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G74–7: A TRUE DA,F (DAZ) WHITE DWARF

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ABSTRACT

We report the first results of an observational attempt to confirm the existence of DA,F white dwarfs (cool, hydrogen-rich with calcium lines) using precision digital spectrophotometry. We have carried out high-resolution observations of 16 cool white dwarfs ($T_e \lesssim 9500$ K), variously classified as DA, DA,F, or DF stars. This survey has yielded only one object, G74–7, with a sharp and narrow Ca II K line of equivalent width 0.7 Å. Upper limits on the width of the K line in the other objects are typically ~ 0.25 Å. The corresponding photospheric calcium abundance in G74–7 is Ca/H ~ 1.2 $\times 10^{-9}$, and the line profile is consistent with theoretical predictions. We discuss the origin of the observed calcium and show that the heavy element diffusion time scale in the envelope is short compared to the evolutionary time scale of the white dwarf. We suggest that the observed calcium in G74–7 is the signature of a recent encounter with an interstellar cloud of moderate density.

Subject headings: stars: abundances — stars: individual — stars: white dwarfs

I. INTRODUCTION

The spectral class DA,F—now DAZ in the new classification system of Sion *et al.* (1983)—comprises white dwarfs with spectra exhibiting broad Balmer lines together with the Ca II K line (the H line is blended with Hϵ). Introduced a few decades ago, this spectral type has traditionally been assigned on the basis of photographic (e.g., Greenstein 1960) and, later, image tube (e.g., Hintzen and Strittmatter 1974) spectra. The prototype of that class of objects has usually been Ross 627, a cool hydrogen-rich star ($T_e = 7400$ K; Shipman 1979 and Liebert and Wehrse 1983), with a weak, diffuse K line reported by Greenstein (1960)[3].

Several pieces of information, gathered over the past few years, have called into question the very existence of hydrogen-rich white dwarfs with Ca II lines. First, Wegner (1972) was unable to detect the K line on his photographic spectra (49 Å mm^{-1}) of Ross 627. Second, Shipman (1977) has shown that the profile of the λ3933 line in Ross 627 could not be fitted by his calculations of van der Waals broadening in pure hydrogen atmospheres, although the equivalent width could be fitted with a calcium abundance Ca/H ~ 3×10^{-9}. In this case, however, the predicted line is narrow and sharp, in contrast to Greenstein's (1960) spectra which reportedly showed a broad and shallow feature. Shipman suggested that inaccurate broadening parameters, or perhaps an unknown broadening mechanism, were the cause of this discrepancy.

More recently, Bessell and Wickramasinghe (1977) have cast further doubt on the existence of this class of stars. Their observations of three of these objects showed two of them to be subdwarfs, while the third one showed no evidence of the K line on a good spectrum at 10 Å mm^{-1} dispersion. They suggested that the DA,F stars were probably rarer than previously thought and, in fact, pointed out that no new DA,F star had been confirmed since the advent of detectors with sky-subtraction capabilities. Finally, Liebert and Wehrse (1983) have recently reported high-resolution (~ 3 Å) digital spectrophotometry of Ross 627 and failed to detect the K line [$W(\lambda 3933) = 0.25 \pm 0.5$ Å]. They reclassify Ross 627 as DA.

In order to clarify the observational status of the DA,F stars and, especially, to check on the Bessell and Wickramasinghe (1977) suggestion, we have secured high-resolution digital spectrophotometry of 16 objects, variously classified as DA, DAwk, DAs, DA,F, or DF in the McCook and Sion (1977) catalog. These observations are part of a detailed study of the atmospheric properties of cool DA white dwarfs which is presently being carried out by us.

The new observations are presented in § II, where we report the detection of the Ca II K line in one object, G74–7. The implications of these observations are discussed in § III, where we discuss some of the problems posed by the presence of metals in the photospheres of cool, hydrogen-rich white dwarfs.

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[3] There seems to be some confusion in the literature concerning the reported equivalent width of the K line in Ross 627. Greenstein (1960) classifies it as DA,F and gives $W(H\gamma) = 5.6$ Å and $W(\lambda 3933) = 1.1$ Å. However, its reclassification by Eggen and Greenstein (1965*a*) as DF has occasionally—and mistakenly—been understood to mean that $W(\lambda 3933) = 5.6$ Å (McCook and Sion 1977; Bessell and Wickramasinghe 1977).

