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IUE SPECTROPHOTOMETRY OF THE DA4 PRIMARY IN THE SHORT-PERIOD WHITE DWARF–RED DWARF SPECTROSCOPIC BINARY CASE 1

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ABSTRACT

Low-resolution ultraviolet *International Ultraviolet Explorer* spectra of the DA white dwarf Case 1 are presented. The spectra show the presence of the λ1400 feature—already discovered in several other DA stars—and of a shallower trough in the 1550–1700 Å range. A model atmosphere analysis of the ultraviolet energy distribution and of the Lyα red wing yields $T_e = 13,000 \pm 500$ K. Possible interpretations of the λ1400 feature are reviewed. Case 1 is the coolest white dwarf found in a short-period, detached white dwarf–red dwarf binary, and its cooling time is consistent with estimates of the efficiency of angular momentum removal mechanisms in the phases subsequent to common envelope binary evolution.

Subject headings: stars: binaries — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

Case 1 (WD 1213+528, EG 87) was first identified as a DA white dwarf by Stephenson (1960) through an ultraviolet objective prism survey. Greenstein (1965) had noted the presence of emission lines in the spectrum of Case 1, which indicated the existence of an unresolved companion. The spectrum of the companion was determined to be approximately dM2 from an infrared objective prism plate taken by Stephenson (1971). Recently, Lanning (1982) obtained a radial velocity curve from the variation of the Hα emission line and showed that Case 1 is a spectroscopic binary with a semiamplitude $K = 116$ km s^{-1} and an orbital period $P = 16$ hr. Lanning's result thus adds still another short-period close binary containing a white dwarf or subdwarf and a late-type dwarf detached from its Roche lobe to a growing list which includes Abell 41 (Grauer and Bond 1983), V471 Tauri (Nelson and Young 1976; Guinan and Sion 1982), Feige 24 (Thorstensen *et al.* 1978), HZ 9 (Lanning and Pesch 1981), PG 1413+01 (Green, Richstone, and Schmidt 1978), BE UMa (Ferguson *et al.* 1981), and UU Sge (Bond, Liller, and Mannery 1978). The obvious similarity of Case 1 to these systems, which may all have evolved from common envelope binaries with considerable mass loss, led us to investigate the system with the *International Ultraviolet Explorer* (*IUE*). Our objective was to determine the physical properties of the DA white dwarf, and thus obtain further clues on the evolutionary status of the system. Our *IUE* spectra have revealed two interesting findings: (1) The white dwarf is considerably cooler ($T_e = 13,000 \pm 500$ K) than the white dwarf primaries in similar systems (listed above); and (2) we report the detection of a strong, broad, and heretofore unidentified absorption feature centered at 1394 Å, and possibly of another broad shallow feature in the 1550–1700 Å range, in an otherwise normal DA spectrum.

In § II, we describe our *IUE* observations. These are analyzed in § III, where we present our fit to the ultraviolet energy distribution and to the Lyα red wing. The origin of the λ1400 absorption feature and the evolutionary implications of our results are discussed in § IV.

II. OBSERVATIONS

Case 1 was observed at low resolution with the *IUE* satellite on 1982 February 5 and 6. Two images were obtained with the short wavelength prime camera (SWP 16272 and 16273) and one image with the long wavelength redundant camera (LWR 12518). The second SWP (16273) frame was taken through the small aperture, with the original intention of reducing the geocoronal contamination of the Lyα absorption profile. Unfortunately, the high radiation level during the exposure substantially reduced the usefulness of that image; consequently, our analysis makes use of only the two images obtained with the large aperture. The exposure times for these were 50 minutes (SWP; slightly underexposed), and 50 minutes (LWR; optimal). The data reduction was carried out with the standard *IUE* data reduction package available at the *IUE* data reduction facility at the Goddard Space Flight Center. As in the case of 40 Eri B (Greenstein 1980), the main-sequence companion is unresolved in the large aperture but does not contribute to the ultraviolet flux.

