous. Their atmospheric abundances are most likely similar to the DF and DG stars like vMa2 and

R640 that seem to have H and metals reduced by 10^4–10^5 from the solar value. Thus these stars could represent an extension of a cooling sequence of H and metal-poor white dwarfs extending from the hot DB's through the DC's down to even lower effective temperatures.

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