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PHOTOSPHERIC SOFT X-RAY EMISSION FROM HOT DA WHITE DWARFS

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ABSTRACT

Soft X-radiation ($\sim$150 eV) from four hot DA white dwarfs (EG 187, Gr 288, Gr 289, and LB 1663) has been detected with the imaging proportional counter of the *Einstein Observatory*. The observed pulse-height spectra are very soft and suggest that the emission arises from the hot photosphere with implied effective temperatures in the range 30,000–60,000 K. *International Ultraviolet Explorer* (*IUE*) ultraviolet spectra and Hβ line profiles have been obtained for all four stars, and fitted, along with the X-ray fluxes, with a grid of hot, high-gravity, homogeneous model atmospheres of mixed hydrogen-helium composition. We find that, in all four cases, the data require the presence of some X-ray opacity in the photosphere. For metal-free models, the implied He/H ratio is in the range (2–600) $\times 10^{-5}$. The implications of this result are discussed in the context of diffusion theories for the surface layers of white dwarfs.

We have also examined the limits imposed on the hot white dwarf population by the *Einstein* Medium Sensitivity Survey and derived constraints on the space densities of DA stars with effective temperatures exceeding 40,000 and 60,000 K. These are the most sensitive limits yet available for temperatures in this range. We find the results to be essentially compatible with predicted space densities based on current theories of white dwarf evolution.

Subject headings: stars: white dwarfs — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

The detections of soft X-radiation from Sirius and HZ 43 (Mewe *et al.* 1975*a*, *b*; Hearn *et al.* 1976; Margon *et al.* 1976*b*) and of intense extreme-ultraviolet (EUV) radiation from HZ 43, Feige 24, and G191B2B (Margon *et al.* 1976*a*; Lampton *et al.* 1976; Holberg *et al.* 1980) have sparked considerable interest in the further use of short-wavelength ($<$1000 Å) observations to probe physical conditions in white dwarf atmospheres. As first suggested by Shipman (1976), EUV/soft X-ray emission observed from hot, DA white dwarfs is likely to be photospheric in origin. Since the optical depth for X-rays is much less than unity in the outer regions of the photosphere, thermal X-radiation produced deep in the inner hotter regions can still escape. White dwarfs with photospheric effective temperatures as low as 30,000 K can therefore be significant soft X-ray emitters. Auer and Shipman (1977) showed that such a thermal model could successfully explain the extreme-ultraviolet emission from HZ 43. In addition, although initially rejected for Sirius B (Cash, Bowyer, and Lampton 1978), this explanation now appears to suffice for the X-ray emission from that object as well (Martin *et al.* 1982).

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In this paper, we report the discovery of soft X-ray emission from four additional DA white dwarfs with the *Einstein Observatory*. EG 187 (WD 1254+22, GD 153, L1336−41, BPM 21641, LTT 13724), Gr 288 (WD 0346−01, GD 50), and Gr 289 (WD 0548+00, GD 257) were detected as sources during planned pointed observations, whereas LB 1663 was discovered serendipitously in connection with the *Einstein* Medium Sensitivity Survey (Maccacaro *et al.* 1982). The observed intensities are indicative of effective temperatures in the range 30,000–60,000 K, somewhat cooler than the temperatures inferred for HZ 43 (Auer and Shipman 1977; Malina, Bowyer, and Basri 1982). The X-ray measurements are useful since the flux is a sensitive diagnostic of the surface elemental composition, particularly the helium and metal abundances. We have obtained optical and ultraviolet spectra of each star and fitted all of the data with homogeneous, mixed hydrogen-helium atmospheric models in order to derive constraints on the He/H ratio. We find that the fits to all four stars require helium to be present in the atmosphere at levels He/H $\gtrsim 10^{-5}$, provided that the atmosphere is metal-free.

This paper is organized as follows: in § II, we present our observations and preliminary analysis in the three wavelength bands; in § III, we describe the model atmosphere analysis and the constraints on stellar parameters; in § IV, we discuss the *Einstein* Medium Sensitivity Survey and the limits it imposes on the space density of hot white dwarfs; finally, in § V we discuss the implications of our results in terms of diffusion theory for white dwarf atmospheres.

II. OBSERVATIONS

a) *X-Ray*

The X-ray data were acquired during observations with the imaging proportional counter (IPC) of the *Einstein Observatory*

(Giacconi *et al.* 1979) performed under the Guest Observer Program. Part of this project was motivated by an earlier survey of X-ray emission from hot DA white dwarfs using the low-energy detectors (LEDs) of the A-2 experiment flown on *HEAO 1* (Lampton and Kahn 1978). A list of hot DA candidates (selected on the basis of apparent magnitude and color) was compiled for cross-checking with the *HEAO 1* LED count rates. The sensitivity of the survey was 5×10^{-3} LED counts cm^{-2} s^{-1} which is $\sim 3\%$ of the flux from HZ 43 in the energy range 0.1–3 keV. Of the 50 objects surveyed by *HEAO 1*, five exhibited $\gtrsim 4\ \sigma$ excesses above background at the correct position of the white dwarf. However, considering the large field of view of the LED ($1^\circ.5 \times 3^\circ$) and the high angular space density of low-luminosity X-ray sources, this success rate was not significantly different from that expected for completely random positions on the sky. Thus confirmation was required with the considerably higher sensitivity and spatial resolution of the *Einstein* IPC.

The five white dwarf candidate sources are listed in Table 1 along with the IPC exposure times and IPC count rates. As can be seen, two of the program stars, EG 187 and Gr 288, were detected as quite strong sources ($\sim 100\ \sigma$), while upper limits were obtained for the other three. The IPC count rates for the two detected sources are consistent with the count rates derived from the *HEAO 1* LED data after corrections are made for the different spectral responses and effective areas of the two instruments. Two additional objects are listed in Table 1: Gr 289, which was proposed (on the basis of apparent magnitude and color) as a candidate source under a different guest program, and LB 1663, which was discovered serendipitously during an observation of an optically bright, radio-quiet quasar and optically identified as part of the *Einstein* Medium Sensitivity Survey program (Maccacaro *et al.* 1982). As can be seen, both of these additional white dwarfs were detected as weaker, but still extremely significant ($> 10\ \sigma$), point sources.

For all of the detected sources, the count rates are sufficiently high to allow for pulse-height spectral analysis. Normalized, background-subtracted IPC pulse-height spectra are displayed for each of the four stars in Figure 1. As can be seen, these are extremely soft sources. Fits to the data assuming simple blackbody or thermal bremsstrahlung models yield characteristic temperatures less than 100 eV and imply absorbing column densities less than 10^{20} cm^{-2}.

TABLE 1

SUMMARY OF X-RAY OBSERVATIONS

Star	Exposure (s)	IPC Count Rate (counts s^{-1})
	HEAO 1 Survey	
EG 25	1905.0	<0.0076[a]
EG 113	2368.0	<0.0069[a]
EG 187	494.7	0.7867 ± 0.0067
Gr 275	1610.2	<0.0079[a]
Gr 288	1794.6	0.2133 ± 0.0027
	Other Observations	
Gr 289	3556.2	0.0827 ± 0.0043
LB 1663	4096.0	0.0203 ± 0.0018

[a] 3 σ upper limits.