III. ANALYSIS

a) *Ultraviolet Spectrophotometry*

Figure 1 shows the untrailed short-wavelength low-resolution spectrum (SWP 16272) of Case 1, which confirms

[1] Guest Observer with the *International Ultraviolet Explorer* satellite.

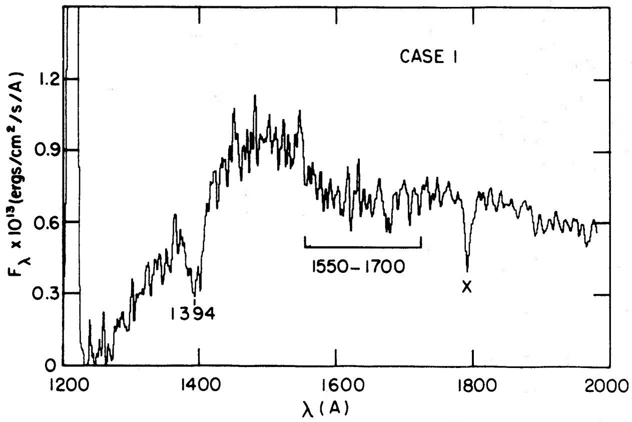

FIG. 1.—The short-wavelength scan SWP 16272 of Case 1, obtained 1982 February 5 with the *IUE*. The geocoronal Lyα emission is present near the center of the broad photospheric line, of which only the red wing is shown. The absorption feature at 1394 Å and the broad depression between 1550 and 1700 Å are indicated. The cross identifies a reseau mark.

Stephenson's (1960) DA classification. In addition to the broad Lyα wing, which extends out to $\sim$1500 Å, the spectrum clearly shows additional depressions near 1400 Å and in the 1550–1700 Å region. The λ1400 feature is centered at 1394 Å and has a central residual intensity of 0.45 and an equivalent width of $\sim$10 Å. It is similar to, but stronger than, the features reported earlier in the spectra of the DA stars 40 Eri B and LB 3303 (Greenstein 1980; Wegner 1982). The 1550–1700 Å depression centered near 1615 Å is broader and shallower (central residual intensity $\gtrsim$0.76) than the λ1400 feature. Dips or depressions in that wavelength range were reported in 40 Eri B and LB 3303 (Greenstein 1980; Wegner 1982) but were attributed to sensitivity problems. However, broad and shallow depressions, similar to that observed in Case 1, have also been reported in the short wavelength spectra

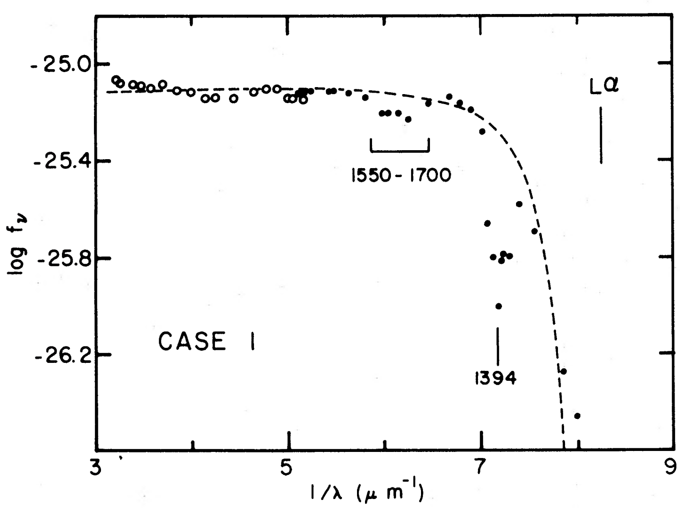

FIG. 2.—The spectral energy distribution of Case 1 from *IUE* ultraviolet observations. *Filled circles*, *IUE* SWP scan 16272; *open circles*, *IUE* LWR scan 12518. The best fitting theoretical energy distribution is for a $T_e = 13{,}000$ K, log $g = 8.0$ pure hydrogen model atmosphere. Lyα, the absorption feature at 1394 Å, and the broad depression between 1550 and 1700 Å are indicated.

