

MASS LOSS, LEVITATION, ACCRETION, AND THE SHARP-LINED FEATURES IN HOT WHITE DWARFS

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ABSTRACT

We have studied eight white dwarfs, seven DA and one He-rich types, observed at a high resolution ($\lambda/\Delta\lambda \approx 10^4$) with the *International Ultraviolet Explorer (IUE)*. Of the seven DA white dwarfs, three show spectral signatures of ionized heavy elements, such as Si II, Si III, C IV, Si IV, and N V, arising in the immediate environment of these stars. The shortward-shifted lines in two (G191-B2B and 2111+49) of the three DA types showing metallic lines are tentatively interpreted as an indication of mass loss from these stars. The He-rich white dwarf shows the features due to C IV and He II, which also arise in the immediate environment of that star. Although the statistical sample presented here is limited, we tentatively suggest a temperature and effective gravity range ($T_{\text{eff}} \geq 20,000$ K and $\log(g) \leq 8.0$) in DA white dwarfs within which metallic lines are present either in the photosphere or in the halo of the stars. We examine the physical processes relevant to the appearance of such metallic lines. We tentatively propose that radiative levitation can explain the appearance of the observed lines in the hot DA white dwarfs, although the role of radiation forces in mass loss is not clear.

Subject headings: stars: accretion — stars: mass loss — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

a) Background

Based upon their spectra at visual wavelengths, the white dwarfs have been traditionally split into two basic groups, each of very high chemical purity. One group, the DA stars, traditionally only display the hydrogen Balmer lines, and their atmospheres are considered to be composed of almost pure hydrogen. The other group consists of white dwarfs with almost pure helium atmospheres. However, there are hot DAO stars such as HZ 34 in which He II $\lambda 4686$ has been detected (Koester, Liebert, and Hege 1979), suggesting a mixture of H and He. Only in the cool white dwarf atmospheres ($T_{\text{eff}} \leq 12,000$ K), principally of the He-rich white dwarfs, have trace elements heavier than helium been found at visual wavelengths. In the cool C₂ and DC helium white dwarfs, for example, convection may dredge up from the deeper layers the observed C₂ into the photosphere. Other visual light and *International Ultraviolet Explorer (IUE)* low-resolution UV observations have also shown metal lines in many cool helium-rich white dwarfs (Liebert

1980; Wegner 1981; Cottrell and Greenstein 1980). Where relative abundances have been derived, heavy elements, such as C, Ca, and Fe, typically are found underabundant by 10^3 – 10^4 . In contrast, low-resolution UV spectra from *IUE* show no evidence of heavy elements in hot white dwarfs.

High-dispersion spectra of DA white dwarfs have revealed surprisingly sharp core components in H α and H β profiles (Greenstein *et al.* 1977). Greenstein *et al.* considered the possibility that the Balmer sharp-lined components were formed in a shell about the white dwarf but discarded it since these features showed no real evidence for orbital motion and were thus too narrow unless the shells were far away from the star. These sharp components were presumably formed via non-LTE effects in the outer photospheres of slowly rotating ($V_{\text{rot}} \leq 60$ – 70 km s⁻¹) white dwarfs. Partially on the basis of these results and partially on theoretical grounds, it has been suggested that few, if any, white dwarfs are fast rotators (Liebert 1980).

Only recently have high-dispersion *IUE* results for white dwarfs been presented (Bruhweiler and Kondo 1981, 1982; Sion, Guinan, and Wesemael 1982). The studies by Bruhweiler and Kondo, of ultraviolet interstellar lines in the spectra of four nearby hot white dwarfs, show that three white dwarfs, G191-B2B, HD

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149499B, and W1346, display sharp, narrow resonance features of heavy elements, all longward-shifted by 15–40 km s^{-1} with respect to the interstellar features. The fourth white dwarf, Sirius B, showed interstellar Si II $\lambda 1260$ to be much broader than expected. Three of these stars are DA white dwarfs and one, HD 149499B, is He-rich. Based on other relevant considerations, we interpret these lines to be associated with the observed white dwarfs and not to arise in the interstellar medium (Bruhweiler and Kondo 1981). If we are correct, these observations represent the first definitive detections of heavy elements in both the hot hydrogen-rich DA and hot helium-rich white dwarfs. Our aim in this paper is to discuss these results plus data for four additional white dwarfs. We will investigate how these observations compare with recent theoretical work which predicts the presence of heavy elements in hot white dwarf photospheres. Of particular interest will be the theoretical works which discuss diffusion, levitation, and accretion processes, namely, the work of Vauclair, Vauclair, and Greenstein (1979, hereafter VVG) and also the works of Fontaine and Michaud (1979, hereafter FM) and Alcock and Illarionov (1980*a*, *b*).

b) Observational Data

We will discuss the ultraviolet spectral data obtained either by us or through the National Space Science Data Center for eight hot white dwarfs. The observations were obtained through the large aperture and at high dispersion with the short-wavelength prime (SWP) and the long-wavelength redundant (LWR) cameras. Only the observation of Sirius B was made with the small aperture, in order to exclude the light from Sirius A. The observations themselves, except for 40 Eri B, He 3, HZ 43, and 2111+49, have been discussed in greater detail in Bruhweiler and Kondo (1981, 1982).

i) G191–B2B

The features seen in G191–B2B have been discussed previously in Bruhweiler and Kondo (1981). The spectrum of this DA white dwarf ($T_{\text{eff}} = 55,000 \text{ K}$; Greenstein 1979) shows pronounced interstellar-like N v, C iv, and Si iv (Fig. 1 of Bruhweiler and Kondo 1981), shifted by $16.4 \pm 8.5 \text{ km s}^{-1}$ with respect to the interstellar features (Bruhweiler and Kondo 1981) of C ii, N i, and Si ii. Reextraction of the echelle orders using new IUE observatory software which incorporates an improved method of accounting for thermal effects followed by reanalysis of the features yields heliocentric radial velocities, V_{\odot} , for N v, C iv, and Si iv of $18.3 \pm 4.1 \text{ km s}^{-1}$, in good agreement with that determined by Bruhweiler and Kondo (1981) based upon the previous extraction. The observed radial velocity of G191–B2B, uncorrected for the gravitational redshift, is $V_{\odot} = +67 \pm 19 \text{ km s}^{-1}$ (Trimble and Greenstein 1972).

