THE ASTROPHYSICAL JOURNAL, 304:356–364, 1986 May 1

AN X-RAY SURVEY OF HOT WHITE DWARF STARS: EVIDENCE FOR A n(He)/n(H) VERSUS $T_{\rm eff}$ CORRELATION

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Received 1985 August 2; accepted 1985 October 22

ABSTRACT

We report on observations of 13 white dwarf and subdwarf stars using the *Einstein Observatory* High Resolution Imager. Included are stars of classes DA, DB, DAV, sDO, and sDB, with optically determined effective temperatures in the range 1–6 × 10^4 K. We detected X-ray emission from two of the 13: the very hot (55,000 K) DA1 star WD 2309+105 (=EG 233), with a count rate one-fifth that of HZ 43, and the relatively cool (26,000 K) DA3 star WD 1052−273 (=GD 125). We use the effective temperatures determined from ultraviolet and optical observations to place limits on the He content of the white dwarf photospheres, presuming that trace photospheric He is the missing opacity source which quenches the thermal X-rays in these stars. When we combine our results with those available from the literature we find evidence for a correlation between $T_{\rm eff}$ and n(He)/n(H), in which HZ 43 is a conspicuous exception to the general trend. Both this correlation and the exceptional behavior of HZ 43 are qualitatively accounted for by a radiative acceleration model, in which the rate of upward movement of the He is a function of temperature and surface gravity.

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

I. INTRODUCTION

When HZ 43 and Sirius B were found to be X-ray sources (Mewe *et al.* 1975*a*, *b*; Hearn *et al.* 1976; Margon *et al.* 1976), there was considerable optimism that white dwarf stars might be an abundant class of soft X-ray sources. As was first suggested by Shipman (1976; Auer and Shipman 1977), the X-ray emission from these objects is likely to come from the deep layers of the photospheres of these stars, if metals and helium are depleted from the stellar atmosphere. The most recent estimate of the space density of hot white dwarfs has suggested that there are 50 or more hot ($T \geq 4 \times 10^4$ K) white dwarfs within 100 pc of the Sun that should have been visible to the *Einstein* imaging instruments (Kahn *et al.* 1984). But one of the more disappointing results from the *Einstein Observatory* is its lack of detection of X-ray emission from a substantial number of white dwarf stars, either known or previously undiscovered, although several additional objects have been detected (see, e.g., Kahn *et al.* 1984). This paper, which parallels the similar investigation of Kahn *et al.*, analyzes the data sample from the MIT *Einstein* survey of white dwarf stars and attempts to explain the paucity of bright white dwarf stars in the *Einstein* data base. It turns out that HZ 43 and Sirius B are perhaps a bit unusual among hot DA white dwarf stars in that their He abundances are quite low (less than a few times 10^{-5}).

The three published surveys of white dwarf stars made by *Einstein* have so far only yielded six confirmed white dwarf X-ray sources. Vaiana *et al.* (1981), in their extensive stellar survey, reported that they had measured a total of 34 upper bounds on X-ray emission and listed 15. They listed two detections, both of which were Sirius B and HZ 43, discovered prior to *Einstein.* The second survey, by Fontaine, Montmerle, and Michaud (1982), yielded upper limits for nine DB white dwarf stars, with luminosity limits ranging from 2×10^{28} to 8×10^{28} ergs s^{-1} (0.1–5.0 keV), and a 2 σ signal from the star GD 205, which was not regarded as real. The third set of observations, reported by Kahn *et al.* (1984), was an amalgam of several Guest Investigator programs, and resulted in the detection of four new sources (EG 187, EG 288, EG 289, and the serendipitous source LB 1663).

We report here on a fourth survey, in which a search for X-ray emission from 13 white dwarf stars of various varieties yielded 11 upper limits, one source at the HRI detection threshold, and one extremely bright source which has a count rate about one-fifth that of HZ 43 and an X-ray (0.065–4.5 keV) luminosity of $\sim 1 \times 10^{31}$ ergs s^{-1}. This object has thus far escaped discovery in the X-ray band despite two all-sky, soft X-ray surveys which were sensitive enough to detect it. Using techniques similar to those used by Kahn *et al.* (1984), we have analyzed the X-ray flux from various stars in our sample to determine photospheric He/H ratios.

Section II of this paper discusses the observations. Section III discusses the procedure used to model the HRI count rate from the hot DA stars, describing the model atmospheres, which are different from the ones used by Kahn *et al.*, and focusing on the issue of the calibration of the HRI at energies less than 200 eV. Section IV presents the results of comparing these models with the data, and § V discusses the significance of these results in the context of similar results on other DA stars.

II. OBSERVATIONS

The 13 stars comprising our sample represent portions of two separate *Einstein* observing programs, neither of which had been completed at the time the *Observatory* ceased operation (1981 April). These programs involved searches for X-ray emission from "hot white dwarfs," 10 of which were observed, and from optically rapidly varying white dwarf stars (ZZ Ceti stars), of which three were observed. Table 1 identifies the 13 stars and lists their T_{eff} and spectral type. As can be seen in Table 1, the objects classed as "hot white dwarfs" are actually a rather heterogeneous sample, both in temperature ($1 \times 10^4 < T_{eff} < 6 \times 10^4$ K) and spectral type. The collection includes one DB and five DA white dwarfs. Additionally it includes four stars which are actually subdwarfs (three sDO and one sDB). While the hot DA stars are a priori the most likely candidates for the detection of X-rays from their photospheres, it is worth observing representatives of all classes of collapsed stars: it is always possible that some other mechanism might be responsible for the production of X-ray emission from these stars (e.g., coronal emission from the DB star or the ZZ Ceti stars).

All of the observations were carried out using the *Einstein* High Resolution Imager (HRI), whose properties are described in Giacconi *et al.* (1979). Because the HRI energy response extended to lower energies than did that of usually more sensitive Imaging Proportional Counter (IPC), the two detectors had comparable sensitivity to the extremely soft spectra associated with photospheric emission from white dwarf stars with $T_{eff} < 10^5$ K. Because the spectra of these stars are so soft and the sensitivity of the HRI was strongly energy dependent at energies below 200 eV, extreme care must be exercised when interpreting a positive detection of a white dwarf star. We will address the uncertainties in the HRI calibration at these energies in § III*b*.

The right half of Table 1 summarizes the X-ray observations. Listed in various columns are the HRI exposure time in seconds and the number of counts necessary in a 12″ × 12″ pixel (which defines a detection cell for a point source) for a positive detection. This threshold has been chosen (automatically by the point source detection routine) such that on average one false source (i.e., statistical fluctuation of the background) will be detected per field. This threshold corresponds to between 4 and 5 σ above background.

In all but two instances, no source was detected at the target location. For the 11 nondetections we have listed in Table 1 the upper limit (4 σ) on the count rate from the source, the quotient of the detection threshold divided by the exposure time. The typical upper limit is 3×10^{-3} HRI counts s^{-1}. These count rate upper limits have been converted into the flux upper limits listed in Table 1. The upper limits for the DB, sDO, sDB, and ZZ Ceti stars were estimated in a straightforward but conservative fashion by assuming that the expected photon distribution in the HRI from a white dwarf star will be narrow ($\Delta E \approx 100$ eV) and centered upon 100 eV. Assumption of a wider effective bandpass or a larger effective energy would yield smaller flux limits. For the five DA stars with $T_{eff} > 2 \times 10^4$ K, fluxes and upper limits were inferred by folding the model atmospheres described below through the HRI response function.