Given the softness of these spectra, some care must be taken to allow for possible systematic effects in attempting to infer incident X-ray fluxes from the proportional counter data. In particular, there are usually a number of uncertainties in detector properties: the effective area at very low energies, the resolution kernel, the electronic discriminator, and the ultraviolet rejection efficiency, all of which can give rise to errors of up to several orders of magnitude. The IPC has all of these problems plus an additional one associated with its imaging capability. The statistical precision of each photon position is a function of the avalanche size or the pulse height of the event. For soft spectra, the pulse heights are small, and it is possible that a large fraction of the photons are mispositioned and thus not attributed to the source.

All of these effects, however, are associated with the event pulse height and not the incident photon energy. In addition, since the IPC spectral resolution is very broad at low energies ($> 100\%$), the shape of the pulse-height spectrum for soft sources is relatively insensitive to the detailed shape of the incident X-ray spectrum. Thus the detector can be accurately calibrated at low energies by comparison to a standard source which exhibits a similar, but not necessarily identical, X-ray spectrum. We have carried out such an analysis with the well-studied white dwarf X-ray source, HZ 43. Our IPC measured incident X-ray flux for HZ 43 is close (within 10%) to that measured from a rocket flight by Bleeker *et al.* (1978) assuming the same incident spectrum, although their value differs significantly from that derived from observations with the *HEAO 1* LEDs (G. Reichert, private communication). Thus, the dominant uncertainty in our measured fluxes for the new white dwarf sources is the uncertainty in the calibration standard, HZ 43. We conservatively estimate this systematic uncertainty to be $\sim 50\%$.

b) Ultraviolet

Ultraviolet spectra were obtained with the *International Ultraviolet Explorer* (*IUE*) satellite (see Boggess *et al.* 1978*a*, *b* for a description) in the low-resolution spectroscopic mode ($\lambda/\Delta\lambda \approx 200$). Observations were performed for all four stars with the short-wavelength prime (SWP) camera in the wavelength range $\lambda\lambda$1150–2000 and, except for Gr 288, with the long-wavelength redundant (LWR) camera in the wavelength range $\lambda\lambda$1900–3200. For Gr 288, an additional SWP observation was performed with a small-entrance aperture so as to reduce the contribution of geocoronal Lyα radiation. Two SWP observations were performed for Gr 289 as well. During the first, the telescope was markedly out of focus, and we believe that the flux derived from this observation is thus underestimated. A second spectrum was obtained later when the telescope was well focused, and it exhibits a higher continuum flux; however, it is possible that the data are saturated at the very short wavelength end. We have thus utilized the second spectrum of Gr 289 to derive the continuum flux, but excluded all points at $\lambda < 1350$ Å in performing the fits. The raw *IUE* data were processed at the Smithsonian Astrophysical Observatory (EG 187, Gr 288, LB 1663) and at Steward Observatory (Gr 289) for background subtraction, intensity corrections, and wavelength calibration.

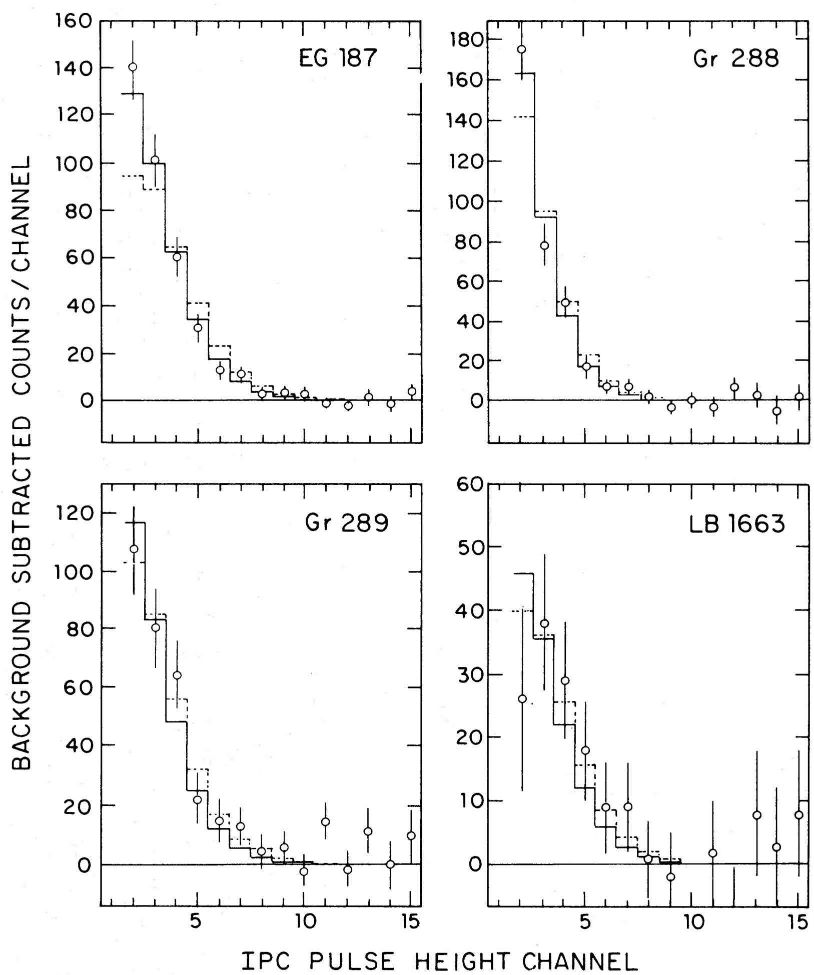

FIG. 1.—IPC pulse-height spectra of the four detected stars plotted vs. pulse-height channel. The data are plotted as circles where the vertical bars are $\pm 1\ \sigma$. The two histograms show representative model-predicted pulse-height spectra: (*solid*) $T_e = 5 \times 10^4$ K, He/H = 10^{-6}; and (*dashed*) $T_e = 3 \times 10^4$ K, He/H = 10^{-3}.

The systematic uncertainty in the derived flux is assumed to be $\sim 10\%$.

Representative SWP spectra for the four stars are displayed in Figure 2. As can be seen, all exhibit a smooth ultraviolet continuum with deep Lyα absorption (partially filled in by geocoronal Lyα radiation) which is expected for hot DA white dwarfs. There is evidence for a weak He II λ1640 absorption feature in the spectrum of Gr 289. We derive an equivalent width for this line of 3 Å with an uncertainty of ~ 2 Å. Upper limits to the equivalent width of similar features in the other stars are: ~ 7 Å for LB 1663, ~ 4 Å for Gr 288, and ~ 3 Å for EG 187.

c) *Optical*

Optical spectra have been taken of all four stars with the aim of obtaining accurate Hβ profiles for comparison with model atmosphere predictions. The observations of EG 187 and Gr 288 were performed with the z-machine spectrometer on the 60″ telescope at the Fred L. Whipple Observatory; the observation of Gr 289 was performed with the Steward analog "red" Reticon spectrograph on the 2.3 m telescope at Steward Observatory, and the observation of LB 1663 was performed with the SIT vidicon spectrometer on the 4 m telescope at Cerro Tololo Inter-American Observatory. Sample Hβ profiles are shown in Figure 3. In each case, the data have been corrected for the instrumental response of the detector by comparison with standard stars. The resolution of these spectra is ~ 5 Å.