If we assume that it shares the space velocities of its K dwarf companion $50''$ away, it has an actual spatial velocity of $V_{\odot} = +34 \text{ km s}^{-1}$, which implies a gravitational redshift correction of 33 km s^{-1} . If we take these data at face value, they suggest that the N v, C iv, and Si iv are formed in an expanding halo about the star as initially suggested in Bruhweiler and Kondo (1981). Conceivably, the quoted errors might still allow the interpretation that they arise in a nonexpanding region at higher energies within the star's gravitational well and at markedly less positive radial velocities than the observed photosphere radial velocity of G191–B2B uncorrected for gravitational redshift. Sources of possible systematic errors in derived radial velocities at visual wavelengths will be discussed further in § III.

ii) HD 149499B

The hot helium-rich white dwarf HD 149499B also displays strong narrow features of C iv at 1548 and 1550 Å. In addition, the broad absorption profile of He ii $\lambda 1640$ displays a sharp narrow absorption core (Fig. 1).

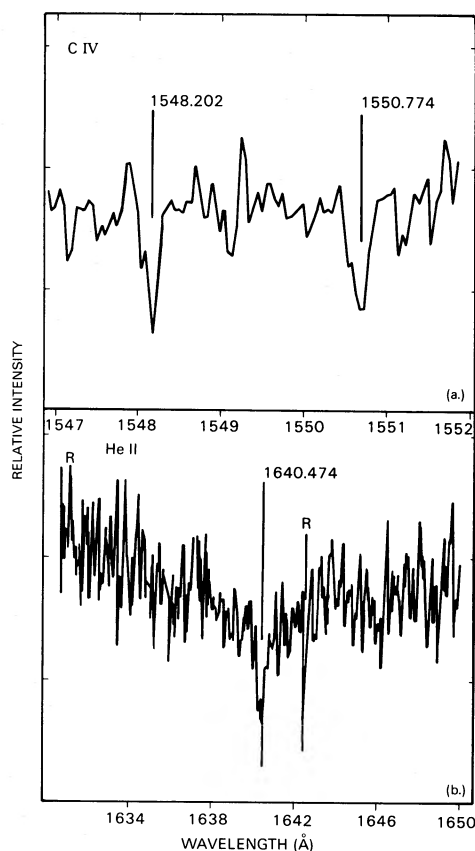


FIG. 1.—Sharp-lined features in HD 149499B. The data displayed are for the C iv resonance doublet (*a*) and the He ii $\lambda 1640$ region (*b*). The rest wavelengths of the C iv and He ii features are indicated. The instrumental reseau marks are denoted by the letter R.

TABLE 1
DATA FOR HOT WHITE DWARFS

wd #	Name	T_{eff} (K)	V_{rs} (km s $^{-1}$)	$\log(g)$ (cm s $^{-2}$)	Type	Ions Observed
0501+52	G191-B2B	61,900	12	7.5	DA	N v, C iv, Si iv
	HD 149499B	55,000	26	8.0	He-rich	C iv, He ii
2032+24	W1346	21,500	31	8.0	DA	Si ii
2111+49	GD 394	33,000	?	?	DA	Si iii, Si iv
1314+29	HZ 43	60,000	...	7.9	DA	...
0642-16	Sirius B	29,000	90	8.7	DA	...
0644+37	He 3	22,000	...	8.4	DA	...
0413-07	40 Eri B	17,000	29	8.0	DA	...

NOTE.—For consistency, effective temperatures and gravities are from Shipman 1979. Exceptions are HD 149499B and 2111+49, which are from Sion, Guinan, and Wesemael 1982 and Koester, Liebert, and Hege 1979, respectively. See text for further discussion.

Furthermore, both the sharp He II $\lambda 1640$ component and the C IV features show a common redshift of $+15$ km s $^{-1}$ with respect to the interstellar lines. Recent work by Sion, Guinan, and Wesemael (1982) has shown that this He II feature can be reproduced with theoretical non-LTE profiles of Wesemael (1981) generated using a pure helium model atmosphere. Although the sharp He II component might be formed in a high-density shell about HD 149499B, the fact that the non-LTE calculations predict such sharp cores implies a photospheric origin for this component. Additionally, Wegner (1978) has determined a heliocentric radial velocity of -31 ± 3 km s $^{-1}$ for the K0 V companion star, HD 149499A. The heliocentric velocity that we obtain from the *IUE* image SWP 6272 for He II $\lambda 1640$ and the C IV lines of HD 149499AB is -10.7 ± 5.8 km s $^{-1}$. If HD 149499B shares the space motion of HD 149499A, this suggests that these features are gravitationally redshifted by 20 km s $^{-1}$, a value comparable to the predicted redshift velocity given in Table 1 (see § II also), and formed deeply in the gravitational well, on or near the surface of the white dwarf. See also the discussion by Sion and Guinan (1983).

iii) W1346

Two separate high-dispersion exposures of the DA white dwarf W1346 ($T_{\text{eff}} = 21,000$ K) reveal narrow resonance features of Si II $\lambda\lambda 1260, 1263,$ and 1265 shifted by $+45$ km s $^{-1}$ with respect to the interstellar features (Fig. 2). Since the heliocentric corrections for the interstellar lines at the time of observation are -2.7 ± 11.1 km s $^{-1}$, the deduced radial velocity of the Si II features is $+42$ km s $^{-1}$ and is in reasonable agreement with the radial velocities of $+35$ and $+38$ km s $^{-1}$ determined from the sharp cores in H α and H β by Greenstein *et al.* (1977) for this star. Again, since two of the observed Si II transitions have lower states that are 287 cm $^{-1}$ above ground, and since the radial velocity of the Si II features agrees with the velocities deduced from the H α and H β cores, one must conclude that they

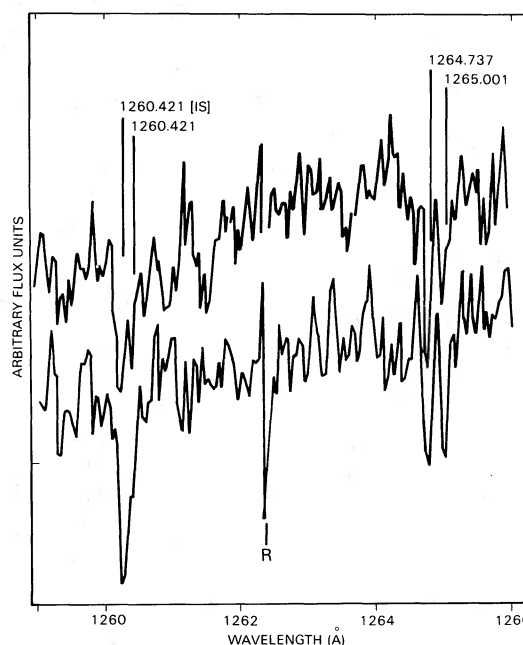


FIG. 2.—The Si II region in W1346. The three longward-shifted Si II features at $\lambda\lambda 1260.421, 1264.737,$ and 1265.001 are indicated. Also, the interstellar Si II feature is denoted by [IS]. The transitions at $\lambda\lambda 1264.737$ and 1265.001 arise from levels 287 cm $^{-1}$ above ground. The instrumental reseau marks are denoted by the letter R. The data displayed are from images SWP 13542 (top) and SWP 14415 (bottom).