The single white dwarf star from which a strong positive flux was detected is WD 2309+105 (EG 233). A total of 1660 counts were detected from WD 2309+105 in 2620 s, yielding a count rate of 0.68 counts s^{-1} and a flux in the HRI band (effectively 0.065–1.0 keV for white dwarf stars) of 5.5×10^{-12} ergs cm^{-2} s^{-1}. Given the optically inferred parameters listed below in Table 3, there is no possibility whatsoever that the detected count rate could be a consequence of UV contamination (see § III*b*). The only brighter isolated white dwarf in the X-ray band is HZ 43, whose HRI count rate was a factor of 5 higher (Vaiana *et al.* 1981). The star WD 2309+105 is therefore the brightest X-ray white dwarf discovered by *Einstein*. An interesting observational aspect of this source is its escape from prior detection, despite its soft X-ray flux. Remarkably, it was

TABLE 1

HRI OBSERVATIONS OF WHITE DWARF AND SUBDWARF STARS

DESIGNATION: WD	EG	Other Name	SPECTRAL TYPE[a]	T_{eff}[b] (10^3 K)	HRI EXPOSURE TIME (s)	THRESHOLD (counts per 12 × 12 pixel)	COUNT RATE[c] (10^{-3} s^{-1})	f_x[d]	REFERENCES
				Hot White Dwarfs					
1036+433	71	Feige 34	sDO	>50	1457	5.03	<3.5	<2.9	1, 2
1052+273	221	GD 125	DA3	26	2180	5.55	2.3	5.4	2
1134+300	184	GD 140	DA3	20	1781	5.14	<2.9	<15.0	2, 3
1321+363	...	HZ 44	sDO	38	1642	5.37	<3.3	<2.7	1
1542+182	193	GD 190	DB3	23	3384	7.41	<2.2	<1.8	2, 3, 4
1936+327	226	GD 222	DA1	50	1908	5.30	<2.8	<9.0	2
2240−045	229	PHL 380	DA1	37 ± 5	2089	5.37	<2.6	<5.3	5
2309+105	233	GD 246	DA1	55 ± 5	2621	9.87	680.0	55.0	5, 6, 7
2313−021	157	Feige 108	sDB	28	1630	4.93	<3.0	<2.5	1
2317−054	158	Feige 110	sDO	40	2681	6.10	<2.4	<1.9	1, 8
				Rapidly Varying White Dwarfs (ZZ Ceti Stars)					
0417+361	34	G38-29	DAV5	19.6	1999	5.93	<3.0	2.5	2, 3
0921+354	65	G117-B15A	DAV4	12.5	1835	5.24	<2.9	<2.4	2, 3, 9
2326+049	195	G29-38	DAV4	11.9	1513	5.72	<3.8	<3.1	2, 3, 9

[a] Spectral type based on Sion *et al.* 1983 convention.
[b] If not taken from references, inferred using formulae in Shipman 1979*a*.
[c] Upper limits are threshold counts per exposure time; ≥ 4 σ.
[d] Flux upper limit calculations described in text; fluxes in units of 10^{-13} ergs cm^{-2} s^{-1}.

REFERENCES.—(1) Greenstein and Sargent 1974. (2) McCook and Sion 1983. (3) Greenstein 1984. (4) Greenstein 1976. (5) Schulz and Wegner 1981. (6) Finley, Basri, and Bowyer 1984. (7) Holberg 1984. (8) Heber *et al.* 1982. (9) Shipman 1979*a*.

not detected by either of the two most sensitive soft X-ray all-sky surveys, *SAS 3* (Marshall 1982) and *HEAO 1* A-2 (Nugent *et al.* 1983), even though its flux was well above the source detection threshold of both instruments. Interestingly, both surveys appear to suffer from a lack of exposure in the region containing WD 2309+105.

In contrast to WD 2309+105, the other white dwarf star detected, WD 1052+273 (GD 125), was barely detected with the HRI. Only 5 counts were recorded in 2180 s in the pixel containing the optical position of the star, a number that is actually smaller than the detection threshold for the observation of 5.5 counts. However, the probability that a fluctuation at this level ($\sim 4\,\sigma$) would occur in a specific pixel, which happens to contain the intended target, is proportional to the inverse of the number of independent detection cells in the image, approximately 10^{-4}. With such a low significance detection of a relatively cool (2.6×10^4 K) star, we must consider the possibility that the HRI is detecting only UV photons. With $d = 40$ pc, equation (1) of § III*b* suggests that the UV flux is less than 0.01 times the threshold count rate, and that the detected photons are therefore X-rays. Nevertheless, we will adopt the conservative viewpoint that the detection of WD 1052+273 is marginal; if we consider the positive detection to be instead an upper limit, the conclusions we reach below are not seriously affected.

The flux upper limits on many of these stars are not particularly informative. The upper limit on WD 1542+182, the lone DB star, is comparable with those obtained by Fontaine, Montmerle, and Michaud (1982) for 10 DB stars, using the IPC. The opacity of helium to X-rays precludes a search for photospheric X-ray emission from these stars, but the temperature range in which coronal X-ray emission might be generated by DB stars includes WD 1542+18 (Fontaine, Montmerle, and Michaud 1982). The three ZZ Ceti stars observed, G38−29, G29−38, and G117−B15A, have temperatures between 1.0×10^4 K and 1.2×10^4 K. Although these stars are too cool to emit a photospheric X-ray flux detectable by *Einstein*, the temperature range in which they lie is exactly that in which DA stars might possess coronae (Böhm 1979). We thus place the first, however unrestrictive, upper limits on the X-ray flux from coronae of DA stars. Moreover, we can rule out the existence of any unexpected mechanism for strong X-ray emission from these stars. The possibility of some such mechanism is suggested by the unusual behavior of these stars, specifically their rapid optical brightness fluctuations usually ascribed to nonradial oscillation modes (Robinson 1979). Finally, the B and O subdwarf stars are the least likely candidates of all for X-ray emission. Optical and UV spectra reveal evidence of metals in their atmospheres; as in DB stars, X-rays generated in the deeper layers of the photosphere will be photoelectrically absorbed before they escape.

We will devote the remainder of this paper to the only realistic candidates for detectable photospheric X-ray emission, the five hot ($T_{\rm eff} > 2 \times 10^4$ K) DA stars. We compare the observed X-ray count rates from these stars with what is expected based on models of white dwarf atmospheres and on stellar parameters inferred from published optical and UV results. Before doing so (§ IV), we first describe the models (§ III*a*), and, since our modeling is critically dependent on the spectral response function of the HRI for energies less than 200 eV, we discuss the reliability of the HRI calibration and possible sources of contamination (§ III*b*).

III. SPECTRAL MODELING

Because the HRI possessed no intrinsic spectral resolution it provides for a point source a single datum, a count rate (or upper limit), integrated over the HRI bandpass (nominally 0.1–4.0 keV). Since we thus have at most a single degree of freedom when performing spectral modeling, any physical interpretation of our observations must be strongly dependent on the validity of both certain assumptions (e.g., that we are using correct spectral model) and source parameters derived from measurements in other bands (e.g., $T_{\rm eff}$). Our ability to make correct inferences also obviously depends on how reliably the HRI spectral response function is known. We must combine all this information into a model and then compare the count rate so predicted with what is observed to determine whether a given model adequately describes the data. We will assume that the X-ray emission observed (or expected) from the hot DA white dwarf stars is photospheric in origin and describe the calculations used to model such emission.

a) The Model Atmospheres

The model atmospheres used here were calculated using the ATLAS model atmosphere program (Kurucz 1970). There are some minor differences between the assumptions used in these models and in the Wesemael models used in Kahn *et al.* (1984); the major difference is that they were calculated using a completely different computer program. The composition of the atmosphere is pure hydrogen with trace helium added. The addition of these small quantities of helium does not affect the opacity at wavelengths longward of 504 Å, where most of the flux comes out, and so the temperature stratification at each value of $T_{\rm eff}$ is determined by converging a pure hydrogen model to flux constancy. Hydrogen line blanketing was included for $T_{\rm eff} < 6 \times 10^4$ K; at the highest model temperature considered in this grid, 5×10^4 K, the inclusion of line blanketing makes a very small difference (3% in the value of the Eddington flux H_ν, even in the X-ray region where the atmosphere is pure scattering) in the emergent flux. The models did allow for non–LTE effects in the continuum. Line transitions were assumed to be in detailed balance. As has been stated by previous authors (Wesemael *et al.* 1980), the effects of departures from LTE on continuum fluxes are negligible.