III. MODEL ATMOSPHERE CALCULATIONS

a) *Model Description and Assumptions*

A grid of hot, high-gravity atmospheres was computed specifically for the present work covering the temperature range 20,000–60,000 K and helium abundances He/H = 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-6}. All models assume local thermodynamic equilibrium (LTE), plane-parallel geometry, and include the blanketing of hydrogen lines. Much of the physics and many of the numerical methods used in these computations have already been discussed by Wesemael *et al.* (1980) in the context of pure hydrogen atmospheres.

For each model, hydrogen line profiles for Lyα and Hβ were computed using the theory developed by Vidal, Cooper, and Smith (1973). For the more helium-rich models, profiles

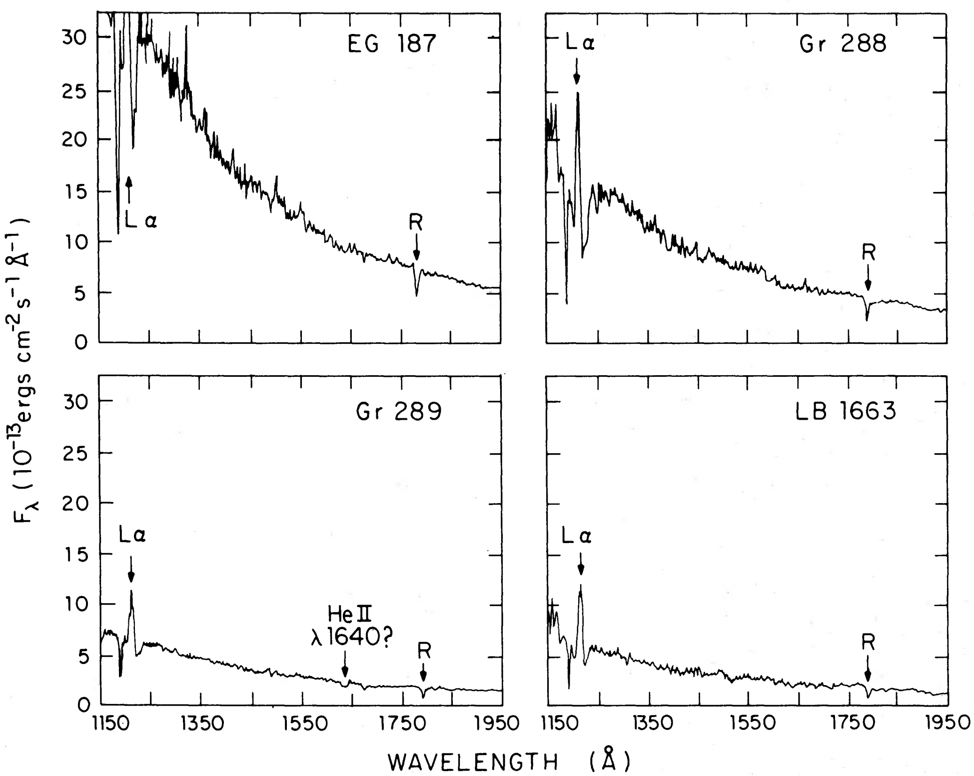

FIG. 2.—SWP ultraviolet spectra of the four stars shown as a function of wavelength. Camera reseau features are marked with an "R".

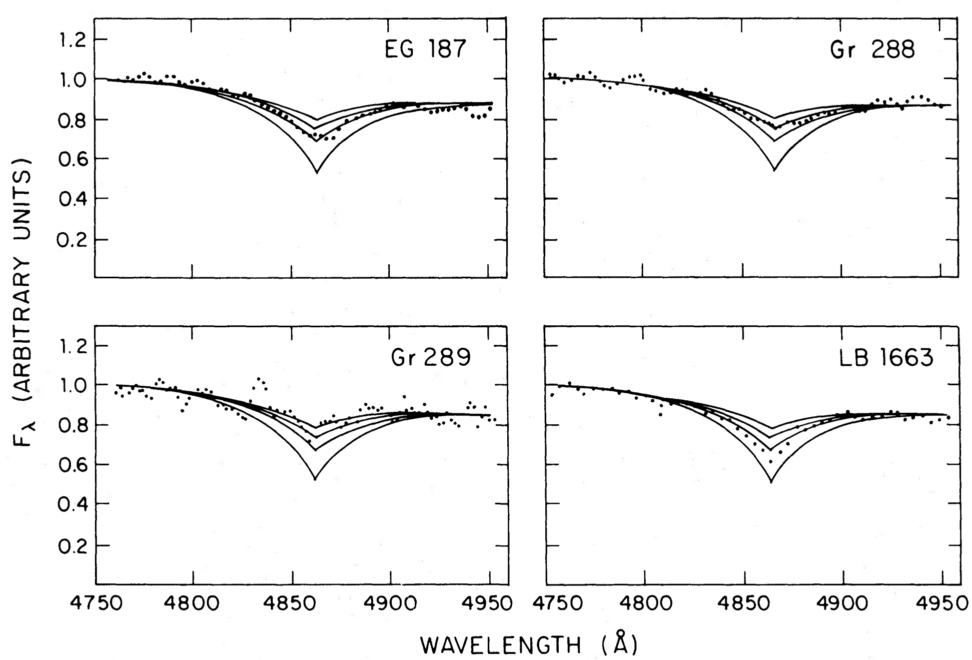

FIG. 3.—Hβ profiles of the four white dwarfs. Data are plotted as dots. The solid lines are model-predicted profiles, not corrected for instrumental resolution, for (from lowest to highest): T_e = 3, 4, 5, and 6 × 10^4 K respectively.

of the He II $\lambda1640$ and $\lambda4686$ transitions were also computed using the broadening theory summarized by Griem (1974).

The reliability of model atmosphere computations for pure-hydrogen or hydrogen-rich, high-gravity stars has been discussed extensively by Shipman (1979). For these hot stars, one expects the optical and ultraviolet fluxes to be accurate at the 1%–2% level, a fact substantiated by direct comparison of independent model atmosphere calculations (Auer and Shipman 1977; Wesemael *et al.* 1980). In the soft X-ray region, no detailed comparative analysis is yet available. However, our own tests show that, for a given composition, the emergent fluxes near 50 Å (250 eV) could be uncertain by $\sim$20%–30%, depending on the details of the calculation (see Martin *et al.* 1982 for an independent estimate). The assumption of LTE is not likely to introduce significant uncertainties. Non-LTE effects have been shown to be negligible in the optical and ultraviolet continua of DA white dwarfs (Wesemael *et al.* 1980; Holberg *et al.* 1980) and should be even smaller for the soft X-ray flux, which is formed very deep in the photosphere (e.g., for $T_e = 40{,}000$ K and He/H $\sim 10^{-3}$, $\tau_{60\,\text{Å}} \sim 1$ at $\tau_{\text{Rosseland}} \sim 5.6$). In the Balmer lines, the preliminary calculations of Wesemael *et al.* (1980) suggest the possible presence of non-LTE effects in the inner core ($\Delta\lambda \lesssim 2$ Å) of Hβ, but no departures from LTE predictions in the line wings.