are formed in a common high-density region. It is likely that these lines are formed in the upper photosphere of the star, but a dense region above the photosphere cannot be ruled out.

iv) 2111+49 (GD 394)

This object has been classified as DO and the visual spectrum has been recently studied by Koester, Liebert, and Hege (1979). Through fits to the color indices and

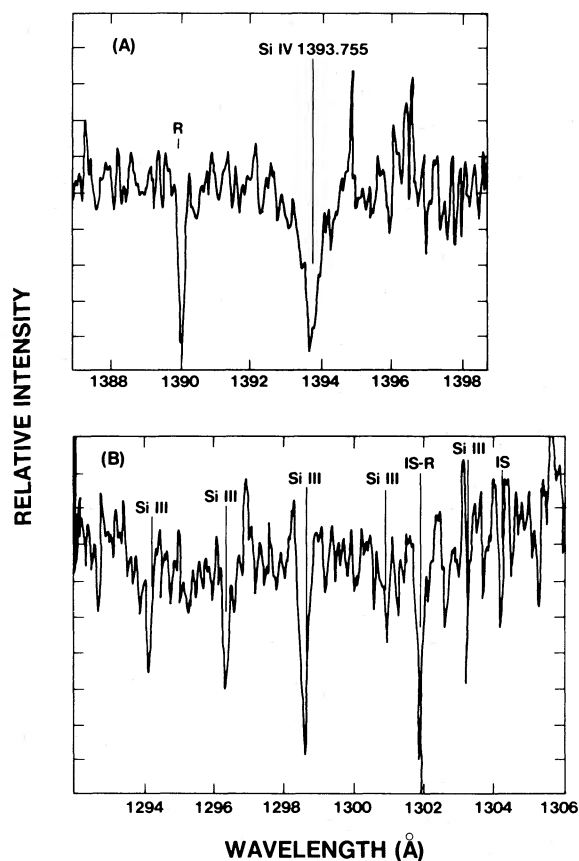


FIG. 3.—The region of Si IV λ 1393 (a) and the Si III region (b) in white dwarf 2111+49 (GD 394). The shifted Si III and Si IV features are indicated. The rest wavelengths are given in Table 2. The feature marked IS-R (Fig. 3b) denotes a reseau superposed on an interstellar feature. The data displayed are from image SWP 16891.

constraints imposed by the hydrogen spectrum, they find an effective temperature of $33,000 \pm 3000$ K. They also find no detectable He I or He II. The *IUE* image obtained by us (SWP 16891) also shows no hint of He II at 1640 Å. Because of the absence of He, we suggest that 2111+49 be classified as a DA white dwarf. Analysis of the UV spectrum of 2111+49 yields the expected interstellar features with a heliocentric velocity, V_{\odot} , of -12.6 ± 5.4 km s $^{-1}$. In addition to the interstellar lines, sharp features of the resonance lines of Si IV with rest wavelengths at 1393.755 and 1402.770 Å and Si III at 1206.510 Å are seen (Fig. 3). Nonresonance absorption lines of Si III are identified as transitions of the $^3P^o-^3P$ multiplet. These transitions are the only nonresonance lines of an element heavier than helium so far identified in spectra of hot white dwarfs. No other lines are seen in the spectrum of 2111+49. The lines identified are listed in Table 2. Since, for normal composition, carbon is more abundant than silicon and the $^3P^o-^3P$ transitions

TABLE 2
NONINTERSTELLAR FEATURES IN 2111+49 (GD 394)

Ion	λ_{rest}	Multiplet	f^a
Si III ...	1206.510	$^1S-^1P^o$	1.70
	1294.543	$^3P^o-^3P$	0.423
	1296.724	$^3P^o-^3P$	0.565
	1298.89	$^3P^o-^3P$	0.141
	1298.96	$^3P^o-^3P$	0.423
	1301.146	$^3P^o-^3P$	0.188
Si IV	1393.755	$^2S-^2P^o$	0.536
	1402.770	$^2S-^2P^o$	0.266

^aOscillator strengths are from Wiese, Smith, and Miles 1969.

in Si III are analogous to the $^3P^o-^3P$ transitions of C III near 1175 Å, one might expect to see strong lines near 1175 Å. The *IUE* image SWP 16891 was reasonably well exposed at 1175 Å but did not reveal any detectable C III. Furthermore, no evidence of shifted C II at 1334.53 and 1335.71 Å or C IV at 1548.31 and 1550.82 Å is seen in the spectrum. The presence of Si III and Si IV and, at the same time, the apparent absence of detectable C II, C III, and C IV, especially when the ionization range of carbon brackets that of silicon, indicate, as in the case of W1346, that Si is overabundant with respect to carbon.

The radial velocities of the Si III and Si IV features were measured, and they all possess a common radial velocity, $V_{\odot} = +25$ km s $^{-1}$, and a $\sigma = 4.1$ km s $^{-1}$, where the relative mean error associated with a single measurement is ± 1.89 km s $^{-1}$. This mean error may be fortuitously small and does not include the inherent errors of the *IUE* wavelength scale, which is accurate to ± 4 km s $^{-1}$. The inherent errors of the *IUE* wavelength scale are included in the quoted σ errors for all the objects studied here.