of G29–38, G67–23, and G226–20 by Holm *et al.* (1983), who argue that absolute calibration errors in that spectral region at a $\sim$20–30% level appear unlikely (also Bohlin *et al.* 1980). However, Hackney, Hackney, and Kondo (1982) discuss exposure-dependent calibration problems in SWP images which can cause a flux deficit of up to 10% near 1650 Å. The Holm *et al.* (1983) investigation thus suggests that the 1550–1700 Å depression may be yet another unidentified feature in the ultraviolet spectrum of DA white dwarfs. Its presence is attributed by these authors to quasi-molecular absorption by two hydrogen atoms in the singlet state which leads to a satellite band at $\lambda \approx 1623$ Å. We note, however, that the semiclassical line shape calculations of Sando and Wormhoudt (1973) predict no significantly enhanced absorption near 1400 Å; this may imply that the Holm *et al.* suggestion may not be relevant to the identification of the 1400 Å feature. Finally, we point out that a similar, and as yet unidentified, broad 1600 Å feature has also been observed in the ultraviolet spectra of several λ Boo stars by Baschek *et al.* (1984).

b) *Effective Temperature Determination*

The *IUE* observations of Case 1 were binned over 30 Å intervals to produce mean fluxes which are shown in Figure 2. The measured Johnson and Strömgren colors of the system, $(U-B) = -0.48, (B-V) = +0.53, (u-b) = +0.773, (b-y) = +0.340$ (Eggen and Greenstein 1965; Graham 1972), are contaminated by the late-type secondary and were not used in the energy distribution fit.[2] Greenstein's (1980) analysis of 40 Eri B shows that the dM2 secondary will not contribute to the observed energy distribution in the ultraviolet, e.g., beyond $1/\lambda \gtrsim 3\ \mu\mathrm{m}^{-1}$.

Our effective temperature determination relies on the temperature sensitivity of the Lyα wing and of the ultraviolet continuum slope. In Figure 2, we show the energy distribution for a blanketed, pure hydrogen model atmosphere at $T_e = 13{,}000$ K, and log $g = 8$, which represents the best fit to the ultraviolet energy distribution. This model calculation is similar to those described in Wesemael *et al.* (1980) but includes convective energy transport; the unified Stark-broadening theory of Vidal, Cooper, and Smith (1973) is used to study the red wing of the Lyα line. Of course, these calculations do not predict the λ1400 feature (nor the shallower 1550–1700 Å trough, if real), and allowance must be made for this in the fit.

This effective temperature determination also permits an independent derivation of the absolute visual magnitude of the companion. The observed system brightness ($V = 13.34$, Eggen and Greenstein 1965; $V = 13.30$, Dahn *et al.* 1982) and absolute parallax ($\pi = 0\farcs0334 \pm 0\farcs0041$, Dahn *et al.* 1982), coupled with an adopted mass of $M = 0.7 \pm 0.3\ M_\odot$ yield $M_{v,2} = 11.5^{+0.9}_{-0.6}$ for the main-sequence companion. At $T_e = 13{,}000$ K, $M_{v,1} = 11.7$ and both components are equally bright at V. The derived magnitude is that of an M4 dwarf (Joy and Abt 1974) compared to the M2 V objective prism classification of Stephenson (1971). Stephenson's spectral class

[2] We note here that Koester, Schulz, and Weidemann (1979) have analyzed the *composite* colors of the system and thus have derived an effective temperature for the white dwarf which is much too low ($T_e = 5890$ K).