The model atmospheres used here all had log $(g) = 8$. X-ray fluxes for a log $(g) = 7$ unblanketed model with $T_{\rm eff} = 5 \times 10^4$ K were somewhat less than the corresponding log $(g) = 8$ model by factors ranging from 15% (at 2×10^{16} Hz = 80 eV) to 4.5 (at 4×10^{16} Hz = 160 eV). However, the flux at 4×10^{16} Hz is two orders of magnitude lower than that at 2×10^{16} Hz, and so the X-ray counting rate will change by only 20% for an order of magnitude change in g.

There is considerable debate in the literature about the acceptable range of white dwarf masses, with some authors (Koester, Schulz, and Weidemann 1979) claiming values as narrow as ± 0.10 solar masses, while others (Shipman and Sass 1980) arguing for ± 0.20 solar masses. In addition, the existence of selection effects makes the mean white dwarf mass dependent on this mass range (Shipman 1979*a*), increasing it from 0.6 solar masses (with no selection effects) to 0.75 solar masses if the mass range is large enough (± 0.2 solar masses) for selection effects to become important. The net result of all these considerations is that the surface gravity of any particular white dwarf star in an X-ray sample could be between 7.5

and 8.5. However, based on the above considerations, the uncertainty in the predicted HRI count rate arising from this uncertainty in the log (g) value for a particular star is $\pm 10\%$, considerably less than the uncertainty arising from the HRI calibration (see below).

The existence of a second set of hot white dwarf photospheric models, used in this paper, allows one to clear up some of the uncertainties mentioned by Kahn *et al.* (1984) in connection with the reliability of the models. Comparisons of pure hydrogen LTE models, blanketed for $T_{\rm eff} < 50{,}000$ K and unblanketed otherwise, indicates that the calculated Eddington flux ratios of H_ν(ATLAS)/H_ν(Wesemael) are, for a set of four wavelengths ranging from 100 Å to 200 Å (for $T_{\rm eff} < 5 \times 10^4$ K) and from 23 Å to 115 Å (for $T_{\rm eff} > 6 \times 10^4$ K), 0.97 ± 0.07, with the extreme values being 0.88 and 1.12. The set of X-ray fluxes from ATLAS are tabulated here so the reader can make his or her own comparisons for particular temperatures. This accuracy is quite encouraging, because the X-ray fluxes are on the exponential tail of the Planck distribution, where the source function is very temperature dependent, and the atmospheres are virtually pure scattering atmospheres with $\alpha\ [= \sigma/(\kappa + \sigma)$, where σ is the continuum scattering coefficient and κ is the continuum absorption coefficient$] > 0.95$ at monochromatic optical depths τ_ν near 1 for the most extreme case. For the sake of completeness, Table 2 summarizes the fluxes used in this paper. For wavelengths longward of 504 Å, the fluxes are essentially independent of He/H, and so these fluxes can be combined with the fluxes of Wesemael *et al.* (1980) if anyone wants to form a more complete grid of models.

b) The HRI Response at Low Energies

The HRI efficiency increased rapidly between its nominal low-energy cutoff at 100 eV and the carbon absorption edge of its filter at 280 eV. In contrast, as is apparent from Table 2, the X-ray photon spectra of hot white dwarfs are extremely soft, decreasing rapidly above 100 eV. For these observations the effective bandpass of the HRI is therefore quite narrow, and a proper interpretation of the observed count rates depends critically on the accuracy of the HRI calibration at $E < 200$ eV. (For the five DA stars, all of which are at medium to high Galactic latitudes and [except for WD 2240−045] relatively nearby, the absorption of soft X-rays by intervening matter is expected to be negligible, with a cutoff below 100 eV.) We must actually consider the HRI sensitivity in three regimes: within the nominal bandpass, especially for 100 eV $< E <$ 200 eV; in the EUV band below 100 eV; and in the UV (1500–1700 Å).

In the energy band between 100 and 200 eV, no measurement of the complete *Einstein* telescope/HRI effective area was made. However, separate measurements of the telescope effective area and the microchannel plate detector efficiency were made at 67 and 114 Å (Van Speybroeck 1979; Henry *et al.* 1977). The primary source of uncertainty in the HRI efficiency is the aluminum/Parylene N filter, whose purpose was to block out unwanted EUV and UV radiation. The two filter components provided approximately equal attentuation (~80%) at 100 eV. Their thicknesses are known to ~10%, which introduces an uncertainty in the effective area of the HRI by as much as 30% at 100 eV. (At the higher photon energies typical of most cosmic X-ray sources observed by the HRI, the attenuation of the filter was substantially less, and so the effect of uncertainties in the thickness of its component layers is substantially reduced.)

The fractional contribution of detected photons below 100 eV to the total count rate may be estimated by folding the model spectra described above through the HRI spectral response function, extrapolated below 100 eV. Such an extrapolation is relatively straightforward. As in the