Our models all assume $\log g = 8.0$. This is motivated by the gravity determinations of DA white dwarfs reported by Koester, Schulz, and Weidemann (1979) and Shipman and Sass (1980) which indicate an extremely narrow $\log g$ spectrum centered about this value. There is no evidence in any of our four X-ray sources for a very different $\log g$ value. In addition, continuum fluxes at UV and X-ray wavelengths are virtually independent of $\log g$ for values in the white dwarf range ($\log g = 7.5$–8.5).

A more critical assumption in our analysis involves the omission of metal continuum opacity sources. The presence of metals, such as CNO, can alter the emergent thermal soft X-ray flux in hot DA white dwarf atmospheres, as first discussed by Shipman (1976) and shown graphically by Böhm and Kapranidis (1980). Theoretical considerations suggest that metal abundances should be much less than solar because of diffusion processes; however, it is difficult to make exact predictions as to the extent of the metal deficiency. In particular, the calculations of Vauclair, Vauclair, and Greenstein (1979) show that, at $T_e = 40{,}000$ K, if CNO were present at near solar abundance, the downward acceleration on the metals due to gravity and thermal diffusion would greatly exceed (by a factor of $\sim$20) the upward acceleration due to radiation pressure (near the X-ray photosphere), so that these elements could not be supported. However, their calculations also show that, if these elements are initially underabundant, under certain ideal conditions (unsaturated lines, transitions with large f-values near the peak of the emergent flux), radiative forces could be much larger and may be able to keep trace amounts of CNO in the photosphere. Observationally, some constraints can be derived from ultraviolet studies which have failed to detect photospheric metal lines in the spectra of a number of hot DA white dwarfs (Greenstein and Oke 1979; Bruhweiler and Kondo 1981, 1982, 1983). The absences of C IV $\lambda1550$ and Si IV $\lambda1400$ suggest metal abundances down from the solar values by at least a factor of 10^3 (Shipman 1980). However, at least one hot DA star, Feige 24, shows evidence of photospheric C IV, Si IV, and N V lines (Dupree and Raymond 1982), and C IV features have been observed for a handful of hot DO stars (Wesemael, Green, and Liebert 1984). In addition, the cooler DA star Wolf 1346 may have photospheric Si II lines (Bruhweiler and Kondo 1983).

Shipman (1976) has investigated semiquantitatively the influence of metals on the emergent soft X-ray flux for the particular case of Sirius B and concluded that O/H had to be less than $\sim 2 \times 10^{-3}$ the solar value if oxygen was not to provide significant X-ray opacity. We have investigated this question in more detail by performing sample calculations of DA atmospheres with traces of metals. We find that, near 50 Å, the soft X-ray flux drops by a factor of 2–5 as the metal abundance is increased from 0 to 10^{-3} solar. As the metal content is increased beyond that value, the emergent flux drops more abruptly (by an additional factor of 300–1500 between 10^{-3} the solar value and 10^{-2} the solar value in the models studied). Hence, we view 10^{-3} the solar value as the limiting heavy element abundance beyond which metal opacity would quench the emergent X-ray flux.

The case for the presence and importance of small amounts of helium in hot DA atmospheres rests on firmer ground. Analyses of HZ 43 and Feige 24 over a large frequency baseline require a nonzero abundance of helium (Shipman 1979), and, in fact, a He II $\lambda227$ absorption edge has been explicitly detected in EUV spectra of HZ 43 (Malina, Bowyer, and Basri 1982). A weak He II $\lambda4686$ feature has also been detected in several, so-called DAO stars (Wesemael, Green, and Liebert 1984; Méndez *et al.* 1981), indicating a helium abundance as high as He/H $\sim 10^{-2}$ in these objects.

In view of our rather primitive knowledge of the element (mostly metal) abundance patterns in hot white dwarfs, we have chosen to assume that metals are *absent* from the photospheres of the DA stars under consideration. Helium thus provides, in our models, the most significant opacity source below 227 Å. While this assumption appears reasonable, its validity can be checked only by further theoretical studies of radiative forces in hot DA atmospheres, and by additional high-resolution ultraviolet studies of DA white dwarfs, coupled with model atmosphere abundance analyses.

The problem then of determining simultaneously the effective temperature and helium abundance in our objects is neatly separable, since the soft X-ray flux is rather sensitive to the helium abundance while the optical and ultraviolet fluxes and the line profiles are not [e.g., F_λ (1400 Å) changes by only $\sim$7% from He/H $= 10^{-2}$ to He/H $= 10^{-6}$ at $T_e = 40{,}000$ K]. We first use the line profiles to determine the effective temperature, T_e, and the long-wavelength continua to determine the normalization constant, $N \equiv 4\pi R^2/D^2$, where R is the stellar radius and D is the distance. The soft X-ray flux is then free to constrain He/H. Previous model analyses of the X-ray and EUV emission from hot DA white dwarfs have utilized only continuum measurements and have been hampered by the strong coupling between the derived T_e and He/H values (cf. Auer and Shipman 1977).

b) *Results*

The limits imposed by the continuum fits in the three wavelength bands are summarized in Figure 4 which shows the