TABLE 1

DA White Dwarfs with Reported λ1400 Features

Star	EG/Gr	WD	$T_e/10^3$ K	W_{1400} (Å)	Reference
G226–29	368	1647+59	11.1	17.1	1
G29–38	159	2326+04	11.4	15.4	1
Case 1	87	1213+53	13.0	~10	2
Wolf 485A	99	1327−08	14.0	7.3	3
G231–40	378	2117+53	15.0	8.7	3
Grw +73°8031	144	2126+73	15.4	5.6	1, 4, 5
LB 3303	...	0310−68	16.0	5.7	6
40 Eri B	33	0413−07	16.9	3.1	5
GD 140	184	1134+30	22.0	<4	3

References.—(1) Holm *et al.* 1983. (2) This work. (3) Wegner 1983. (4) Greenstein and Oke 1979. (5) Greenstein 1980. (6) Wegner 1982.

and absolute magnitude ($M_{v,2} = 10.1$) are incompatible with the measured parallax and with the observed V magnitude, irrespective of the white dwarf effective temperature.

IV. DISCUSSION

a) The λ1400 Feature in Cool DA White Dwarfs

The detection of the λ1400 line in Case 1 brings the number of cool white dwarfs with that feature reported in their spectra to nine. Table 1 summarizes some relevant information on these objects. All of them have hydrogen-dominated atmospheres and have effective temperatures between 11,000 K and 22,000 K. The low-temperature boundary of the λ1400 phenomenon is still uncertain, as the spectrum of G67–23 obtained by Holm *et al.* (1983) is too noisy to rule out the presence of the λ1400 line in the cooler object ($T_e =$ 10,500 K). A search for that line in other cool DA stars in currently in progress (Wegner 1983). At the hot end, GD 140—at $T_e \approx 21{,}600$ K—shows only a weak feature (Wegner 1983); we note also that Greenstein and Oke (1979) failed to detect λ1400 absorption in G35–29, HZ 7, and Wolf 1346, three DA stars in the 20,000–21,000 K range.[3] Within the observed ~10,000 K strip, the λ1400 line strengthens as T_e decreases.

Two suggestions have been put forward to explain that feature in cool DA stars (Greenstein 1980), and both suffer from various deficiencies. The identification with Si IV can now be dismissed, in view of the strengthening of the feature with decreasing effective temperature (also Holm *et al.* 1983). The identification with H_2 molecular bands is more plausible, as it readily satisfies the trend exhibited in Table 1. However, detailed model atmosphere calculations have yet to show that sufficient amounts of H_2 can survive in the atmospheres of DA stars at $T_e \gtrsim 15{,}000$ K to produce the features observed in LB 3303 and 40 Eri B. Furthermore, other predicted transitions of the Lyman band are not seen, e.g., in LB 3303 (Wegner 1982).

Another possibility, initially brought to our attention by G. Michaud, is that Si II autoionization lines contribute to the λ1400 feature. These lines, which involve configurations with inner shell excited electrons, have been suggested by Jamar, Macau-Hercot, and Praderie (1978) and Artru *et al.* (1981*a*) as a major contributor to the λ1400 feature which is observed in some chemically peculiar, silicon-rich Ap stars between 9000 and 16,000 K. In the wavelength range 1370–1440 Å, Artru *et al.* identify several series originating on the $3d\ ^2D$, $4d\ ^2D$, $3p4s\ ^2P^o$, and $3p^2\ ^2P$ levels and connecting to levels lying in the continuum. Because of the short lifetime of autoionizing levels, the natural width of such lines is much larger than would be the case for normal transitions (e.g., Goldberg 1966): for the upper autoionized levels of interest here, the damping width can reach $\gamma \approx 1.4 \times 10^{14}$ s^{-1} (Artru *et al.* 1981*a*), which corresponds to a full width at half-maximum of 14 Å. When further degraded at the *IUE* resolution, autoionization lines could contribute to the absorption feature observed in low-dispersion spectra near 1394 Å.

We have investigated this suggestion in more detail by performing preliminary spectrum synthesis calculations of Si II autoionization lines in model atmospheres of DA stars at $T_e = 13{,}000$ K and 20,000 K. The required *gf*-values and damping widths were extracted from the extensive compilation of Artru *et al.* (1981*b*).