TABLE 1

SUMMARY OF OBSERVATIONS

STAR	WD	EG/Gr	SPECTRAL TYPE Old[a]	SPECTRAL TYPE New[b]	$T_e/10^3$ K	REFERENCES	$W(\lambda 3933)$ (Å)
G74–7	0208+39	168	DAs, DA[c]	DAZ7	7.4	1	0.70 ± 0.14
G217–37	0009+50	381	DC, DA,F	DA7	7.0	2	$\lesssim 0.20$
G250–26	0648+64	342	DA,F	DA8	6.0	2	$\lesssim 0.65$[d]
G144–51	2059+19	377	DAwk, DA,Fwk	DA7	6.8	1	$\lesssim 0.25$
G128–13	2240–01	154	DA, DA,Fs	DA5	9.2	3, 4	$\lesssim 0.26$
G128–7......	2248+29	283	DAswk, DF	DA9	5.8	5	$\lesssim 0.17$
G156–64	2253–08	178	DA,F, DAswk	DA7	7.4	1	$\lesssim 0.23$
G271–115 ...	0135–05	11	DAs	DA7	7.3	1, 4	$\lesssim 0.12$
GD 66	0517+30	...	DA	DA6	9.4	6	$\lesssim 0.11$
GD 69	0532+41	319	DAs	DA7	7.6	4	$\lesssim 0.16$
GD 290......	0543+57	341	DA	DA5	9.8	3	$\lesssim 0.11$
G108–26	0644+02	484	DAs	DA7	7.2	2	$\lesssim 0.27$
G90–28......	0752+36	345	DAwk, DAs	DA6	7.9	1, 4	$\lesssim 0.16$
G259–21	1756+82	199	DAss	DA7	7.5	1	$\lesssim 0.19$
G92–4	1953–01	135	DAs	DA6	8.2	1, 4	$\lesssim 0.13$
G187–32	2111+26	447	DAs	DA5	9.3	1	$\lesssim 0.20$

REFERENCES.—(1) Shipman 1979. (2) Shipman's (1979) calibration of $(G-R)$. (3) Shipman 1977. (4) Koester, Schulz, and Weidemann 1979. (5) Wehrse and Liebert 1980. (6) Koester, Schultz, and Weidemann (1979) calibration of $(B-V)$.

[a] Taken from McCook and Sion (1977).

[b] Based on the new white dwarf spectral classification system of Sion *et al.* (1983).

[c] Greenstein (1976) has classified this star DA,F on the basis of multichannel scanner data.

[d] Cool faint star ($V_{MC} = 16.6$) with possible broad shallow Ca II feature.

II. OBSERVATIONS

Digital spectrophotometry of the 16 objects listed in Table 1 was obtained on 1982 October 7, 8 and 11 using a photon-counting Reticon detector system behind an ultraviolet-sensitive image tube package on the Steward Observatory 2.3 m reflector and Cassegrain spectrograph. All objects were observed with the 832 lines mm^{-1} grating, which provides good coverage of the region between 3600 Å and 4400 Å. Typical exposure times were ~ 48 m for a 15th mag star. The small-scale noise in all spectra was removed by a four-channel smoothing, and the resulting spectral resolution is typically 2.25 Å.

Fifteen of the 16 objects observed showed no feature near 3933 Å deeper than 10%–15% on the smoothed spectra. Upper limits on the equivalent width of the K line have been estimated and are summarized in Table 1; they are typically less than 0.25 Å, except for G250–26, the faintest object observed, which has weak high Balmer lines and, at most, a broad shallow depression near 3930 Å. However one object, G74–7 (= WD 0208+39, EG 168, G133–72, G134–8, LHS 151, $\alpha_{1950} = 02^h08^m.2$, $\delta_{1950} = +39°41'.5$), shows a sharp K line, in addition to the Balmer series—visible up to H9. This star is classified DAs in Eggen and Greenstein (1965*b*). However, these authors added as a footnote: "possible weak K line?"; later Greenstein (1976) listed it DA,F on the basis of multichannel scanner data at 40 Å resolution.