TABLE 2

EDDINGTON FLUXES[a] FOR TRACE HELIUM MODEL ATMOSPHERES

LAMBDA	n(He)/n(H): 0	10^{-5}	10^{-4}	10^{-3}
	$T_{\rm eff}$ = 25,000 K			
911.2	5.35E-6	5.35E-6	5.35E-6	5.35E-6
504.7	2.72E-8	2.72E-8	2.72E-8	2.72E-8
503.0	2.61E-8	2.60E-8	2.46E-8	1.62E-8
374.7	1.00E-9	9.8E-10	8.1E-10	2.6E-10
299.8	2.11E-9	2.03E-9	1.40E-9	3.6E-11
228.1	6.26E-8	6.10E-8	4.88E-8	4.83E-9
227.1	6.51E-8	3.52E-8	1.28E-9	4.8E-13
200.0	1.65E-7	8.63E-8	2.32E-9	1.9E-13
150.0	3.33E-7	1.89E-7	4.40E-9	5.7E-14
100.0	6.21E-8	4.60E-8	3.86E-9	1.6E-14
75.0	8.4E-10	7.3E-10	2.3E-10	7.2E-15
50.0	7.7E-15	7.6E-15	7.2E-15	3.9E-16
	$T_{\rm eff}$ = 30,000 K			
911.2	3.41E-4	3.41E-4	3.41E-4	3.41E-4
504.7	3.43E-6	3.43E-6	3.43E-6	3.43E-6
503.0	3.40E-6	3.37E-6	3.15E-6	1.77E-6
374.7	2.43E-6	2.41E-6	2.22E-6	1.01E-6
299.8	4.31E-6	4.28E-6	4.00E-6	2.10E-6
228.1	7.72E-6	7.68E-6	7.35E-6	4.75E-6
227.1	7.75E-6	4.01E-6	1.17E-7	7.3E-11
200.0	8.01E-6	4.24E-6	1.02E-7	2.3E-11
150.0	4.91E-6	3.02E-6	9.08E-8	3.0E-12
100.0	8.99E-7	7.00E-7	8.50E-8	4.6E-13
75.0	1.05E-7	9.24E-8	2.85E-8	...
50.0	1.6E-10	1.6E-10	9.8E-11	...
	$T_{\rm eff}$ = 50,000 K			
911.2	2.00E-3	2.00E-3	2.00E-3	2.00E-3
504.7	1.25E-3	1.25E-3	1.25E-3	1.25E-3
503.0	1.25E-3	1.25E-3	1.25E-3	1.23E-3
374.7	1.01E-3	1.01E-3	1.01E-3	9.87E-4
300.0	8.82E-4	8.82E-4	8.80E-4	8.62E-4
228.1	6.79E-4	6.79E-4	6.78E-4	6.68E-4
227.1	6.74E-4	4.46E-4	2.25E-5	1.39E-7
200.0	5.53E-4	3.94E-4	2.84E-5	3.08E-8
150.0	2.79E-4	2.29E-4	4.56E-5	2.61E-9
100.0	5.50E-5	5.07E-5	2.51E-5	7.09E-8
75.0	9.64E-6	9.23E-6	6.29E-6	2.25E-7
50.0	2.58E-7	2.53E-7	2.14E-7	4.68E-8
37.4	4.86E-9	4.81E-9	4.36E-9	1.83E-9
30.0	5.3E-11	5.3E-11	5.0E-11	2.9E-11
	$T_{\rm eff}$ = 60,000 K			
911.2	3.63E-3	3.63E-3	3.63E-3	3.63E-3
504.7	3.09E-3	3.09E-3	3.09E-3	3.09E-3
503.0	3.09E-3	3.09E-3	3.09E-3	3.02E-3
374.7	2.75E-3	2.75E-3	2.69E-3	2.69E-3
300.0	2.45E-3	2.45E-3	2.45E-3	2.45E-3
228.1	1.90E-3	1.90E-3	1.90E-3	1.90E-3
227.1	1.90E-3	1.48E-3	2.09E-4	1.38E-6
200.0	1.59E-3	1.32E-3	2.57E-4	2.55E-7
150.0	8.71E-4	7.94E-4	3.02E-4	2.14E-7
100.0	2.04E-4	1.95E-4	1.32E-4	4.07E-6
75.0	4.27E-5	4.17E-5	3.39E-5	4.68E-6
50.0	1.62E-6	1.62E-6	1.44E-6	5.62E-7
37.4	5.89E-8	5.89E-8	5.50E-8	3.09E-8
30.0	1.82E-9	1.82E-9	1.74E-9	1.18E-9

[a] Eddington flux $H_\nu = f_\nu/4\pi$ ergs cm^{-2} s^{-1} sr^{-1}.

$E > 100$ eV band, the microchannel plate detector and the telescope responses varied slowly, and the most strongly varying component of the instrument was the filter transmission. Using published values of the linear absorption coefficients of Parylene N (Stern and Paresce 1975) and aluminum (Henke *et al.* 1982) it is possible to generate a filter transmission curve extending below 100 eV that matches the HRI response curve above 100 eV. Folding this extended response curve through the white dwarf flux models reveals that, in the absence of interstellar absorption, up to 50% of the observed count rate could have come from sub–100 eV photons. For the column densities we use below (10^{19}–2×10^{20} cm^{-2}), photons in this band contribute between 0 and 45% of the total rate depending upon the particular star. This EUV flux is of course included in our modeling. As in the 100–200 eV band, the uncertainty in the sub–100 eV flux will be approximately $\pm 30\%$, due to the uncertainty in the filter layer thicknesses.

Finally, we consider the sensitivity of the HRI to radiation in the 1500–1700 Å band (Golub *et al.* 1984), where Parylene N has a small but finite transmission window. Such a consideration is essential to establish the reality of the X-ray detection of such a copious UV emitter as a white dwarf star with $T_{\rm eff} > 2 \times 10^4$ K. Using the effective area in the 1500–1700 Å band quoted by Golub *et al.* (1984) of 2×10^{-7} cm^2, we find that for a white dwarf star of radius R, at a distance d, and with $2 \times 10^4 \text{ K} < T_{\rm eff} < 6 \times 10^4$ K, the count rate in the HRI contributed by contamination from UV photons may be expressed as

$$C_{\rm uv} \approx 2 \times 10^{-4} (R/7000 \text{ km})^2 (10 \text{ pc}/d)^2 \text{ photons s}^{-1} . \quad (1)$$

We have used UV fluxes from models similar to the ones discussed in § III*a* (Wesemael *et al.* 1980) and have assumed zero interstellar extinction. Unless the estimate of the HRI effective area in the UV has been underestimated by an order of magnitude (and Golub *et al.* mention only factors of 2), the degree of UV contamination in our two detections is negligible.

The discussion above indicates that a count rate predicted from folding a white dwarf spectral model through the HRI spectral response function should be accurate to $\pm 30\%$. To provide ourselves some margin in the event that there is some inaccuracy we have not correctly taken into account or neglected totally, we will attach a factor of 2 uncertainty on all modeled count rates for the remainder of the paper.

c) Stellar Parameters and Interstellar Column Densities

Listed in Table 3 are the values of the parameters needed in order to perform model fitting: $T_{\rm eff}$, the distance d, the stellar radius (here in units of R/R_0), log (g), and the interstellar column density $N_{\rm H}$. We must rely on the inferences of others (e.g., Schulz and Wegner 1981) for these values. When the value of log (g) was unavailable from the literature, we assumed log (g) = 8.0. For missing values of R/R_0 and d, we used the empirical formulas of Shipman (1979*a*), along with optical determinations of $T_{\rm eff}$ and the observed V magnitude. In order to place the most conservative estimates on n(He)/n(H) for undetected stars, we used $R/R_0 = 0.007$, which is smaller than any of the inferred stellar radii in the relevant temperature range.

For four of the five hot DA stars, the most uncertain parameter in these calculations is the interstellar column density. The higher the value of $N_{\rm H}$, the less stringent a lower limit we can place on n(He)/n(H). Although we expect a small $N_{\rm H}$ for all these nearby stars, only for WD 2309+105 does any direct evidence exist that $N_{\rm H}$ is small (Finley 1984). For the other stars, the only available information is in the form of global column density maps based on measurements of $N_{\rm H}$ to many stars (Paresce 1984). We have used the compilation of Paresce to estimate the column density to three of the other stars. WD 2240−045 is within 20° Galactic longitude of WD 2309+105 and at higher Galactic latitude; it should therefore have a similar $N_{\rm H}$. Since its inferred distance is slightly more than twice that to WD 2309+105, we will use for it an $N_{\rm H}$ factor of 3 higher ($N_{\rm H} = 3 \times 10^{19}$ cm^{-2}).

IV. RESULTS

Figure 1 shows the predicted HRI count rates versus $T_{\rm eff}$ for a white dwarf star at $d = 100$ pc with pure hydrogen atmosphere in the presence of various amounts of interstellar absorption. We have assumed $R/R_0 = 0.0127$ and log (g) = 8.0. For stars with $T_{\rm eff} \leq 3 \times 10^4$ K, the count rate is not reduced below the HRI threshold for a 2000 s observation by interstellar absorption until $N_{\rm H}$ reaches 1×10^{19} cm^{-2}. Because $N_{\rm H}$ is smaller than this throughout most of the $d < 100$ pc sphere (Paresce 1984), Figure 1 suggests that virtually any pure H atmosphere white dwarf with $T_{\rm eff} > 3.0 \times 10^4$ K and $d < 100$ pc was detectable by the HRI in a typical 2000 s exposure. If the atmospheres of DA white dwarfs are truly helium free, then the white dwarfs observed by the HRI should have been strong X-ray sources. Additionally, the HRI, which observed a few percent of the sky, should have serendipitously detected some small fraction of the 100–200 such stars expected to exist (Shipman 1979*b*; Kahn *et al.* 1984). Since it is unlikely that the presence of intervening matter (in the form of small clouds) satisfactorily accounts for the observational situation, we must conclude that the atmospheres of most hot DA white dwarf stars ($T_{\rm eff} > 30{,}000$ K) contain some source of opacity.