The lower terms involved in the autoionization lines lie $\gtrsim 10$ eV above the ground state of Si II. Thus for temperatures in the range 8000–20,000 K, the Boltzmann exponential factor will be determinant in depleting the population of these levels, even though Si II is the dominant ionization stage in the photosphere. Indeed, our preliminary calculations suggest that Si/H values above solar would be required to produce autoionization lines of the strength of the λ1400 feature observed in DA white dwarfs. Furthermore, transitions originating on lower levels closer to the ground state would then most likely be excited concurrently.[4] The evidence available at this time thus suggest that autoionization lines of Si II are probably not a major contributor to the λ1400 feature observed in DA stars.

Our analysis thus leaves no compelling identification for the λ1400 line observed in DA white dwarfs. Observationally, further high-dispersion *IUE* observations of DA stars in the range 10,000–20,000 K may prove useful in searching for potential concurrent weak metal lines, as would a continuing survey of the λ1400 feature in order to delineate the extent of that phenomenon in cool DA stars. Clearly the λ1400 line, together with the equally puzzling λ1600 trough, may—once decoded—represent major building blocks in our understanding of the properties of white dwarf photospheres.

[3] We note, however, that in the case of Wolf 1346, Greenstein and Oke report a rather poor energy distribution fit with a DA model atmosphere at $T_e = 21{,}000$ K for $1/\lambda > 6\ \mu m^{-1}$; they claim that it is unlikely that a model can be found for which the regions on both sides of $1/\lambda = 6\ \mu m^{-1}$ and the Lyα profile in Wolf 1346 can all be fitted simultaneously. Their Figure 3 indeed shows that the theoretical energy distribution rises above the *IUE* observations near $1/\lambda = 6\ \mu m^{-1}$, and again around 7.2 μm^{-1}. It is tempting to interpret the broad dips at these wavelengths as the counterparts of the 1550–1700 Å and 1400 Å features detected in Case 1, but in a much hotter object. As discussed above, the effective temperature of Wolf 1346 is similar to that of GD 140, where only a weak λ1400 line is reported (Wegner 1983).

[4] A high-dispersion *IUE* spectrum of 40 Eri B which exhibits a λ1400 feature (see Table 1) is discussed by Bruhweiler and Kondo (1983). F. C. Bruhweiler has kindly agreed to reexamine that spectrum for us; it shows a possible feature near 1260 Å, corresponding to Si II λ1260.421, with a possible small interstellar contribution. However, there is no indication of the $\lambda\lambda$1264.737, 1265.001 Si II components such as those reported in Wolf 1346.

TABLE 2

KNOWN SHORT-PERIOD DETACHED SYSTEMS CONTAINING A RED DWARF AND A WHITE DWARF OR SUBDWARF

Name	P (days)	Spectral Types	$T_{e,1}/10^3$ K	$M_1/M_\odot$	Reference
Abell 41	0.113194	sdO+M? V	~50	?	1, 2
PG 1413+01	0.344331	D?+M3 V	~50	0.7 ± 0.3	3
UU Sge	0.465069	sdO+K? V	~35	1.1	4
V471 Tau	0.521184	DA+K2 V	32.5	0.79	5, 6
HZ 9	0.56433	DA+M4.5 V	22	0.20 ± 0.05	7, 8
Case 1	0.667651	DA+M4 V	13	>0.40	9, 10
BE UMa	2.291171	sdO/DO+M2 V/IV	~80	0.6 ± 0.1	11, 12, 13
Feige 24	4.2319	DA+M2 V	~70	0.85 ± 0.40	14, 15