The integrated spectrum of G74–7, consisting of six separate exposures on three different nights (total exposure: 96m) is shown on Figure 1, and an enlargement of the 3930Å region is shown on Figure 2. We measure

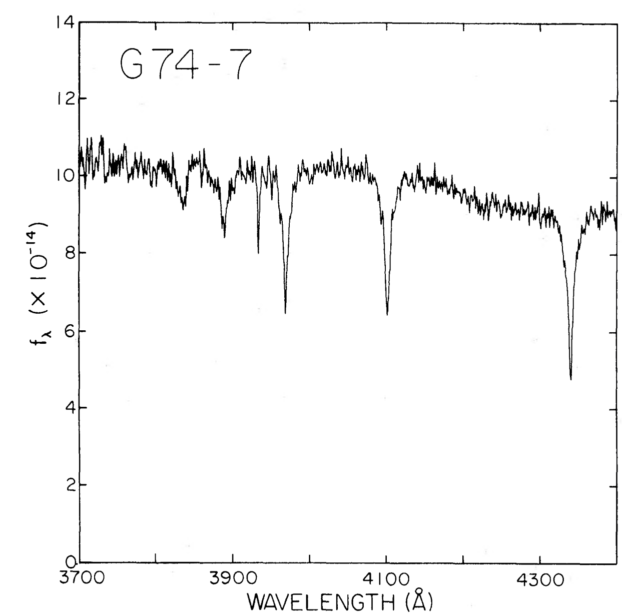

FIG. 1.—Integrated blue Reticon spectrum of G74–7. The hydrogen lines (up to H9) and the sharp Ca II λ3933 line are clearly visible. The resolution is 2.25 Å.

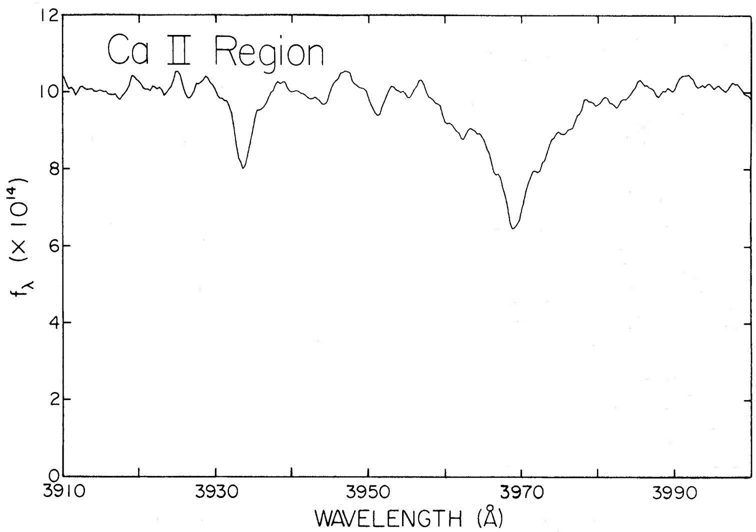

FIG. 2.—The region around 3950 Å in the spectrum of Fig. 1

W (λ3933) $= 0.70 \pm 0.14$ Å, and a full width at half-central depth $w_{0.5} = 2.6 \pm 0.3$ Å. In addition, we have at best a marginal detection of the Ca I λ4227 line at $W \simeq 0.20 \pm 0.2$ Å. There is no doubt that the observed feature near 3933 Å is real. It was detected on each of the six separate measurements, i.e., two independent Reticon arrays on each of three nights. Furthermore, the feature was not detected in any of the exposures immediately preceding or following those of G74–7.

The heliocentric velocity measured from the Ca II K line, 18 km s^{-1}, is in adequate agreement with the value of 29 km s^{-1} measured from the hydrogen lines by Greenstein and Trimble (1967) but agrees less well with the mean for Hγ and Hδ of +2 km s^{-1}. We note that radial velocity standards were not used for this project and that the spectrograph—which includes a two-stage magnetic image tube—has not been tested for careful radial velocity work.

Finally, we measured the following equivalent widths over intervals limited to ±50 Å about the line center: W(Hγ) = 6.0 Å, W(Hδ) = 4.4 Å, W(Hε + Ca II H) = 3.1 Å, W(H8) = 2.4 Å, and W(H9) = 1.2 Å. These values should be accurate to ±15%, the principal uncertainty being in the placement of the continuum amid overlapping Balmer wings.