For each of the five hot DA stars in our example, we have

TABLE 3

PROPERTIES OF HOT DA WHITE DWARFS

WD	$T_{\rm eff}$(10^3 K)	d (pc)	(R/R_0)	log (g)	$N_{\rm H}$	n(He)/n(H)	Notes[a]
1052+273	26	44	0.012	8.0	$\leq 10^{19}$	1–5×10^{-5}	1, 2, 3, 4
1134+300	20	24	0.007	8.0	$\leq 10^{19}$	≥ 0.0	1, 2, 3, 4, 5
1936+327	50	38	0.007	8.0	2×10^{20}	$\geq 10^{-3}$	1, 2, 3, 4
2240−045	37 ± 5	125	0.0123	8.0 ± 0.4	3×10^{19}	$\geq 3 \times 10^{-4}$	6
2309+105	55 ± 5	55	0.0123	8.0 ± 0.5	1.5–10×10^{18}	1.5–15×10^{-4}	6, 7, 8, 9
1314+293 (HZ 43)	55	62	0.0123	8.0	$\leq 10^{19}$	$\leq 5 \times 10^{-4}$	9, 10

[a] NOTES.—(1) McCook and Sion 1983. (2) Paresce 1984. (3) Log (g) assumed to be 8.0. (4) Values of R/R_0 chosen based on Shipman 1979*a*. (5) Greenstein 1984. (6) Schulz and Wegner 1981. (7) Finley, Basri, and Bowyer 1984. (8) Holberg 1984. (9) Finley 1984. (10) Heise 1984.

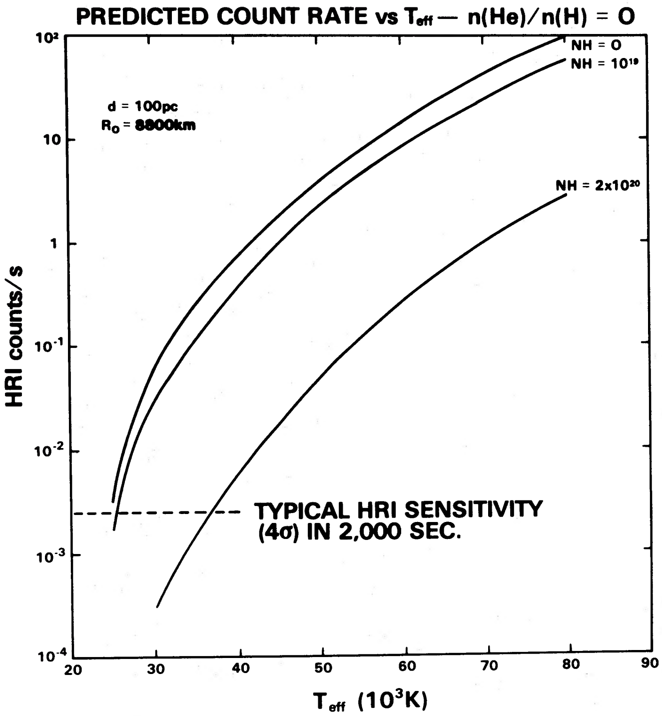

FIG. 1.—Predicted HRI count rate for white dwarf stars with pure hydrogen atmospheres as a function of effective temperature, for various column densities. The threshold of a typical HRI observation is indicated.

folded the atmosphere models with varying amounts of trace helium through the HRI response function. We have included the estimated N_H values from Table 3. The results of this folding also appear in Table 3. For four of the five stars, a nonzero atmospheric helium abundance is required. WD 1134−30 is too cool to provide a useful measurement. The n(He)/n(H) values for the other four stars fall in the range 10^{-5} to 10^{-3}; these compare favorably with the ratios inferred by Kahn *et al.* (1984) for four other DA stars.

As a test of the validity of our approach we have also attempted to estimate the helium abundance in HZ 43, whose HRI count rate was included in Vaiana *et al.* (1981). We find, given the uncertainties in the HRI response function, that the He abundance of HZ 43 we infer is between zero and 5×10^{-4}. The most recent reevaluations of the He abundance in HZ 43 suggests $n(\mathrm{He})/n(\mathrm{H}) \leq 1 \times 10^{-5}$ (Finley 1984; Heise 1984); our estimate is consistent with this. We have included HZ 43 in Table 3.

For WD 2309+105, the most interesting of the observed stars (by virtue of its strong X-ray flux), there exists evidence from other wavebands which both supports our inference of atmospheric helium and provides additional constraints to its relative abundance. Schulz and Wegner (1981) report observation of a slight depression in its optical spectrum at 4686 Å which could be a He II absorption line. Greenstein (1969), however, did not report the presence of this line. One might infer from these observations that the 4686 Å line is just at the threshold of detectability, which would suggest that $n(\mathrm{He})/n(\mathrm{H}) \approx 10^{-3}$ (Greenstein 1979), consistent with our result. The He II 1640 Å line is absent in the *IUE* spectra of WD 2309+10, which also supports the inference that $n(\mathrm{He})/n(\mathrm{H}) \leq 10^{-3}$ (Finley 1984).

V. DISCUSSION

With the publication of these results, the existence of trace amounts of photospheric He, or very strong constraints thereon, have been reported for a number of DA white dwarfs: along with the four reported here are the four from Kahn *et al.* (1984), Sirius B, and HZ 43. The inferred helium abundances from all these stars are summarized in Table 4. Also included in Table 4 is Feige 24, for which the analysis of *Apollo-Soyuz* data (Shipman 1979*b*, 1985) yields n(He)/n(H) between 3×10^{-5} and 3×10^{-3}, and the magnetic white dwarf WD 1658+440, for which the analysis of *Einstein* IPC and *EXOSAT* data place an upper limit of 2×10^{-4} on n(He)/n(H) (Pravdo *et al.* 1986). Since we have shown the usefulness of X-ray flux upper limits in establishing lower limits to n(He)/n(H), we have surveyed all reported upper limits in the literature, principally in Vaiana *et al.* (1981) and Kahn *et al.* (1984) for X-ray upper limits that can be converted into useful lower limits on n(He)/n(H). For most stars observed, either T_{eff} is too small or N_H too large. Only for one star, WD 1544+008 (EG 113), does a flux upper limit (Kahn *et al.* 1984) yield a new, weak lower limit on n(He)/n(H) of 2×10^{-5}. To infer this limit we folded the response function of the *Einstein* Imaging Proportional Counter (IPC) through our models in the manner described above for the HRI. This result is included in Table 4.

One initial comment which should be to be made about Table 4 is that perhaps the most unusual object in it is HZ 43, the first known, and brightest, X-ray emitting white dwarf. All of the other white dwarfs with $T_{\mathrm{eff}} \geq 4 \times 10^4$ K have finite photospheric helium abundances. Whatever process is operating to enhance the helium abundance in the other stars appears to be nonfunctional in HZ 43.