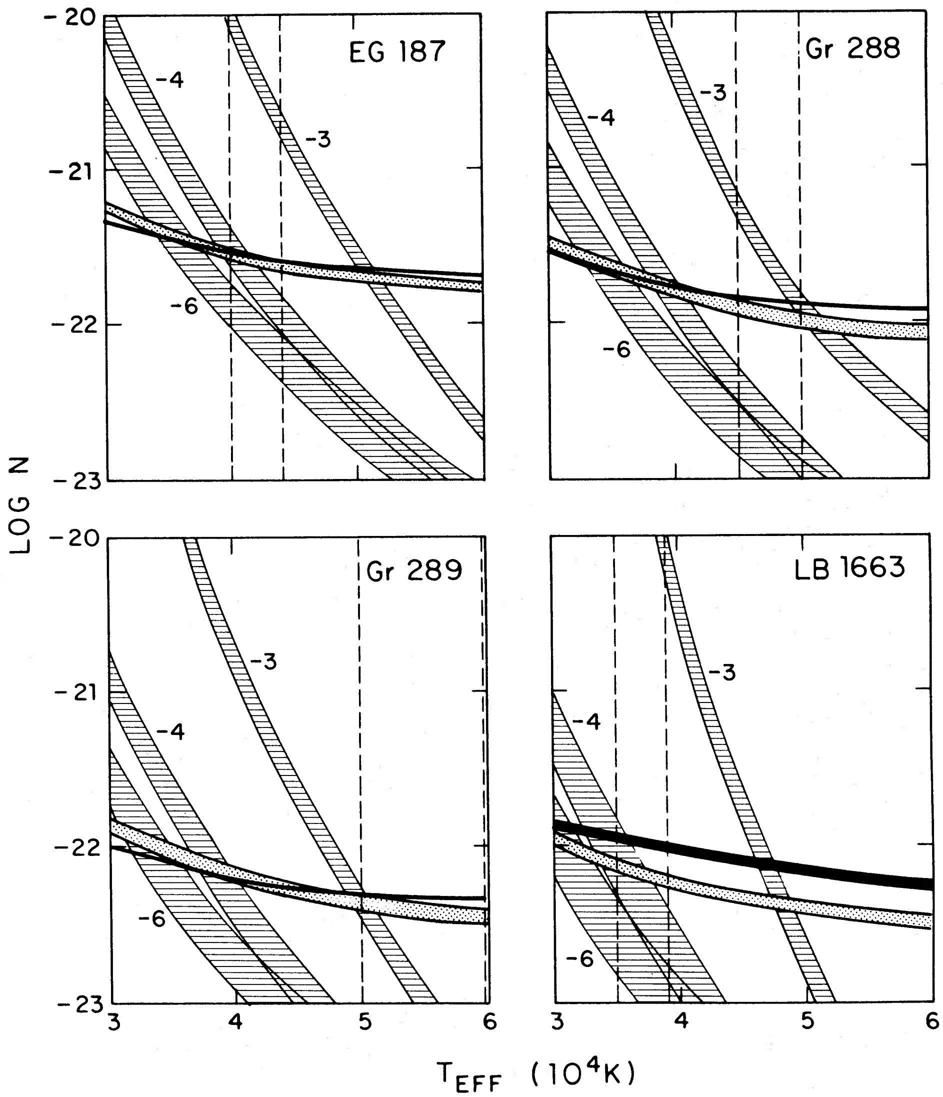

FIG. 4.—Constraints in the log N vs. T_e plane imposed by the various observations. The cross-hatched regions show the X-ray constraints applicable to log (He/H) = −3 (highest), −4, and −6 (lowest), as indicated in the figure. The dotted region illustrates the ultraviolet continuum constraint, whereas the solid black line shows the optical constraint. Limits on T_e derived from the Hβ profile are plotted as vertical dashed lines.

allowed ranges in log N versus T_e space. The X-ray constraints are derived by folding the computed model atmosphere spectra through the instrument response of the IPC and comparing with the observed pulse-height distributions. Because of the severe broadening of the IPC at low energies, the actual shape of the pulse-height distribution carries little information about the detailed shape of the incident spectrum, and, in fact, statistically acceptable fits are obtained with models covering virtually the full range in T_e and He/H (typical examples of the predicted pulse-height spectra are shown for each case in Fig. 1). An exception to this rule occurs for the cases of high helium abundance (He/H = 10^{-2}) *and* high temperature ($T_e \geq 50{,}000$ K). In this range, soft photons are absorbed by the helium in the photosphere while harder photons get through and contribute to the higher energy channels. The predicted pulse-height distribution is consequently considerably flatter than observed so that these models can be excluded by the X-ray data alone.

In contrast, the normalization derived from the X-ray count rates, N, is quite sensitive to model parameters, as evidenced by the steepness of the X-ray curves in Figure 4 and the order of magnitude separation between curves of different helium abundance. However, there is a significant uncertainty in N associated with the uncertainty in the absorbing column density, N_H, along the line of sight. If we assume a density for the local interstellar medium of ~0.01–0.1 atoms cm^{-3} (Cash, Bowyer, and Lampton 1979), we can conservatively adopt (for all four stars) an allowed range in N_H of 1×10^{18}–3×10^{19} atoms cm^{-2} (corresponding to a range in optical depth at 50 Å of 0.004–0.121). The difference in derived normalization for this range in N_H has thus been added in quadrature to the counting statistics and systematic uncertainties (see § II) to produce the error regions shown for the X-ray curves in Figure 4.

Fits to the shape of the ultraviolet continuum are also relatively insensitive to the effective temperature even if one uses the entire range covered by both SWP and LWR observations. In all four cases, the spectra are sufficiently steep to rule out models for which $T_e < 30{,}000$ K, but it is difficult to distinguish between models of higher temperature. The ultraviolet constraints on log N versus T_e shown in Figure 4 were derived by visually fitting the model continua to all *IUE* data available, assuming negligible interstellar reddening. The error regions (indicated by the thicknesses of the dotted bands) include the effects of systematic uncertainties ($\sim 10\%$) as well as visual estimates of the noise level of the spectra.

We have computed the optical constraints in Figure 4 by using published visual magnitude measurements (McCook and Sion 1977, and references therein) and comparing to model predictions of the flux at $\lambda 5500$. For the particular case of LB 1663, only crude photographic magnitude estimates are available (Luyten and Anderson 1958), so we have utilized our calibrated spectrophotometry to estimate the flux at $\lambda 5000$ for comparison with the models. Systematic uncertainties of ~ 0.01 magnitudes have been assumed in computing the error regions, again indicated by the thicknesses of the lines.

Estimates of the effective temperature, T_e, of the four stars can in principle be obtained by looking at the regions of intersection between the optical and ultraviolet curves of Figure 4. However, due to the high temperatures involved, the UV/optical flux ratio is relatively insensitive to temperature, so that large ranges are allowed in all cases. More accurate estimates of T_e can be obtained from the line profiles, particularly Hβ. In Figure 3, we have plotted the theoretical Hβ profiles for $T_e = 30{,}000$, 40,000, 50,000, and 60,000 K. The curves have been normalized by eye so as to match the data in the line wings. Based on the fits to these profiles, we derive limits on T_e for each star which are summarized in Table 2 and plotted as vertical dashed lines in Figure 4. Line profiles have also been computed for Lyα and compared to the *IUE* data. However, due to contamination by geocoronal Lyα at line center, fits can be performed only to the line wings, and the limits on T_e are consequently less constraining. In all four cases though, the Lyα limits are consistent with the Hβ results.

TABLE 2

DERIVED STELLAR PARAMETERS

Star	T_e ($\times 10^4$ K)	(He/H)[a] ($\times 10^{-5}$)	D[a] [$\times R/(0.013\ R_\odot)$ pc]
EG 187	4.2 $\pm$ 0.2[b]	2–40	60–65
Gr 288	4.75 $\pm$ 0.25	30–200	85–92
Gr 289	5.5 $\pm$ 0.5	80–600	147–152
LB 1663	3.7 $\pm$ 0.2	2–60	95–111

[a] As derived from the normalization, N, implied by the optical constraint curve of Fig. 4. Where the optical and UV results differ, the optical has been taken as more reliable because of the possibility of significant reddening effects (see text).

[b] Koester, Schulz, and Weidemann 1979 obtained $T_e = 40{,}400$ K, log g = 7.85 for this star, based on broad-band and Strömgren photometry.