III. DISCUSSION

It is very likely that the observed Ca II line in G74–7 is of photospheric origin. An interstellar feature of that strength would require a distance to the star of ~2.4 kpc, according to the standard Ca II equivalent width-distance relation in the interstellar medium (e.g., Beals and Oke 1953)! The possibility of an interstellar cloud on the line of sight to G74–7 appears also quite unlikely. The mean absolute parallax adopted by Shipman (1979), $\pi_{abs} = 0''.059 \pm 0''.005$, based on Naval Observatory and Yerkes data, yields a distance to G74–7 of ~17 pc. To produce an interstellar K line of the observed strength, the neutral hydrogen column density required within 17 pc would then have to be of the order of 2×10^{21} cm^{-2}. However, Bohlin, Savage, and Drake (1978) report a column density of neutral hydrogen of only $(3.6 \pm 1.1) \times 10^{20}$ cm^{-2} in the direction of HD 14633 ($\alpha_{1950} = 02^h19^m.8$, $\delta_{1950} = +41°15'.5$), a star located at 2 kpc and quite close to G74–7 in the sky.

It is possible to obtain an estimate of the calcium abundance in G74–7 from the published analysis of Shipman (1977), as Ross 627 and G74–7 have essentially identical multichannel $G - R$ colors, and thus effective temperatures ($T_e \sim 7400$ K). This happy circumstance allows us to use Shipman's results for Ross 627, namely that the equivalent width of the K line originally reported in that object (1.1 Å) could be fitted with an abundance ratio of Ca/H = 3×10^{-9}.[4] At that effective temperature, the K line is saturated (Shipman 1977). Working on the square root part of the curve of growth,

[4]In this case, however, Shipman could not fit Greenstein's (1960) reported profile of the Ca II line and had to resort to additional rotational broadening for that purpose. The other calcium abundance ratio reported in Shipman's paper Ca/H = 1.2 × 10^{-10}, was obtained by increasing the van der Waals broadening parameter by three orders of magnitude in order to fit the observed line width. Clearly, there is no need to postulate either large rotational velocities or an unknown broadening agent for the fit to G74–7, as the observed sharp Ca II profile appears consistent with the theoretical predictions of van der Waals broadening in a hydrogen-rich atmosphere.

TABLE 2

CALCIUM ABUNDANCE IN COOL HYDROGEN-RICH STARS

Star	EG/Gr	$T_e/10^3$ K	[M/H][a]	References
G74–7	168	7.4	−3.2	This work
G128–7	283	5.8	< −4	1
BPM 4729......	56	5.5	< −4	2
LP 658−2[b]	45	4.3	−5.2	3
Wolf 489[b]	100	4.1	−5.9	3
LP 701–29[b]	...	4.0	~ −3	4

REFERENCES (1) Wehrse and Liebert 1980. (2) Wickramasinghe and Bessell 1979. (3) Shipman 1977. (4) Cottrell, Bessell, and Wickramasinghe 1977.

[a] $[M/H] \equiv \log[(Ca/H)/(Ca/H)_\odot]$.

[b] Star too cool to show hydrogen lines. The model atmosphere analysis *adopted* a hydrogen-rich composition.

we obtain a calcium abundance $Ca/H \approx 1.2 \times 10^{-9}$, or $[M/H] \approx -3.2$, in G74–7. This abundance is compared to other determinations of the Ca/H ratio in cool hydrogen-rich white dwarfs in Table 2.

Likewise, the coincidence with the ~ 7400 K temperature of Ross 627 permits the hydrogen line strengths of G74–7 to be compared with those of that star and the Liebert and Wehrse (1983) predictions. Within the measuring errors, the strengths of Hγ through H9 reported here match those measured for Ross 627. Thus G74–7, like Ross 627, shows much too flat a Balmer decrement to have a helium-enriched atmosphere. Helium enrichment should thus not play a role in the origin of the Ca II line. Rather, the spectrum of G74–7 appears to be similar in the hydrogen line strengths to that of other cool DA's, though this topic will be pursued more rigorously in a subsequent paper.

The presence of calcium in detectable amounts in the photosphere of G74–7 revives the problem posed by the presence of metals in the atmospheres of white dwarfs. The early diffusion calculations of Fontaine and Michaud (1979*a*) and Vauclair, Vauclair, and Greenstein (1979) showed that the diffusion time scale of metals at the bottom of the convection zone in the envelopes of DA white dwarfs were always much shorter than the cooling time scale, and thus that primordial metals would rapidly settle out of the stellar photosphere. For example, for a 0.6 $M_\odot$ DA star with a pure hydrogen envelope at $T_e = 7400$ K, calculations analogous to those of Fontaine and Michaud (1979*a*) yield diffusion time scales for Ca of 3.2×10^2–3.5×10^3 yr depending on the ionization state of calcium at the bottom of the convection zone.