There are now enough stars with abundance determinations to begin studying possible sources of photospheric helium. In their paper, Kahn *et al.* (1984) discuss the possible mechanisms for maintaining trace helium in a white dwarf photosphere. The two mechanisms they consider viable are accretion of interstellar matter and radiative acceleration. In the former case one might expect some correlation between n(He)/n(H) and the density of the interstellar medium in which a star is embedded; in the latter one might expect a temperature dependence of n(He)/n(H). Below we consider the compiled helium abundances in the context of these two mechanisms.

TABLE 4

HELIUM ABUNDANCES OF HOT WHITE DWARFS

WD	Other Name	n(He)/n(H) ($\times 10^{-5}$)	References
0232+035	Feige 24	3–300	1
	LB 1663	2–60	2
0346−011	EG 288	30–200	2
0548+000	EG 289	80–600	2
0642−166	Sirius B	<1	3
1052+273	GD 125	1–5	4
1254+223	EG 187	2–40	4
1314+293	HZ 43	≤1	3, 5
1544+008	EG 113	>2	2, 4
1658+440	...	<20	6
1936+327	EG 226	>100	4
2240−045	EG 229	>30	4
2309+105	EG 233	15–150	4

REFERENCES.—(1) Shipman 1985. (2) Kahn *et al.* 1984. (3) Heise 1984. (4) This paper. (5) Finley 1984. (6) Pravdo *et al.* 1986.

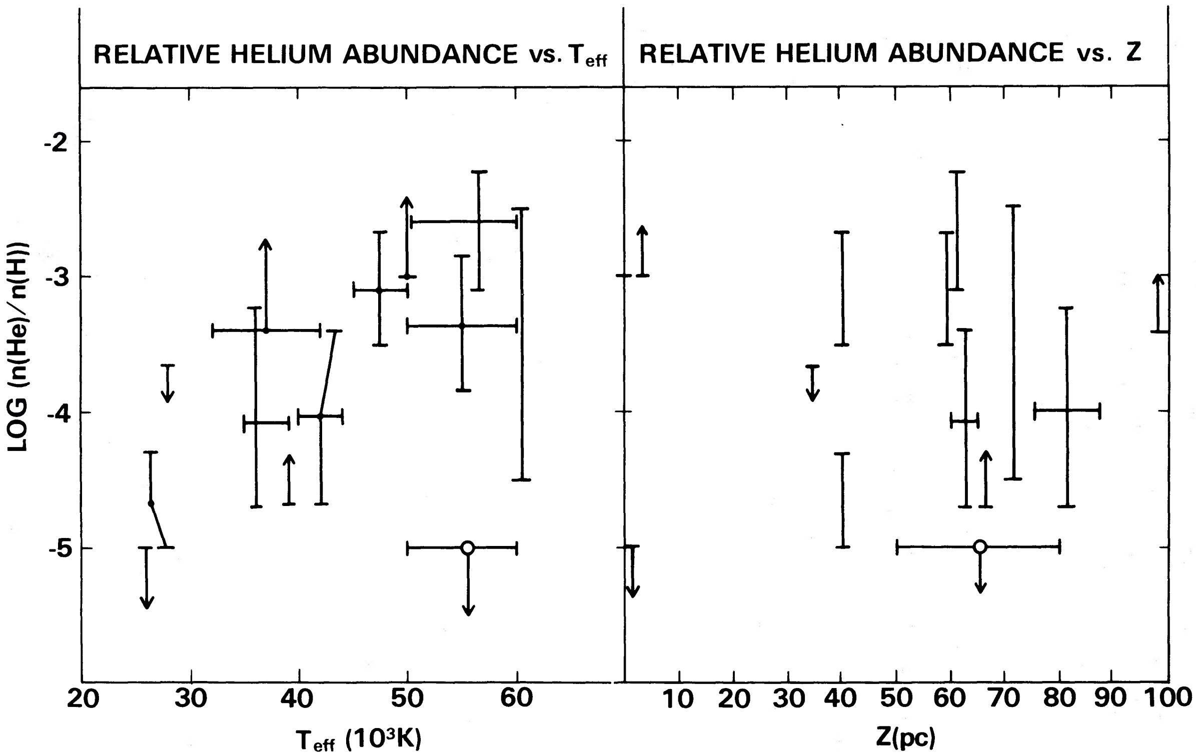

FIG. 2.—(*left*) Relative photospheric helium abundance vs. effective temperature for the white dwarf stars observed in the X-ray band. If the data point representing HZ 43 (*open circle*) is disregarded, a correlation between T_{eff} and N(He)/N(H) is suggested by the data. (*right*) Relative photospheric helium abundance vs. height above the Galactic plane for the same set of white dwarf stars.

In Figure 2*a*, we plot n(He)/n(H) as a function of T_{eff}. If one neglects HZ 43, there is evidence that there is a positive correlation between the He/H ratio and the effective temperature. We believe that the most natural way to explain this correlation is to hypothesize that it is radiation pressure that pushes the helium—or whatever the source of X-ray opacity is—up into the stellar photosphere. While there is no theoretical investigation on the temperature dependence of the radiative acceleration of He in white dwarf stars, simple considerations of the spectrum and of the radiation acceleration mechanism (e.g., Michaud *et al.* 1979; Vauclair, Vauclair, and Greenstein 1979) dictate that the radiative acceleration on He should be an increasing function of temperature. At the temperatures we consider here, He is in the form of both He I and He II. The strongest lines and continua of both ions lie in the EUV spectral region, between 200 and 600 Å, and the flux in those spectral regions is increasing with T_{eff}. Consequently, one would naively expect that the radiative acceleration, and hence the abundance of He radiatively levitated in an H-dominated photosphere, is an increasing function of T_{eff}. Fontaine (1985) has presented a functional relationship between n(He)/n(H) and T_{eff} which provided a reasonably good fit to the data based on simple assumption; this is clearly an area ripe for further theoretical investigation.

Some additional pieces of evidence support the hypothesis that radiation pressure is levitating the He that we observe. Radiation pressure is effective in levitating elements so long as their lines are unsaturated, and the highest He abundances seen here, roughly 10^{-3}, are precisely those where the lines are unsaturated. In addition, Bruhweiler and Kondo (1983) claim that there are blueshifted lines of Si II, Si III, Si IV, and C IV in three DA white dwarfs. These data suggest the possibility of a stellar wind in hot white dwarf stars, a possibility also suggested on theoretical grounds, and on the basis of reasonable extrapolations from planetary nebulae, by Iben and MacDonald (1985). If these stellar winds are radiatively driven, which seems to be the most reasonable possibility, then the observations by Bruhweiler and Kondo provide support to our hypothesis that radiative acceleration is operative in hot white dwarf stars.

One can also speculate why HZ 43 is so unusual, compared with WD 2309+105. The effectiveness of radiative acceleration is dependent on both the temperature and the gravity of the white dwarf star. At a given temperature, radiative forces could support elements in a low-mass, low-gravity star, and would not support elements in a high-gravity star. At the high temperature of HZ 43, low-mass stars have gravities considerably lower than the nominal value of log $(g) = 8$ set by the mass-radius relation (Koester and Schonberner 1985; Hubbard and Wagner 1970), because thermal pressure can contribute to the equation of hydrostatic equilibrium. However, high-mass stars, like Sirius B, are less affected and can retain their high gravities [log $(g) = 8.65$ in an extreme case like Sirius B]. We suggest that possibly HZ 43 is a high-mass, high-gravity star like Sirius B, which also happens to be one of the stars with the lowest inferred He abundances. (We note that the low He abundance of Sirius B could easily be explained by its cool temperature.)