The heliocentric radial velocity obtained at visual wavelengths based upon the broad Balmer line profiles is $V_{\odot} = +98 \pm 19$ km s $^{-1}$ (Trimble and Greenstein 1972). Thus, like the case of G191-B2B, the Si III and Si IV features in 2111+49 are shortward-shifted by 73 km s $^{-1}$ with respect to the photosphere. Therefore, these features likely originate either in a stable or an expanding halo about the white dwarf.

v) Sirius B

No features other than the interstellar lines (see Fig. 2 of Bruhweiler and Kondo 1982) are seen in the *IUE* spectrum of Sirius B. These lines, however, appear broader than comparable interstellar features observed in the other white dwarfs observed using *IUE*. On the other hand, only transitions from the zero energy ground-state J levels are observed, with no detection of lines arising from the higher J levels of the ground

configuration of C II or Si II. Even though the Si II feature appears broad, we must conclude that the observed features are entirely of interstellar origin.

vi) 40 Eridani B

Greenstein (1978) previously observed 40 Eri B at high dispersion using *IUE*, but unfortunately the spectrum was overexposed by a factor of 3. He attempted to reconstruct the spectrum by using the unsaturated ends of each echelle order. This reconstructed spectrum produced features tentatively identified as a combination of H₂ and broad Si IV resonance lines at 1400 Å. Yet errors in the echelle ripple correction (Ake 1982) make such attempts at reconstruction very risky. A well-exposed high-dispersion *IUE* image obtained by us shows no indication of any Si IV features. Yet, it may be too early to rule out the existence of this feature, since it is reported to be both broad and shallow. Also, this feature has been reported in other white dwarfs (Wegner 1982). No spectral features due to heavy elements other than the interstellar features of C II λ1334.8 and possibly Si II λ1260 are seen in either the SWP or LWR data.

II. INTERPRETATION

The strong gravitational field in white dwarfs gives rise to rapid gravitational settling, or sedimentation, of heavier elements in their atmospheres. Four mechanisms, (a) levitation due to a strong radiation field interacting with ions with a high cross section, (b) levitation of ions by magnetic fields, (c) accretion of interstellar material, and (d) convection, have been suggested as means to counteract gravitational settling and produce observable concentrations of heavy elements in white dwarf photospheres. We will see if our observational data can be interpreted on the basis of these proposed mechanisms.

a) *Levitation Due to Radiation Pressure*

The work of VVG and FM predict that the force exerted by a strong radiation field in hot white dwarfs ($T_{\text{eff}} \geq 20,000\text{--}30,000$ K) can selectively levitate or, alternatively, halt settling of certain elements, such as carbon and nitrogen, that have large cross sections to the radiation field in the photosphere. The work of VVG presents detailed models which predict equilibrium concentrations of carbon, nitrogen, and oxygen for both hydrogen- and helium-rich white dwarfs. In the nonequilibrium situation the radiative acceleration may become stronger than gravity, and these elements might leave the star via a "selective" wind.

i) *Relevant Parameters for Eight White Dwarfs*

Before we can compare our results with the predictions of VVG, we must know where our observed white dwarfs lie in the $T_{\text{eff}}\text{--}\log(g)$ plane. The white dwarfs

analyzed here have measured trigonometric parallaxes (McCook and Sion 1977), and all have reasonably well determined values of effective temperature. Only 2111+49 does not have a trigonometric parallax. The effective temperatures and gravities for Sirius B have recently been determined by Böhm-Vitense, Dettmann, and Kapranidis (1979), and those for HD 149499B, by Sion, Guinan, and Wesemael (1982). A compilation of physical parameters of white dwarfs is also available from Shipman (1979). In Table 1, we give the relevant physical parameters for the observed white dwarfs. The values for W1346 and 40 Eri B from Greenstein (1979) are essentially the same as given by Shipman. For consistency we have adopted the values of Shipman except for HD 149499B and 2111+49, whose values come from Sion, Guinan, and Wesemael (1982) and Koester, Liebert, and Hege (1979), respectively. Since the effective temperature for G191-B2B given by Greenstein is lower than that given by Shipman and since the *IUE* data suggest an expanding halo for G191-B2B, we recalculated the pertinent parameters using the T_{eff} determined by Greenstein. By applying $R_{\star} = [F/(4\pi\sigma T_{\text{eff}}^4)]^{1/2}$, $g = G\mathcal{M}_{\star}/R_{\star}^2$ and using the \mathcal{M}_{\star} versus R_{\star} relation by Hamada and Salpeter (1961), we find R_{\star} and $\log(g)$. From Strand (1971) we find $M_V = 8.4$ mag, which yields a $M_{\text{bol}} = 3.95$ mag, using a bolometric correction, $BC = 4.45$, for the blackbody temperature of 55,000 K. This gives $R_{\star} = 0.0157 R_{\odot}$ and $\log(g) = 8.05 + \log(\mathcal{M}_{\star}/\mathcal{M}_{\odot})$. We find from the $\mathcal{M}_{\star}\text{--}R_{\star}$ relation that $\mathcal{M}_{\star} \leq 0.5 \mathcal{M}_{\odot}$. The upper limit for \mathcal{M}_{\star} is obtained for the maximum allowable hydrogen envelope around the helium core without igniting hydrogen [i.e., $\log(\rho_{\text{H}}) \sim 4.7$; Hamada and Salpeter 1961]. A pure helium white dwarf without a hydrogen envelope implies $\mathcal{M}_{\star} \approx 0.39 \mathcal{M}_{\odot}$, while a pure carbon white dwarf yields $\mathcal{M}_{\star} \approx 0.34 \mathcal{M}_{\odot}$. Cores of higher z may be formed via explosive processes, such as supernovae, resulting in neutron stars or possibly in black holes. However, this is not crucial to determining the lower mass limit for the white dwarfs. Thus, $7.58 \leq \log(g) \leq 7.75$ for G191-B2B. The reduced parameters are comparable to those of Shipman and yield a slightly higher $\log(g)$, but are quite similar to the value (7.5) of Shipman.

ii) *G191-B2B*

There is some question in the case of G191-B2B whether the observed resonance features of N V, C IV, and Si IV can arise in the star's photosphere or in a static or expanding halo about the star. The radial velocities of the N V, C IV, and Si IV profiles have been redetermined, and the apparent common heliocentric radial velocity of these features is most consistent with an expanding halo interpretation.

Since the redshift of the C IV and He II features in HD 149499B agrees better with the photospheric inter-

pretation, it is worthwhile to examine the situation of G191–B2B more closely. Using $V_{rs} = G\mathcal{M}_*/cR$, we have predicted the radial velocity due to the gravitational redshift (V_{rs}) for G191–B2B and the other white dwarfs studied (Table 1). We find that $V_{rs} = +12$ km s⁻¹ for G191–B2B. If $T_{\text{eff}} < 61,900$ K, we can predict a reasonable upper limit $V \leq 20.3$ km s⁻¹. This is lower than the observationally deduced gravitational redshift, V_{obs} , of 33 km s⁻¹ by Trimble and Greenstein (1972) based upon the observed Balmer lines in G191–B2B, but still within their estimated errors. If we are to adopt the predicted value over the Trimble and Greenstein result, the discrepancy between the actual and predicted observed radial velocities, uncorrected for redshift, is substantially less (12 km s⁻¹ versus 33 km s⁻¹). However, it is still difficult to claim that the highly ionized features originate in the photosphere of G191–B2B.