The approach used in these earlier computations ignores the effects of screening on the interaction potential between the diffusing particles. As pointed out by Fontaine and Michaud (1979*b*), this leads to diffusion time scales that may be substantially underestimated, especially under the physical conditions encountered in the dense white dwarf envelope plasma. In order to estimate the importance of screening effects on the diffusion time scale of calcium in G74–7, we have used improved transport coefficients kindly made available to us by C. Paquette. In this approach, the collision integrals are evaluated numerically assuming an interaction potential of the Debye-Hückel type (Paquette 1983). We find diffusion time scales for calcium now ranging between 3.5×10^3 and 8.2×10^3 yr. These results are in excellent agreement with those of Muchmore (1983)—who also considered screened potentials—from which we estimate a calcium diffusion time scale of $\sim 5 \times 10^3$ yr. Because the true helium abundance in these cool DA stars is poorly known (see, however, Liebert and Wehrse 1983), we have also performed additional diffusion calculations in envelopes with equal numbers of hydrogen and helium atoms. For these, we find calcium diffusion time scales between 5.0×10^4 and 2.6×10^5 yr. These estimates suffer from large uncertainties because the physical conditions at the bottom of the convection zone of the mixed composition model are much more extreme than in the pure hydrogen case. We cannot rule out even longer time scales, but it seems likely that they will remain substantially shorter than the evolutionary time scale of the white dwarf. The conclusion that unhindered element diffusion will quickly deplete the heavy ion content of the white dwarf envelope thus appears inescapable. Furthermore, the possibility of explaining the "disappearance" of the K line in objects previously classified DA,F or DF, and now reclassified DA, by the settling of the calcium over a ~ 10 yr period (Bessell and Wickramasinghe 1977) can now properly be put to rest.

Among the mechanisms proposed to compete with the settling and complete disappearance of heavy elements in white dwarf atmospheres, accretion from the interstellar medium has been the subject of several recent investigations (Alcock and Illarionov 1980; Vauclair, Vauclair, and Greenstein 1979; Fontaine and Michaud 1979*a*; Wesemael and Truran 1982). During most of its cooling time, a white dwarf will travel through the tenuous interstellar medium and accrete at the Eddington rate. At that accretion rate, the steady-state calcium abundance in the stellar envelope will be negligible. However, most of the accretion onto a white dwarf during its lifetime occurs during the occasional crossing of an interstellar cloud of higher density (e.g., Wesemael 1979). The accretion rate of cloud material necessary to produce a steady state calcium abundance equal to that of G74–7 is given by

$$\dot{M} \approx 4\pi R^2 \rho_c v_d [(Ca/H)_{G74-7}/(Ca/H)_{accreted}]$$

$$\sim 2.2 \times 10^{-16} M_\odot \text{ yr}^{-1}, \quad (1)$$

where ρ_c and v_d are the mass density and calcium diffusion velocity at the base of the convection zone respectively (an average ionization state $Z_{Ca} = 10$ was adopted at that location), and where $(Ca/H)_{accreted}$ is the calcium-to-hydrogen ratio in the accreting cloud material, assumed here to be solar. The required accretion rate of equation (1) is comparable to that expected from fluid dynamical accretion onto a white dwarf traveling through a cloud of modest density (Wesemael 1979; Alcock and Illarionov 1980).

For typical interstellar medium parameters, a white dwarf will spend a few percent of its time crossing clouds and accreting at a rate comparable to that of equation (1). Alternatively, one expects a few percent of all white dwarfs to exhibit metal features in their spectra as a consequence of accretion processes. While additional high-resolution observations of the kind reported on here will be necessary to ascertain the true fraction of cool DA white dwarfs with weak metal features, our present knowledge of these stars is consistent with the possibility that the observed calcium in G74–7 be the signature of a recent accretion event.

We are grateful to C. Paquette for providing us with his latest numerical diffusion coefficients and to H. L. Shipman for providing additional information on the Ross 627 fit. These observations offer an improvement over previous results due to the development of a photon-counting Reticon detector behind a magnetically-shielded, blue-sensitive image intensifier package. We thank the engineering staff at Steward Observatory—under D. Mitchell, R. Cromwell, and R. Macklin—for making this precision instrument possible. This work was supported in part by the NSF grant AST 80-24324, by the Natural Sciences and Engineering Research Council Canada and by the fund FCAC (Québec).

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