Another consideration is the possibility that what we, and what Kahn *et al.*, have referred to throughout as "helium" is in fact something else. Helium is the most natural candidate for two reasons: the DAO stars, hotter than the stars discussed here, have marginally higher He abundances [n(He)/n(H) $\approx 10^{-2}$ by number; Wesemael, Green, and Liebert 1985], and in one case (Feige 24) the *Apollo-Soyuz* data directly indicate the existence of an absorption edge near 54 eV. But the discovery of lines from C, N, and Si in W1346 and Feige 24 (Dupree and Raymond 1982; Bruhweiler and Kondo 1983; Wesemael, Henry, and Shipman 1984) suggests that the most natural candidate may not be the actual opacity source. Radiative acceleration will also work on metals, and Wesemael, Henry, and Shipman (1984) argue that it is the source of the metals observed in W1346 and Feige 24.

We now briefly consider the second possible helium (or metal) source, the accretion of interstellar material. White dwarfs accrete interstellar material episodically, with encounters occurring, typically, every $t(\text{encounter}) \approx 4 \times 10^7$ yr (Wesemael 1979). The hottest stars in our sample, with $T(\text{eff}) \approx 50{,}000$ K, have been cooling for $t(\text{cool}) \approx (0.5$–$1) \times 10^7$ yr (Lamb and Van Horn 1975; Koester 1978; Koester and Schonberner 1985). Consequently, only a small fraction of the hot white dwarf stars, roughly

$$t(\text{cool})/t(\text{encounter}) \approx 10\%\text{–}25\% ,$$

should have encountered an interstellar cloud during their evolution as a white dwarf and show any helium at all. The amount of He remaining after an encounter will depend on the interplay between gravitational settling and radiation pressure; if the latter is unimportant, only those hot white dwarfs which are currently inside an interstellar cloud would still have significant helium, and the fraction of hot objects with helium would then be considerably less than 10%–25%.

The cooler stars in our sample, with $25{,}000 \text{ K} < T(\text{eff}) < 35{,}000$ K, have been cooling for $(4$–$10) \times 10^7$ years, and so most of them would have experienced at least one cloud encounter. However, the settling times for helium in hot white dwarf envelopes are very short, of order 100 yr or less (Fontaine and Michaud 1979; Muchmore 1984; Iben and MacDonald 1985; Paquette *et al.* 1986). Consequently, only those stars which are currently accreting will contain significant helium, provided that radiation pressure is unimportant (as we expect it to be in these cooler stars). To calculate what this fraction is, consider first that a star-cloud encounter will last for (Wesemael 1979)

$$t(\text{cross}) = D/v = 0.05 \times 10^6 \text{ yr}[D(\text{pc})/(v/20 \text{ km s}^{-1})] ,$$

where D is the cloud diameter and v is the star-cloud relative velocity. Maps of the structure of the local interstellar medium (Tinbergen 1982; Frisch and York 1984; White 1984; Aannestad and Sion 1985) indicate that $D \approx 10$ pc is more appropriate for a cloud diameter in the nearby interstellar medium than the value of 1–7 pc adopted by Wesemael, and so we adopt $t(\text{cross}) \approx 0.5 \times 10^6$ yr. The time a white dwarf spends in the 25,000–35,000 K range is 0.75 times the time it takes to cool to 25,000 K [which we call t(cool)], and so the fraction of stars with significant He will then be

$$t(\text{cross})/0.75\ t(\text{cool}) \approx (0.8\text{–}1.6) \times 10^{-2} .$$

Putting this all together, one would expect that if accretion is the dominant process regulating the helium content of hot white dwarfs, that there might still be a positive correlation between n(He)/n(H) and T_{eff}, but in a more generalized sense; about 25% of the hottest stars might show significant n(He)/n(H) (though this fraction could be less), whereas only about 1% of the cooler stars would show a significant helium content. Our finding that all of the few cooler stars we see show no helium is consistent with this prediction. But at hotter temperatures, nine of the 10 stars in Figure 2 with $T_{\text{eff}} > 40{,}000$ K show significant n(He)/n(H); the accretion hypothesis predicts that this fraction should be at most 25%. The small number of stars in the sample and its heterogeneous nature prevents us from stating that these results definitively rule out the accretion hypothesis, but it is certainly not encouraging. If anything, our sample is biased toward the selection of white dwarfs with low helium abundance since a number of the stars in it (HZ 43 and a number of the objects in Kahn *et al.* 1984) were selected for study because of their discovery as X-ray sources. Consequently, one would expect that selection effects would result in an over-representation of H-rich hot white dwarfs in our sample, whereas we find that the H-rich stars with $T_{\text{eff}} \approx 50{,}000$ K are underrepresented.

Another way of empirically testing the idea that interstellar accretion is the source of the He that we see is to look for a correlation between the helium abundance in various stars and various indications of the density of the ISM. One rather global indicator is z, the height of a star above the Galactic plane. In Figure 2*b* we plot n(He)/n(H) as a function of z. No real trend exists, but this figure does not rule out interstellar accretion. Since the Galactic scale height for gas is ~ 180 pc, and none of these stars has $z > 100$ pc, one would expect only a mild correlation even if a smooth gas gradient existed. This idea could be tested if measurements were available for a larger number of stars, where the density fluctuations could be averaged out.

One possible source of the photospheric He, dismissed by Kahn *et al.*, is that the He is primordial and settles out of the photosphere. It is true that in such a scenario one would also expect a positive correlation between He/H and T_{eff}, since the hotter stars would have formed more recently and the He would have not settled out as much. But recently, an estimate of this functional dependence by Iben and MacDonald (1985) has

$$\text{He/H} \approx 10^{-5}[T_{\text{eff}}/68{,}000 \text{ K}]^{40} ,$$

which is radically steeper than what we observe.

Another reason for observing more stars is that the stars plotted in Figure 2 are not a homogeneous sample. The stars which we analyze in this paper have the virtue of coming from only two observing programs, but they still represent a rather heterogeneous sample—especially considering that neither observing program was completed when the *Einstein* satellite failed. The Kahn *et al.* (1984) sample is considerably less homogeneous, including one last-minute target substitution and a serendipitous source. To the extent that target objects were selected from previously discovered X-ray sources (as was the case of one of the guest investigator programs of Kahn *et al.*, and as is clearly the case with HZ 43 and Sirius B), the selection of stars for Table 4 and Figure 2 is biased in favor of stars with low He abundances. We have obtained observation time on *EXOSAT* to investigate the reality of this correlation based on a different, temperature-selected sample.

It is of course possible that both diffusion and radiative acceleration operate to some extent. One would then expect that accretion would supply the helium in those stars whose high surface gravity precludes radiative acceleration. It might even be possible that the highly evacuated regions known to surround HZ 43 and Sirius B may have been produced by these stars accreting all the local material. Since the diffusion time scales for white dwarfs are extremely short (e.g., Muchmore 1984), one therefore also expects the observed absence of metals in these stars.

VI. SUMMARY

We have observed 13 dwarf and subdwarf stars of various types with the *Einstein* HRI. Two DA white dwarfs were detected: WD 2309+105 ($T_{eff} = 5.5 \times 10^4$ K) as a bright source and WD 1052+273 ($T_{eff} = 2.6 \times 10^4$ K) at the detection threshold of the HRI ($\sim 4\ \sigma$). We interpret the X-ray emission as arising from the photospheres of these stars. For these stars along with two other hot DA stars, WD 1936+327 and WD 2240−045, we have combined the X-ray fluxes and upper limits with data from other bands and model atmosphere calculations to infer photospheric n(He)/n(H) ratios in the range $\sim 10^{-5}$ to 10^{-3}. When these n(He)/n(H) ratios are combined with those available from the literature we find evidence for a correlation between T_{eff} and n(He)/n(H), if one excludes HZ 43 and Sirius B. Both this correlation and the exceptional behavior of HZ 43 and Sirius B are qualitatively accounted for by a radiative acceleration model, working only in stars with log (g) $\leq$ 8.0 (Bruhweiler and Kondo 1983). Future X-ray and EUV observations will allow us to fill in the n(He)/n(H) versus T_{eff} diagram sufficiently to determine whether this is the proper interpretation.