In any event, if we apply the calculations as presented in the figures of VVG to G191–B2B, the equilibrium abundances of N and C for a hydrogen white dwarf with $T_{\text{eff}} = 50,000$ K and $\log(g) = 8.0$ show that N and C can be levitated and the radiative acceleration is more for N than for C; this would lead to an overabundance of N relative to C. Yet the overall abundances would be much diluted in the photosphere. If cosmic abundances are assumed, and if the observed features in G191–B2B can be represented by a scattering curve of growth, then the steady state ionization curves of Shapiro and Moore (1976) imply that the temperature must be greater than 10⁵ K in order to explain the observed N v features. On the other hand, if N is overabundant, then much lower temperatures can be deduced.

Unfortunately, as previously pointed out, detailed diffusion-levitation calculations have not incorporated Si, but the strong oscillator strengths of Si IV should also lead to observable amounts of Si IV, if N v and C IV are also observable.

iii) HD 149499B

The white dwarf HD 149499B has been found to be He-rich (Wray, Parsons, and Henize 1979; Sion, Guinan, and Wesemael 1982). It has been predicted (FM) that below $T \approx 60,000$ K the atmosphere should be convective for a He-rich white dwarf of 0.612 M_{\odot} . Then, the elemental composition is governed by the relative contribution of g_{rad} and g_{th} at the inner boundary of the convection zone.

For $T > 29,000$ K, VVG predict that carbon will be supported by the stellar radiation field. However, their calculations also indicate that N should be supported, and with even a greater radiative force. In a He-rich ($T_{\text{eff}} \approx 50,000$ K) atmosphere, like that of HD 149499B, nitrogen should be much more abundant than in a hydrogen white dwarf like G191–B2B; it should also be more abundant than carbon. Yet no N v is observed in

HD 149499B, which has an effective temperature comparable to G191–B2B. If selective winds are possible in white dwarfs, the photosphere may have been swept clean of nitrogen by the strong stellar radiation field. Alternatively, another mechanism may be responsible for the observed C IV.

Since convection has been predicted by VVG to be important in He-rich white dwarfs for $T_{\text{eff}} \leq 60,000$ K, convection may be dredging carbon up to the photosphere from the carbon core. This dredging process may also be operating in cooler He-rich white dwarfs. However, it is still unclear why the effects of radiation pressure would be squelched in He-rich white dwarfs.

iv) W1346

The ion Si II is observed in the white dwarf W1346, but Si is not included in any of the known diffusion calculations involving white dwarfs. A perusal of the list of gf -values for resonance lines of Morton and Smith (1973) indicates that the radiative force per ion should be much greater for Si II and Si III than for C II and C III in white dwarfs, in which the effective temperature favors the presence of these ions. Thus, levitation or a lower downward diffusion rate may explain why Si is seen, while cosmically more abundant C is not seen in W1346. We note that C is included in both the calculations of VVG and FM; they show that C should be observable in white dwarfs hotter than W1346 depending on $\log(g)$.

Using predicted emergent fluxes (H_{ν}) for white dwarf model atmospheres (Wesemael *et al.* 1980), we have crudely calculated the radiative acceleration on C and Si. We have represented W1346 by fluxes from a $T_{\text{eff}} = 20,000$ K, $\log(g) = 8.0$ model atmosphere. Using conventional notation as given by Mihalas (1970), the radiative acceleration is expressed as

$$\frac{1}{m} \left[\frac{dp(\nu)}{dr} \right] = \frac{4\pi}{c} \frac{dK_{\nu}}{dr},$$

where K_{ν} is in the second moment of the radiation field, m is the atomic mass, and $dp(\nu)/dr$ is the derivative of the momentum per unit frequency with respect to the radius. Using the relations of the radiation moments, the total radiative acceleration for a single atom of element A is given by

$$g_{\text{rad}} = \frac{1}{m} \left(\frac{dp}{dr} \right) = \frac{1}{c} \frac{\pi e^2}{m_e c} \frac{1}{N_A} \sum_i N_{A,i} \sum_l \int f_l \phi_{\nu} J_{\nu} d\nu.$$

The total acceleration is summed over the spectral lines (l), each with an oscillator strength f_l , and the stages of ionization i of element A, where

$$N_A = \sum_i N_{A,i}.$$

Since

$$\bar{J}_\nu \equiv \int \phi_\nu J_\nu d\nu \quad \text{and} \quad 4\pi H_\nu = J_\nu^C \sim \bar{J}_\nu,$$

for the weak-line case, we then write

$$\left(\frac{1}{m_A}\right) \frac{dp}{dr} \approx \left(\frac{4\pi}{c}\right) \left(\frac{\pi e^2}{m_e c}\right) \left(\frac{1}{N_A}\right) \sum_i N_{A,i} \sum_l f_l H_\nu.$$

At great depth in the atmospheres we have an isotropic radiation field ($J_\nu = 3K_\nu$) and $J_\nu = B_\nu$. Then applying the relations of the radiation field indicates that the above expression in the limit approaches equation (9) of VVG.

For further simplicity and convenience we neglect contributions from subordinate lines. This does not degrade the accuracy by more than 10%. In Table 3, the quantities λ , H_ν , $\Sigma f H_\nu$, and acceleration (a_{mult}) are given for all the relevant multiplets for the expected dominant ionization stages of C and Si in the photosphere of W1346, namely, Si II, Si III, C II, and C III. Also given is the total acceleration (values in parentheses) acting on a given ion at the stellar surface. The radiative acceleration at the stellar surface is shown to be much stronger for silicon ions than for carbon ions.

Since we actually see "photospheric" absorption features of Si II near 1265 Å, one can argue that the flux (J_ν) in the center of the Si II lines near 1265 Å is much less than the local continuum flux (J_ν^C). This implies

that the radiative acceleration for these transitions predicted by assuming $J_\nu \sim J_\nu^C$ is an overestimate. However, even if we did not include the strong Si II lines near 1200 and 1265 Å, the radiative acceleration on the Si II ions due to the weaker transition of Si II would still be large, $\log(g_{\text{rad}}) = 8.14$, compared with C (see Table 3).