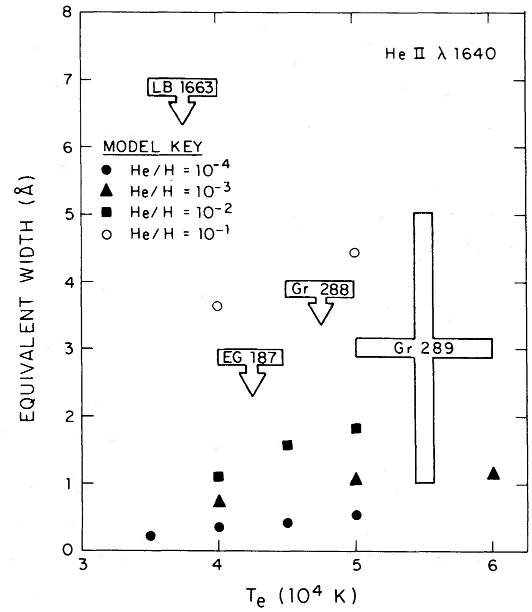

FIG. 5.—The equivalent width of the He II $\lambda 1640$ line is plotted as a function of effective temperature. Upper limits for EG 187, Gr 288, and LB 1663 are shown as indicated, where the horizontal width of the bar above the arrow illustrates the allowed range in T_e implied by the Hβ profiles. The cross shows the allowed range in equivalent width and T_e derived for Gr 289. Model predicted equivalent widths are plotted as symbols for various He/H and T_e values.

As can be seen from Figure 4, the Hβ temperature limits generally lie at the high end of the range implied by the UV/optical overlap, and for LB 1663, are in fact inconsistent with that range. This effect may possibly be associated with interstellar reddening which should suppress the ultraviolet flux (and thereby lower the estimate of T_e) but leave the Hβ lines unaffected. Support for this interpretation comes from the fact that the effect is apparently correlated with distance; it is more pronounced for the stars which are farther away (low N) and least pronounced for EG 187 which is closest (highest N). In any case, if reddening is present, then the optical constraints on log N versus T_e should be taken as more reliable than the UV curves.

Given the derived limits on T_e and log N, we can then interpolate between the X-ray curves to obtain constraints on He/H. The results of that analysis are summarized in Table 2. Note that, in all four cases, our fits *require* the presence of helium in the atmosphere at levels He/H $> 10^{-5}$. Limits on the distances derived from the normalizations are also included in Table 2.

In § II*b* we discussed a possible detection of a He II $\lambda 1640$ feature in the ultraviolet spectrum of Gr 289. The derived equivalent width is plotted in Figure 5 in the relevant temperature range along with the upper limits for the other stars. Also plotted in Figure 5 are the predictions for the equivalent width of this feature based on the model calculations. As can be seen, given the uncertainties, both the upper limits and the detection are consistent with the model predictions. Further ultraviolet observations of these stars with higher sensitivity will clearly be valuable, since the equivalent width of the He II line provides a useful check on our derived helium abundances.

IV. CONSTRAINTS ON THE SPACE DENSITY OF HOT DA WHITE DWARFS FROM THE *EINSTEIN* MEDIUM SURVEY

The *Einstein* Medium Sensitivity Survey (Maccacaro *et al.* 1982) is a systematic search for serendipitous sources in *Einstein* IPC fields at high galactic latitudes, $|b| > 20°$. Typical IPC exposures were in the range 10^3–10^4 s, and the total sky coverage was $\sim 0.18\%$. For the early survey reported by Maccacaro *et al.* (1982), 104 sources were detected at greater than 4 σ significance, 63 of which were significant at greater than 5 σ, and the error circles for this latter sample were searched for optical counterparts (Stocke *et al.* 1983). The white dwarf LB 1663 appeared in the 4 σ list but not the 5 σ list,[9] and no other white dwarfs appeared in the survey at all. It should be noted that, had other hot DA white dwarf sources been present in the survey, they would have almost certainly been correctly identified since they are both optically bright (relative to QSO X-ray sources) and very blue (relative to normal stellar X-ray sources).

The Medium Sensitivity Survey results thus provide a limit on the space density of hot DA white dwarfs. Previous studies of this kind (Wesemael 1978, 1981) have utilized soft X-ray surveys with limiting fluxes $\sim 10^3$ times higher. The increase in sensitivity allows us to investigate the space density of cooler stars ($T_e \geq 40{,}000$ K) which has never before been possible, and to place tighter limits on the very hot stars ($T_e \geq 60{,}000$ K) by looking out to greater distances. Our procedure is as follows: using the model atmosphere calculations discussed in § III*a*, we compute the expected IPC count rate, $f_x(D)$, as a function of distance, D, for a given set of stellar parameters. This calculation requires an assumption about the average interstellar hydrogen density, $\langle n_H \rangle$, along the line of sight, since absorption plays a significant role in limiting the soft X-ray flux. We have thus computed $f_x(D)$ for the two cases $\langle n_H \rangle = 0.1$ cm^{-3} and $\langle n_H \rangle = 1$ cm^{-3} which should bracket the true situation. From T. Maccacaro (private communication), we have obtained the solid angle surveyed as a function of limiting flux, $\Omega(f_x)$, so that we can compute the function, $\Omega(D)$, i.e., the solid angle surveyed out to a limiting distance, D, at which a white dwarf (of the given parameters) could be detected. The total observable volume, V, covered by the survey is then given by:

$$V = \int_0^\infty D^2 \Omega(D) dD . \tag{1}$$

However, because of the high sensitivity of *Einstein*, the limiting distance surveyed is large (>1 kpc for $T_e = 60{,}000$ K, $\langle n_H \rangle = 0.1$ cm^{-3}), so that it is necessary to take account of the expected decrease in space density at large vertical distances from the galactic plane. In particular, assuming that white dwarfs are distributed in z, the height above the plane, as

$$n(z) = n_0 \, e^{-|z|/\beta} , \tag{2}$$

where β is the scale height in parsecs, and that the Medium Sensitivity Survey evenly sampled the region of sky for $|b| > 20°$, we expect a distribution in distance D of

$$n(D) = n_0 \, e^{-[(D\langle \sin|b| \rangle)/\beta]} = n_0 \, e^{-D/\beta'} , \tag{3}$$

where $\beta' \equiv 1.22\beta$. Thus, the expectation value for the number of white dwarfs detected in the survey, $\bar{N}$, should be given by

$$\bar{N} = n_0 \int_0^\infty D^2 \Omega(D) e^{-D/\beta'} dD . \tag{4}$$

No white dwarfs were detected in the survey (at >5 σ significance). At 90% confidence, this implies that $\bar{N} < 2.30$ so that

$$n_0 < 2.30 \Big/ \left[\int_0^\infty D^2 \Omega(D) e^{-D/\beta'} dD \right] . \tag{5}$$

We have carried out this calculation for two separate models: (1) $T_e \geq 40{,}000$ K, He/H $= 10^{-4}$ and (2) $T_e \geq 60{,}000$ K, He/H $= 10^{-4}$, each computed for the two cases of interstellar density previously discussed. The assumed value of the scale height for hot white dwarfs was $\beta = 250$ pc (Green 1980). The results are illustrated in Figure 6 where we have plotted the logarithm of the integrand, log $[D^2 \Omega(D) e^{-D/\beta'}]$, versus the distance D. As can be seen, the results are quite sensitive to $\langle n_H \rangle$. Our derived upper limits to n_0 are listed in Table 3.