REFERENCES.—(1) Grauer and Bond 1983. (2) Green, Liebert, and Wesemael 1984. (3) Green, Richstone, and Schmidt 1978. (4) Bond, Liller, and Mannery 1978. (5) Nelson and Young 1976. (6) Guinan and Sion 1982. (7) Lanning and Pesch 1981. (8) Guinan and Sion 1983. (9) Lanning 1982. (10) This work. (11) Ferguson *et al.* 1981. (12) Ferguson 1983. (13) Crampton, Cowley, and Hutchings 1983. (14) Thorstensen *et al.* 1978. (15) Holm 1976.

b) The White Dwarf Effective Temperature: Evolutionary Implications

Lanning's (1982) identification of Case 1 as a short-period close binary system containing a white dwarf and a red dwarf adds yet another system to the growing list of presumed products of common envelope binary evolution (e.g., Paczyński 1976). The overall properties of those systems for which the binary period is less than 5 days are summarized in Table 2, where we list the spectral type of the components, together with the primary effective temperature and mass.

Examination of Table 2 shows an interesting, and perhaps unexpected trend, in that—for those systems with $P < 1$ day—shorter period systems tend to contain hotter primaries. One would perhaps expect white dwarf cooling to proceed concurrently with angular momentum loss and hence for the coolest primaries to tend to appear in the shortest period systems. Table 2 thus suggests that the common envelope phase may produce binary remnants with a substantial range of initial orbital periods (as emphasized by the contrast between Abell 41 and Feige 24), an altogether not too surprising result.

It is clear, nevertheless, that Case 1 is the coolest white dwarf/subdwarf primary yet found in post–common envelope systems. Its cooling time may thus be used to help constrain the characteristic time scale for angular momentum loss from the cataclysmic variable precursor. Current thinking suggests that the loss of angular momentum from the post–common envelope system could proceed through a combination of gravitational radiation, tidal friction, and magnetic braking via flares or winds (e.g., Eggleton 1976, 1983; Verbunt and Zwaan 1981; Taam 1983). The characteristic time scale for these processes is estimated to be $\sim 10^9$ yr (Eggleton 1976, 1983), except for gravitational radiation which operates over a time scale $\gtrsim 10^{10}$ yr.

The elapsed time since the formation of the red dwarf–white dwarf system in Case 1 can be obtained from the white dwarf cooling time. From the models of Winget, Lamb, and Van Horn (1983) for a degenerate configuration of ^{12}C at 0.6 $M_\odot$, we infer $\tau_{\rm cool} \approx 3.4 \times 10^8$ yr down to $T_e = 13{,}000$ K. We note that any additional energy source, such as wind accretion onto or nuclear burning on the white dwarf surface, can only delay the cooling process and thus lengthen the cooling time down to the present effective temperature. Furthermore, the quoted cooling time represents a lower limit to the time scale for angular momentum removal, as the orbital period has to decrease further in order to trigger mass transfer from the secondary. This limit is consistent with the theoretical estimates discussed above.

V. CONCLUSIONS

Our low-resolution *IUE* spectrophotometry of the white dwarf–red dwarf spectroscopic binary Case 1 has led to the following results:

1. The effective temperature of the DA white dwarf primary in that system is $T_e = 13{,}000 \pm 500$ K. The secondary is of spectral type dM4.
2. The *IUE* spectra show the presence of the λ1400 feature, with an equivalent width of ~10 Å. A shallower and broader depression is also noted in the 1550–1700 Å range. Both features have previously been detected in other DA stars.
3. Case 1 is the coolest primary observed to date in detached white dwarf–red dwarf systems, which are thought to be the products of common envelope binary evolution. The white dwarf cooling time sets a lower limit on the characteristic time scale for angular momentum loss in pre-cataclysmic variable systems of $\sim 3 \times 10^8$ yr, a limit consistent with current theoretical estimates of the efficiency of angular momentum removal processes.

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NOTE ADDED IN PROOF.—The spectral type of the red dwarf in Case 1 has recently been redetermined by R. G. Probst (1984, *Ap. J. Suppl.* **53**, 335) on the basis of *JHK* photometry. His result (dM4.5) is in excellent agreement with that presented here.

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