Whether an element rises or sinks in a white dwarf atmosphere depends upon the relative strength of the radiative acceleration (g_{rad}) to the downward acceleration (g_{GT}), the latter being the sum of the accelerations due to gravity and the thermal gradient (see VVG). However, near the stellar surface $g_{\text{GT}} \approx g_{\text{grav}}$, where g_{grav} is the effective gravity of the star. Thus, our calculations suggest that Si can be levitated near the surface in typical 20,000 K white dwarf atmospheres with $\log(g) \approx 8.00$, as in W1346. We might add that if we were to increase the abundance of Si in the outer layers, J_ν in the lines would decrease, and Si atoms would begin to sink until the equilibrium abundance is again obtained.

The above result is not in disagreement with the diffusion calculations of VVG and FM. They find that metals (i.e., C, N, and O) should be present in white dwarf photospheres when $T_{\text{eff}} > 30,000$ K. From detailed calculations, they find that for $T_{\text{eff}} \leq 20,000$ K, no equilibria exist for C, N, and O and $|g_{\text{GT}}| > |g_{\text{rad}}|$. Thus, the radiation field will not support or levitate these ions and they will diffuse downward or gravitationally settle to deeper atmospheric layers. But, as we have shown here, $g_{\text{rad}}(\text{Si}) > g_{\text{rad}}(\text{C})$ at 20,000 K. Since the effective temperature of W1346 is 21,000 K, the radiation field may

TABLE 3
RADIATIVE ACCELERATION ON SILICON AND CARBON IONS

Ion	λ_{mult}	Σf	H_ν	$\Sigma f H_\nu$	a_{mult} (cm s ⁻²)
C II	1335	0.270	2.73×10^{-4}	7.37×10^{-5}	1.75×10^7
	904	0.520	2.81×10^{-7}	1.46×10^{-7}	3.46×10^4
	1036	5.9×10^{-2}	3.13×10^{-4}	1.85×10^{-5}	4.39×10^6 (2.2×10^7)
C III	997	0.81	3.27×10^{-4}	2.65×10^{-4}	6.28×10^7
Si II	1800	7.40×10^{-3}	2.36×10^{-4}	1.75×10^{-6}	4.15×10^5
	1525	1.5×10^{-1}	2.55×10^{-4}	3.83×10^{-5}	9.08×10^6
	1305	2.94×10^{-1}	2.75×10^{-4}	8.09×10^{-5}	1.92×10^7
	1265	1.92	2.80×10^{-4}	5.36×10^{-4}	1.27×10^8
	1200	3.89	2.89×10^{-4}	1.13×10^{-3}	2.68×10^8
	1020	9.64×10^{-2}	3.15×10^{-4}	3.03×10^{-4}	7.19×10^7
	990	4.8×10^{-1}	3.216×10^{-4}	1.57×10^{-4}	3.72×10^7 ($3.7\text{--}5.3 \times 10^8$)
Si III	1206	1.66	2.88×10^{-4}	4.18×10^{-4}	1.06×10^8

NOTE.—Approximate wavelengths in angstroms (λ) are given for relevant multiplets; f -values are from Morton and Smith 1973. Values in parentheses indicate expected range of total acceleration for each ion as discussed in the text. The values of H_ν are from the $T = 20,000$ K, $\log(g) = 8.0$ model atmosphere of Wesemael *et al.* 1980.

well support trace amounts of Si, while C with a smaller g_{rad} will exist in much smaller, undetectable amounts or not be supported at all, if $|g_{\text{rad}}| < |g_{\text{grav}}|$.

Although Si is a heavy atom, it is very easily levitated or supported by radiation pressure. Si II possesses many allowed transitions from the ground state, which have a wide range of oscillator strengths covering the peak of the flux distribution of a 20,000 K white dwarf. Even when some transitions become saturated such that $J_\nu \rightarrow 0$ in the line center, weaker transitions will not have $J_\nu \rightarrow 0$ and may keep g_{rad} large as the Si abundance increases. This property makes Si easily observable in the photosphere. Although we have not performed detailed calculations, we expect g_{rad} (Si) to remain high throughout the photosphere of W1346. Computation of ionic fractions using Saha's equation and a $T_{\text{eff}} = 20,000$ K, $\log(g) = 8.0$ pure-hydrogen model atmosphere show that Si II and C II are the dominant ions of Si and C in the outer photospheric regions.

v) 2111+49 (GD 394)

As discussed above, the presence of Si III and Si IV with the apparent absence of C II, C III, and C IV indicates Si is overabundant with respect to C in 2111+49. This is in accord with the levitation hypothesis.

Under conditions of low density and strong radiation field, the g_{rad} acting on Si III can be amplified. The level $^3P^o$ is the ground state of the triplet system in both C III and Si III with semiforbidden transitions to the zero-volt ground levels (C III] $\lambda 1909$, Si III] $\lambda 1892$). (No hint of emission is seen at 1892 or 1909 Å.) Since the transition probabilities of these semiforbidden transitions are low ($\sim 10^4 \text{ s}^{-1}$), the $^3P^o$ levels are "metastable-like." This metastable nature of the $^3P^o$ level can lead to overpopulation of the $^3P^o$ level and an enhancement of the radiative acceleration upon both C III and Si III. However, the $^3P^o - ^3P$ transitions of C III have oscillator strengths roughly factors of 2–9 lower than Si III, and their wavelength spacings are small, possibly providing some degree of blending. This favors a stronger enhancement of g_{rad} for Si III over C III.

vi) 40 Eridani

The white dwarf 40 Eri B shows no detectable line features in the UV. Both VVG and the FM indicate that when $T_{\text{eff}} \leq 20,000$ K, conditions are unfavorable for supporting those amounts of heavier elements in the photosphere. Since 40 Eri B is a DA white dwarf whose atmosphere is predicted to be not convective and also since it has a $T_{\text{eff}} = 17,000$ K, the lack of observable heavy elements does not conflict with current predictions.

vii) Sirius B

Sirius B has been found to be hot ($T_{\text{eff}} = 26,000$ K), but it also appears to have a high gravity [$\log(g) = 8.65$]

(Böhm-Vitense, Dettmann, and Kapranidis 1979). The high gravity makes it difficult to levitate ions, and it should not be surprising to find no observable heavy elements in its photospheric spectrum.

viii) HZ 43 and He 3

No features other than interstellar features are seen in these objects. Although HZ 43 is hot, it has a higher $\log(g)$ than G191–B2B, 8.0 versus 7.5, and the absence of lines does not conflict with the levitation model. The white dwarf He 3 is both cool and has a large $\log(g)$ and again does not conflict with the levitation model.