As has been emphasized by Wesemael (1978, 1981) and Koester (1978), observational constraints on the space density of hot white dwarfs are useful for testing theories of white dwarf evolution. The space density one expects for white dwarfs with effective temperatures hotter than some limit, T_e, is given by

$$n(T_e) = \chi_{WD}[\tau(T_e) - \tau(T_e{}^0)] , \tag{6}$$

where χ_{WD} is the white dwarf birthrate (assumed constant), $\tau(T_e)$ is the theoretical age of white dwarfs with effective temperatures equal to T_e, and $\tau(T_e{}^0)$ is the age of white dwarfs at the formation of the white dwarf stage. The last parameter is somewhat uncertain, but we may adopt, as an upper limit, $\tau(T_e{}^0) \sim 10^6$ yr, applicable to an initial white dwarf luminosity, $L_0 \sim 10 \, L_\odot$. The birthrate can be derived from space density estimates of cool white dwarfs which imply a value, $\chi_{WD} = 1.4 \times 10^{-12}$ pc^{-3} yr^{-1} (Green 1980). The parameter $\tau(T_e)$ depends, of course, on the evolutionary theory. We have computed space densities based on the recent calculations at $M = 0.6 \, M_\odot$ of Winget, Lamb, and Van Horn (1984) which include neutrino energy losses as well as the effects of hydrogen and helium layers in the outer regions of the atmosphere. The results are listed in Table 3. Since DA stars are expected to dominate ($>80\%$) the hot white dwarf sample, these numbers can be directly compared to our observational

TABLE 3

THE SPACE DENSITY OF HOT DA WHITE DWARFS

Limiting T_e ($\times 10^4$ K)	Observational Constraints ($\times 10^{-6}$ pc^{-3})		Theoretical Predictions (10^{-6} pc^{-3})
	$\langle n_H \rangle = 0.1$ cm^{-3}	$\langle n_H \rangle = 1$ cm^{-3}	
4.0	<57	<920	11–13
6.0	<12	<85	5.1–6.5

[9] The X-ray flux and error quoted for LB 1663 in Table 1 were derived using an IPC error circle and pulse-height range applicable to very soft sources. The automatic procedure used in the Medium Sensitivity Survey was geared more toward harder X-ray sources, and the statistical significance of the source, evaluated according to that procedure, was lower.

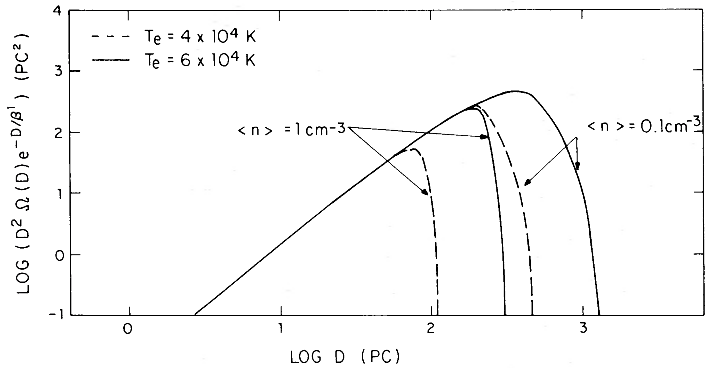

FIG. 6.—The function log $[D^2\Omega(D)e^{-D/\beta'}]$ is plotted as a function of distance D (see text). The dashed curves apply to white dwarfs with $T_e = 4 \times 10^4$ K and the solid curves to white dwarfs with $T_e = 6 \times 10^4$ K. Two curves are drawn in each case, applicable to the two different mean interstellar densities indicated in the figure.

results derived for hot DA's. As can be seen, the observational upper limits lie above the theoretical predictions at both 40,000 K and 60,000 K. However, work on the Medium Sensitivity Survey has continued, and a sample now approximately twice as big has been completely identified with no new white dwarfs discovered (Gioia *et al.* 1984). Thus our observational constraints should probably come down by a factor of 2, which makes them close, in some cases, to the theoretical predictions. It is interesting to note that the theoretical space densities indicate the presence of as many as 50 white dwarfs with effective temperatures higher than 40,000 K within 100 pc (see also Koester 1978) and perhaps another five white dwarfs as yet undiscovered in the *Einstein* data base. Thus a considerable number of additional objects similar to those reported in this paper should be suitable for study with future soft X-ray and EUV instruments.

V. DISCUSSION

The discovery of X-radiation from EG 187, Gr 288, Gr 289, and LB 1663 confirms Shipman's (1976) suggestion that hot DA white dwarfs can be prominent soft X-ray emitters. The observation of very soft X-ray spectra for these sources makes it highly likely that the observed short-wavelength radiation is photospheric in origin, and our model atmosphere analysis has indeed shown that the observed fluxes can be consistently fitted by homogeneous DA atmospheres with traces of helium. In addition, as discussed in § IV, theoretical predictions of the space density of hot white dwarfs are consistent with the presence of such objects and, in fact, suggest that many more should reside at distances accessible to future EUV and X-ray observatories.

Of particular interest in the present investigation is the fact that our model fits require the presence of some X-ray opacity in the photosphere for all four stars. If we assume that the atmosphere is metal-free, i.e., that the metal abundance is less than $\sim 10^{-3}$ the solar value, then we require helium to be present at levels exceeding $\mathrm{He/H} = 10^{-5}$. A similar helium abundance was inferred as well for the previously studied hot DA source HZ 43 (Malina, Bowyer, and Basri 1982; Auer and Shipman 1977). This result may be rather surprising in light of current diffusion theories for high-gravity stars which predict that helium along with the metals should diffuse rather quickly to lower layers of the atmosphere (Fontaine and Michaud 1979; Vauclair, Vauclair, and Greenstein 1979; Alcock and Illarionov 1980). In particular, Fontaine and Michaud (1979) find that for a DA white dwarf with $T_e = 40{,}000$ K, the diffusion time scale for helium to settle below the X-ray photosphere ($\Delta M/M \approx 2 \times 10^{-16}$) should be less than 10^2 years, while the age of such an object is $\sim 10^7$ years. Thus, *no helium should be present at all in the X-ray photosphere.*

The observational results are also puzzling in that the abundances derived do not appear to correlate in any simple way with the ages of the stars. If settling is the dominant mechanism, but for some unknown reason is operating considerably slower than the calculations suggest, we expect the youngest (hottest) stars to exhibit the highest He/H values, and the oldest (coolest) stars to exhibit the lowest. In contrast, the lowest helium abundances are observed for the stars at *both* ends of the T_e range (HZ 43: Malina, Bowyer, and Basri 1982; Sirius B: Martin *et al.* 1982), whereas the highest abundances are derived for stars in the middle (Gr 288 and Gr 289: this paper).