The authors acknowledge useful conversations with D. Finley, J. Patterson, and J. Swank. We thank J. Liebert and R. Green for providing us an unpublished optical spectrum of WD 2309+105, and J. Schmitt for urging us to study the effects of UV and EUV contamination in the HRI. This work was supported in part by the National Science Foundation (grants AST 81-15095, 83-43067) and by NASA (grants 8-494, 5-348).

REFERENCES

Aannestad, P. A., and Sion, E. M. 1985, *Ap. J.*, in press.
Auer, L. H., and Shipman, H. L. 1977, *Ap. J. (Letters)*, **211**, L103.
Böhm, K.-H. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: The University of Rochester), p. 223.
Bruhweiler, F. C., and Kondo, Y. 1983, *Ap. J.*, **269**, 657.
Dupree, A. K., and Raymond, J. C. 1982, *Ap. J. (Letters)*, **263**, L63.
Finley, D. S. 1984, private communication.
Finley, D. S., Basri, G., and Bowyer, S. 1984, in *Future of Ultraviolet Astronomy Based on Six Years of IUE Research*, ed. J. M. Mead, R. D. Chapman, and Y. Kondo (*NASA CP 2349*), p. 277.
Fontaine, G. 1985, presentation at Kitt Peak Workshop on Stellar Remnants.
Fontaine, G., and Michaud, G. 1979, *Ap. J.*, **231**, 826.
Fontaine, G., Montmerle, T., and Michaud, G. 1982, *Ap. J.*, **257**, 695.
Frisch, P. C., and York, D. G. 1983, *Ap. J. (Letters)*, **271**, L159.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Golub, L., Harnden, F. R., Maxson, C. W., Rosner, R., Vaiana, G. S., Cash, W., Jr., and Snow, T. P., Jr. 1984, *Ap. J.*, **278**, 456.
Greenstein, J. L. 1969, *Ap. J.*, **158**, 281.
———. 1976, *A.J.*, **81**, 323.
———. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: The University of Rochester), p. 1.
———. 1984, *Ap. J.*, **276**, 602.
Greenstein, J. L., and Sargent, A. I. 1974, *Ap. J. Suppl.*, **28**, 157.
Hearn, D. R., *et al.*, 1976, *Ap. J. (Letters)*, **203**, L21.
Heber, U., Hamann, W.-R., Hunger, K., Kudritzki, R. P., and Simon, K. P. 1982, in *Proc. 3rd European IUE Conference*, ed. E. Rolfe, A. Heck, and B. Battrick (Noordwijk: ESA Scientific and Technical Publications Branch), p. 297.
Heise, J. 1984, presentation at 18th ESLAB Symposium on X-Ray Astronomy.
Henke, B. L., Lee, P., Tanaka, T. J., Shimabukura, R. L., and Fujikawa, B. K. 1982, *Atomic Data Nucl. Data Tables*, **27**, 1.
Henry, J. P., Kellogg, E. M., Briel, U. G., Murray, S. S., Van Speybroeck, L. P., and Bjorkholm, P. J. 1977, *Proc. Soc. Photo-Opt. Instr. Eng.*, **106**, 196.
Holberg, J. 1984, in *IAU Colloquium 81, Local Interstellar Medium*, ed. F. C. Bruhweiler, Y. Kondo, and B. D. Savage (*NASA CP-2345*), p. 91.
Hubbard, W. B., and Wagner, R. L. 1970, *Ap. J.*, **159**, 93.
Iben, I., and MacDonald, J. 1985, *Ap. J.*, **296**, 540.
Kahn, S. M., Wesemael, F., Liebert, J., Raymond, J. C., Steiner, J. E., and Shipman, H. L. 1984, *Ap. J.*, **278**, 255.
Koester, D. 1978, *Astr. Ap.*, **65**, 449.
Koester, D., and Schonberner, D. 1985, *Astr. Ap.*, in press.
Koester, D., Schulz, H., and Weidemann, V. 1979, *Astr. Ap.*, **76**, 262.
Kurucz, R. L. 1970, *Smithsonian Ap. Obs. Spec. Rept.*, No. 309.
Lamb, D. Q., and Van Horn, H. M. 1975, *Ap. J.*, **200**, 306.
Margon, B., Liebert, J., Gatewood, G., Lampton, M., Spinrad, H., and Bowyer, S. 1976, *Ap. J.*, **209**, 525.
Marshall, F. J. 1982, Ph.D. thesis, Massachusetts Institute of Technology.
McCook, G. P., and Sion, E. M. 1983, *Villanova Obs. Contr.*, No. 3.
Mewe, R., Heise, J., Gronenschild, E. H. B. M., Brinkman, A. C., Schrijer, J., and den Boggende, A. J. F. 1975*a*, *Nature*, **256**, 711.
———. 1975*b*, *Ap. J. (Letters)*, **202**, L67.
Michaud, G., Montmerle, T., Cox, A. N., Magee, N. H., Hodson, S. W., and Martel, A. 1979, *Ap. J.*, **234**, 206.
Muchmore, D. 1984, *Ap. J.*, **278**, 769.
Nugent, J. J., *et al.* 1983, *Ap. J. Supp..*, **51**, 1.
Paquette, C., Pelletier, C., Fontaine, G., and Michaud, G. 1986, *Ap. J.*, submitted.
Paresce, F. 1984, *A.J.*, **89**, 1022.
Pravdo, S. H., Marshall, F. E., White, N. E., and Giommi, P. 1986, *Ap. J.*, **300**, 819.
Schulz, H., and Wegner, G. 1981, *Astr. Ap.*, **94**, 272.
Robinson, E. L. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: The University of Rochester), p. 343.
Shipman, H. L. 1976, *Ap. J. (Letters)*, **206**, L67.
———. 1979*a*, *Ap. J.*, **228**, 240.
———. 1979*b*, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. H. Van Horn and V. Weidemann (Rochester: The University of Rochester), p. 86.
———. 1985, in preparation.
Shipman, H. L., and Sass, C. 1980, *Ap. J.*, **235**, 177.
Sion, E. M., Greenstein, J. L., Landstreet, J. D., Liebert, J., Shipman, H. L., and Wegner, G. 1983, *Ap. J.*, **269**, 253.
Stern, R., and Paresce, F. 1975, *J. Opt. Soc. America*, **65**, 1215.
Tinbergen, J. 1982, *Astr. Ap.*, **105**, 53.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **245**, 163.
Van Speybroeck, L. P. 1979, *Proc. Soc. Photo-Opt. Instr. Eng.*, **184**, 1.
Vauclair, G., Vauclair, S., and Greenstein, J. L. 1979, *Astr. Ap.*, **80**, 79.
Wesemael, F. 1979, *Astr. Ap.*, **72**, 104.
Wesemael, F., Auer, L. H., Van Horn, H. M., and Savedoff, M. P. 1980, *Ap. J. Suppl.*, **58**, 379.
Wesemael, F., Henry, R. B. C., and Shipman, H. L. 1984, *Ap. J.*, **287**, 868.
White, R. E. 1984, *Ap. J.*, **284**, 685.

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