b) Levitation by Magnetic Fields

It has been proposed that magnetic fields may act to levitate ions in white dwarf photospheres (see Cottrell and Greenstein 1980), or at least assist radiative levitation (Alecian and Vauclair 1981). However, magnetic fields preferentially accelerate the lighter and the more highly ionized species. If magnetic fields were the dominant mechanism, one might expect to see a large C II/Si II ratio and a large C III/Si III ratio in W1346 and 2111+49, respectively, but the opposite is true. Also, one would expect to see anomalously high ionization for a given effective temperature, and this is not the case except possibly for N V in G191–B2B. The N V can be explained in terms of levitation by radiation pressure. This is not to say that magnetic fields are not present, but they are not the dominant force responsible for the observed ions in these white dwarfs.

c) The Role of Accretion in White Dwarfs

The time scales for diffusion (t_D) are quite short in atmospheres of white dwarfs. Typically, it is on the order of 10 yr in the photospheric layers above where the continuum is formed ($\tau \approx 1$ in curves of VVG). Heavy elements could settle out of the observable photosphere possibly on periods of $\sim 10^4$ yr. Because of the extremely short diffusion time scales, ignoring radiation pressure, accretion from the interstellar medium (ISM) will yield observable concentrations of heavy elements in white dwarfs only when they are embedded in interstellar clouds.

The number fraction of white dwarfs that are embedded in interstellar clouds is essentially the filling factor for clouds in the ISM. The bulk of the ISM consists of a permeating, hot (10^6 K), low-density (10^{-2} to 10^{-3} cm^{-3}) coronal component in which are embedded the interstellar clouds (Jenkins and Meloy 1974; McKee and Ostriker 1977; Fried *et al.* 1980; Bruhweiler and Kondo 1982). The theory of McKee and Ostriker predicts that the filling factor of clouds is ~ 0.24 . However, there is now overwhelming observational evidence that the actual filling factor in the local ISM is much less (Bruhweiler and Kondo 1982; Fried

et al. 1980; Bruhweiler 1983). In the general ISM, the mean free path between clouds as implied from data for Ca II (Spitzer 1968) and much more sensitive ultraviolet data for other ions (Cowie and York 1978) strongly suggests that the interstellar clouds are larger and more sparsely spaced, more typical of the “standard cloud” as outlined by Spitzer (1968). For Spitzer’s standard clouds the filling factor is on the order of 0.07. If the remaining bulk of the ISM is composed of the hot coronal gas, which now appears to be firmly established, accretion can occur only rarely; only one white dwarf in 15 may have observable concentrations of heavy elements in its photosphere due to accretion. Additionally, the observed UV interstellar column densities toward the white dwarfs displaying lines of noninterstellar origin indicate that these white dwarfs are located within a very low-density plasma, typical of the hot, coronal component (Bruhweiler and Kondo 1981, 1982). This is not to say that accretion cannot occasionally replenish the photospheres of hot white dwarfs with heavy elements, but levitation or some other process must be important in counteracting the downward diffusion and in providing observable heavy-element concentrations over time in these objects.

Another important consideration is that a strong radiation field or a stellar wind from hot white dwarfs might easily negate any accretion process.

III. MASS LOSS IN HOT WHITE DWARFS?

In Table 4, we have presented all the relevant radial velocity information for G191–B2B, HD 149499B, and 2111+49. The predicted observed radial heliocentric velocity for the Balmer lines, $V_{\text{Balmer}}^{\text{pred}} = -6 \text{ km s}^{-1}$, for HD 149499 agrees well with the actually observationally derived velocity, $V_l = -10.7 \pm 5.8 \text{ km s}^{-1}$, for the sharp He II and C IV features. This agreement is consistent with the formation of the He II and C IV features in the stellar photosphere of this He-rich white dwarf. However, for G191–B2B and 2111+49 the large difference between the velocities of the lines (V_l) and the predicted ($V_{\text{Balmer}}^{\text{pred}}$) and the observed radial velocities for the broad Balmer lines ($V_{\text{Balmer}}^{\text{obs}}$) of the photosphere uncorrected for gravitational redshift (ideally $V_{\text{Balmer}}^{\text{obs}}$ should equal $V_{\text{Balmer}}^{\text{pred}}$) strongly supports the interpretation that the observed features of heavy elements arise above the photosphere, most likely in an expanding halo or stellar wind.

Trimble and Greenstein (1972) note that the photospheric Balmer lines, which are used to determine radial velocities in white dwarfs, can be redshifted owing to high pressure. They also imply that their measured radial velocities may be affected by systematic errors introduced by their spectrograph. Nonetheless, they find the total errors introduced by these effects to be small and conclude that they should not alter drastically the derived radial velocities. We point out that in the case of

TABLE 4
RADIAL VELOCITY INFORMATION FOR HOT WHITE DWARFS

wd	V_l	$V_{\text{Balmer}}^{\text{pred}}$	$V_{\text{Balmer}}^{\text{obs}}$	V_s
G191–B2B	18.3 ± 4.2	+46	$+69 \pm 19$	+34
2111+49	$+25 \pm 4.1$...	$+98 \pm 19$...
HD 149499B	-10.7 ± 5.8	-6	...	-31 ± 3

NOTE.—Units are in km s^{-1} . The radial velocity (V_l) for the UV sharp-lined features are shortward-shifted with respect to the broad Balmer lines ($V_{\text{Balmer}}^{\text{obs}}$ or $V_{\text{Balmer}}^{\text{pred}}$) in the cases of G191–B2B and 2111+49. $V_{\text{Balmer}}^{\text{pred}}$ is the radial velocity of the late-type companion (V_s) plus the gravitational redshift (V_{rs}).

W1346, the radial velocity is based upon the narrow components of the Balmer profiles. Besides their narrow width, which reduces the measurement errors, they are most likely formed in the same region as the observed Si II, where the pressure shift is likely negligible, whether the region of formation is a photosphere or a halo. Thus, we might expect the relatively good agreement between the UV-determined radial velocity for the Si II lines and that determined from the narrow Balmer components at visual wavelengths.