Clearly some processes must be competing with the downward diffusion in order to prevent the rapid settling of helium from the photosphere. We consider three possibilities in the following discussion.

a) *Radiative Support*

Radiative forces on helium ions are nonnegligible in hot white dwarf atmospheres and might possibly counteract the downward acceleration under certain conditions. Michaud *et al.* (1979) have considered the problem for main-sequence stars and developed a fitting formula for the radiative acceleration of helium as a function of effective temperature, density, and helium abundance. Using this formula (eq. [17] of their paper), we find for a DA white dwarf with $T_e = 40{,}000$ K and $\mathrm{He/H} = 10^{-4}$ that the upward acceleration on helium due to radiation pressure at the X-ray photosphere is $\sim 8 \times 10^6$ cm s^{-2}, a factor ~ 12 times smaller than the surface gravity. The acceleration is inversely proportional to the square root of the helium abundance (due to saturation effects), so this mechanism may indeed be important for stars with low helium abundances. We note, however, that the fitting formulae developed by Michaud *et al.* do not extend to the higher densities encountered in white dwarf photospheres. Thus further theoretical work in this area is required before this mechanism can be properly evaluated.

b) *Meridional Currents and Turbulent Motions in Rotating Stars*

It is conceivable that the presence of meridional currents in rotating nonmagnetic white dwarfs could disrupt the settling process and thus prevent the separation of elements in the atmospheres of such stars. Recent detailed calculations of meridional circulation flow patterns in rotating white dwarfs have shown, however, that this is unlikely (Tassoul and Tassoul 1983); the meridional circulation velocities in the envelopes of rotating white dwarfs are, in all cases of interest, found to be $\lesssim 10^{-10}$ cm s^{-1}, much smaller than the helium diffusion velocity estimated from our models at the X-ray photosphere ($v_d \approx 8 \times 10^{-3}$ cm s^{-1} for $T_e = 40{,}000$ K, He/H $= 10^{-3}$). Thus this process is not likely to play a role in determining the observed helium abundance.

A related mechanism involves the possible presence of turbulence produced by the shear flow that develops in the differential rotation associated with meridional circulation. The competition between diffusion mechanisms and turbulent mixing has been discussed by Vauclair and Reisse (1977) and Fontaine and Michaud (1979) in the case of white dwarfs. The former authors, in particular, have estimated typical time scales for the onset of turbulence and argue that it should develop over periods of $\sim 10^8$ years, much longer than typical diffusion time scales. Hence, it is unlikely to affect the element separation. In addition, extremely rapid rotation would be required for turbulence to mix through the molecular weight barrier (Vauclair and Reisse 1977). Since no rapid rotators ($v \gtrsim 100$ km s^{-1}) have been found among white dwarfs, this latter possibility appears unlikely. We therefore conclude that turbulence associated with differential rotation is unlikely to disrupt the diffusion processes in white dwarf envelopes.

c) *Interstellar Accretion*

The process of accretion from the interstellar medium has been invoked repeatedly to account for the often puzzling abundance patterns in white dwarf photospheres (Greenstein 1951; Sion 1973; Strittmatter and Wickramasinghe 1971; Wesemael 1979; Alcock and Illarionov 1980; Vauclair, Vauclair, and Greenstein 1979; Wesemael and Truran 1982). Despite these extensive investigations, however, the efficiency of accretion in polluting stellar photospheres is still very much uncertain.

If we assume that the observed helium in the hot DA X-ray sources is associated with accretion, we can derive the required steady state accretion rate by setting the rate at which helium diffuses below the X-ray photosphere equal to the rate at which it is replenished by newly accreted material. In that case,

$$\left(\frac{\mathrm{He}}{\mathrm{H}}\right)_* = \frac{\dot{M}}{4\pi R^2 \rho v_{d_{\mathrm{He}}} + \dot{M}} \left(\frac{\mathrm{He}}{\mathrm{H}}\right)_{\mathrm{ISM}}, \tag{7}$$

where $(\mathrm{He/H})_*$ is the surface helium abundance, $(\mathrm{He/H})_{\mathrm{ISM}}$ is the interstellar helium abundance, $\dot{M}$ is the accretion rate, R is the stellar radius, and ρ and $v_{d_{\mathrm{He}}}$ are the density and diffusion velocity evaluated at the X-ray photosphere. For our model with $T_e = 40{,}000$ K and $(\mathrm{He/H})_* = 10^{-3}$, calculations similar to those of Fontaine and Michaud (1979) imply that $v_{d_{\mathrm{He}}} \approx 8.3 \times 10^{-3}$ cm s^{-1}, so that $\dot{M} \approx 4.9 \times 10^{-18}$ $M_\odot$ yr^{-1}. This accretion rate is intermediate between that obtained from Eddington's single-particle formula ($\dot{M} \sim 5 \times 10^{-21}$ $M_\odot$ yr^{-1}) and that obtained using Bondi's fluid accretion model ($\dot{M} \sim 10^{-16}$ $M_\odot$ yr^{-1}), both evaluated for typical white dwarf, cloud, and interstellar medium parameters.

One important consequence of the accretion hypothesis is that other heavy elements are accreted as well. As a consistency test then, we can use the accretion rates derived from the surface helium abundance to predict the surface abundance of prominent metals and compare it with observed upper limits. For example, for oxygen, we should find:

$$\frac{(\mathrm{O/H})_*}{(\mathrm{O/H})_{\mathrm{ISM}}} = \frac{(\mathrm{He/H})_*}{(\mathrm{He/H})_{\mathrm{ISM}}} \times \left(\frac{v_{d_{\mathrm{He}}}}{v_{d_{\mathrm{O}}}}\right),$$

where $(\mathrm{O/H})_*$ and $(\mathrm{O/H})_{\mathrm{ISM}}$ are the surface and interstellar abundances of oxygen, respectively, and $v_{d_{\mathrm{O}}}$ is the diffusion velocity for oxygen. From Fontaine and Michaud (1979), we find that $v_{d_{\mathrm{O}}} \approx 1.8 \times 10^{-2}$ cm s^{-1} at the X-ray photosphere of the same 40,000 K model (for a mean ionic charge of 3), so that $(\mathrm{O/H})_* \sim 2.8 \times 10^{-3} (\mathrm{O/H})_{\mathrm{ISM}}$. This value is consistent with the observational constraints on surface metal abundances in DA stars and with the upper limit required for negligible contribution of the metals to the continuum soft X-ray opacity (see § III).

Interstellar accretion thus appears to be a viable mechanism for keeping detectable amounts of helium in DA photospheres. Some support for this model comes from the rather large spread (over two orders of magnitude) in derived He/H values which can be easily explained by the patchy density distribution of the local interstellar medium. In particular, the two white dwarfs which exhibit the lowest helium abundance, HZ 43 and Sirius B, are known to be located in very low density regions of the interstellar medium (Holberg *et al.* 1980). If this interpretation of the data is correct, then future EUV/soft X-ray observations of hot white dwarfs may provide us with the important capability of probing the density of the interstellar medium at various localized regions in space. It should be noted, however, that if accretion is indeed an important process in determining the surface chemistry of white dwarfs, then it is very difficult to understand both the absence of hydrogen and the relative metal abundance ratios in the cool helium-rich stars.

In conclusion, we believe that radiation pressure on helium and accretion from the interstellar medium are viable mechanisms that could lead to the presence of detectable quantities of helium in the photospheres of hot DA white dwarfs. However a number of uncertainties, both theoretical and observational, remain to be resolved before these processes are fully understood. Of particular value would be future EUV/soft X-ray spectroscopic observations of these and other stars, which might permit us to detect the K-edges of helium and the L-edges of several metals. Such detections would provide much more accurate estimates of the actual abundances of heavy elements present.

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