The data we are presenting here suggest that mass loss effects extend to the hot, high-gravity white dwarfs. It is well substantiated that the highly evolved O subdwarfs, intermediate in gravity between main-sequence stars and white dwarfs, display pronounced mass loss effects in the N V and C IV profiles. One can speculate that the mass loss process is slowly “choked” as the star evolves to become a higher gravity object. If hot white dwarfs with temperatures similar to O stars exhibit mass loss as suggested here, and if radiation pressure is the driving force, then, as the white dwarf cools, there might be a transition from an expanding halo to a static halo, possibly being fed by a selective wind. As the white dwarf continues to cool, the radiation force decreases, and a point is reached where no halo will be supported. Then, finally $|g_{\text{grav}}| > |g_{\text{rad}}|$ for all ions, and levitation in the photosphere by radiation pressure would no longer be possible.

Other forces may well drive the wind. Although levitation by the radiation field seems responsible for the observed heavy ionic species, if magnetic fields are compressed with the matter, as seems the case in other collapsed objects like neutron stars, large magnetic fields may play some role in driving winds in hot white dwarfs. The role of magnetic fields in mass loss has recently been discussed by Underhill and Fahey (1983). Whatever the mechanism responsible, it appears that the mass loss process is active in hot stars regardless of luminosity. (See also Bruhweiler and Dean 1983.) Unfortunately, in white dwarfs we cannot differentiate between a selective wind and a mechanism that drives a general expansion; the latter process would expel the

neutral and ionized hydrogen as well. Using predicted model-atmosphere fluxes (Wesemael *et al.* 1980), simple calculations of the radiative force in both the Lyman lines and continuum show that radiation could expel small amounts of totally neutral hydrogen at $T_{\text{eff}} \approx 30,000$ K and $\log(g) \approx 7.7$. However, the ionization equilibrium strongly favors H II at $T_{\text{eff}} > 30,000$ K. Also, the radiation field shortward of the Lyman jump drops sharply for $T_{\text{eff}} < 30,000$ K. Thus, any radiation-driven wind would have to be a very selective wind.

The absence of the intercombination lines of Si III] $\lambda 1892$ and C III] $\lambda 1909$ does not necessarily imply high densities ($n_e \approx 10^9 \text{ cm}^{-3}$) and therefore a general wind. The $^3P^o - ^3P$ lines in 2111+49 are weak, suggesting a low abundance of the $^3P^o$ level of Si III.

An important argument against radiative forces driving the mass loss is the extreme sharpness of the ultraviolet shortward-shifted features in G191-B2B and 2111+49. Specifically, they show no hint of profile asymmetry or P Cygni characteristics as might be expected in a radiatively accelerated wind. Even though Bruhweiler and Kondo (1981) ruled out a planetary nebula interpretation for G191-B2B, sharp shortward-displaced features could result in an ejection process of a much smaller scale.

Considering the inherent uncertainties, both in the mechanism and the relative abundances, we have avoided any attempts at estimating the mass loss rates of G191-B2B and 2111+49.

IV. CONCLUSIONS

Four out of the eight hot white dwarfs so far observed show features due to heavy elements which are not interstellar in origin. From this small sample, comparison with present theoretical predictions for diffusion and levitation shows tentative agreement between theory and the hydrogen DA white dwarfs. Based on theory and observation, we tentatively propose a temperature and effective gravity range for white dwarfs, $T_{\text{eff}} \geq 20,000$ K and $\log(g) \leq 8.0$, within which white dwarfs display lines due to the heavy elements in their photospheres (see Fig. 4). Of the He-rich white dwarfs, only one, HD 149499B, has been thus far studied; its observational results do not agree with the predictions of VVG and FM. Convection or some other process may be the dominant mechanism affecting the observed heavy elements in these He-rich objects. We tentatively suggest that, at least in the hottest low-gravity DA white dwarfs, the observed narrow-lined features are formed in expanding halos or winds associated with the white dwarfs. Greenstein *et al.* (1977) argued against the possibility that the narrow Balmer components in white dwarf spectra were formed in a thick shell about the star because the lines were too sharp, and any shell feature would be expected to show evidence for orbital motion about the star. However, if a supporting mechanism, like

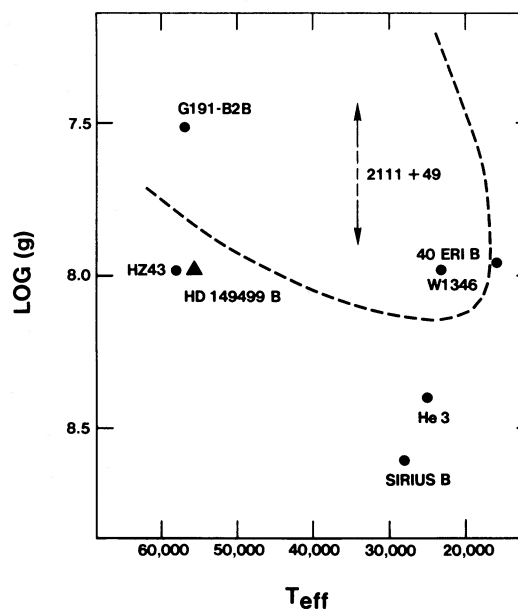


FIG. 4.—Effective temperatures and gravities for the white dwarfs. The DA white dwarfs are represented by circles, and the He-rich white dwarf (HD 149499B) is denoted by a triangle. The $\log(g)$ of 2111+49 is uncertain and is noted accordingly. The boundary of the region in which sharp-lined features occur [$T_{\text{eff}} \geq 20,000$ K, $\log(g) \leq 8.0$] is marked by a dashed line.

radiation pressure or magnetic fields, is acting, particles in a halo need not necessarily show ballistic orbital motion.

Theoretically, stable white dwarf halos should actually be coronae with temperatures in excess of 10^6 K (Lampton and Mewe 1979). However, the observed narrow-lined features discussed here do not suggest such high temperatures. The observed radial velocities certainly do suggest weak stellar winds in two hot white dwarfs, namely, G191-B2B and 2111+49. The features in HD 149499B and W1346 may well be formed in the stellar photosphere.

We emphasize that many of the conclusions presented here are tentative, and further observations of hot white dwarfs are needed to provide more details for these newly observed phenomena. Additionally, we hope that this paper will stimulate further detailed theoretical calculations and thought on the physical processes in white dwarfs.

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Note added in proof.—Recently (A. K. Dupree and J. C. Raymond, 1982, *Ap. J. [Letters]*, **263**, L63) N v, C iv, Si iv have been detected in the hot [$T_{\text{eff}} = 70,000 \pm 15,000$ K, $\log(g) = 6.7-7.2$] DA white dwarf Fe 24. This white dwarf is well within the temperature and gravity domain where metallic lines are expected. These new observations are consistent with the model presented here.

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