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CAN THE *EXOSAT* OBSERVATIONS OF DA WHITE DWARFS BE EXPLAINED BY LAYERED ATMOSPHERIC STRUCTURES?[1,2]

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ABSTRACT

In this paper we demonstrate that the *EXOSAT* broad-band filter observations of DA white dwarfs, which have recently been interpreted with homogeneously mixed H/He atmospheres (Jordan *et al.*; Paerels and Heise), can be explained with stratified theoretical models. In these models a very thin hydrogen layer is floating on top of the underlying helium. The transition zone is determined by diffusive equilibrium. The resulting total hydrogen layer masses are in the range 3×10^{-16} to 5×10^{-14} $M_{\odot}$. Several arguments are discussed that could lead to a decision about the correct interpretation, but a final answer is not possible.

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

I. INTRODUCTION

Observations in the soft X-ray and EUV regions, covering the 228 Å absorption edge of He II, have so far provided the only opportunity to study the He/H abundance ratio in hot DA white dwarfs that show no trace of helium at optical wavelengths. After the pioneering discoveries of EUV radiation from Sirius B, HZ 43, Feige 24, and G191-B2B (Mewe *et al.* 1975*a*, *b*; Hearn *et al.* 1976; Margon *et al.* 1976*a*, *b*; Lampton *et al.* 1976; Holberg *et al.* 1980) a more systematic study has been made possible in recent years with the *Einstein* and *EXOSAT* satellites. A surprising result of these studies was that a small but finite ($\geq 10^{-6}$) amount of helium was necessary in almost all cases to explain the observations (Kahn *et al.* 1984; Petre, Shipman, and Canizares 1986; Jordan *et al.* 1987 [Paper I]; Paerels and Heise 1989). This was surprising, because it is well known that the time scales for gravitational settling of helium in a hot hydrogen-rich atmosphere are very short—of the order of years (Schatzman 1958; Fontaine and Michaud 1979; Koester 1988).

Even less expected was a trend of increasing He abundance with increasing effective temperature of the white dwarf found originally by Petre *et al.* from their analysis of *Einstein* data and confirmed by Jordan *et al.* (1987) from *EXOSAT* observations of nine DA white dwarfs. The only clear exception to that trend in both samples was HZ 43, which seems to have a low He abundance compared to other objects in the same temperature range.

Kahn *et al.* (1984) proposed two possible mechanisms as explanations for the finite observed He abundances: accretion from interstellar matter and selective radiative acceleration on He ions, supporting them against gravity in the atmospheres. In view of the observed relation between He/H and $T_{\rm eff}$, Petre *et al.* favored the second process, because only this can naturally lead to such a correlation. However, Vennes *et al.* (1988) demonstrated that the amount of helium that can be supported by radiative forces is too small by at least two orders of magnitude to account for the observations.

All abundance determinations in the above-mentioned studies were based on the assumption of a homogeneous, mixed He/H atmosphere. As emphasized by Jordan *et al.* (1987) one would instead—in the absence of any forces counteracting gravity—expect a stratified atmosphere with H floating on top of the helium layer, and a transition zone determined by the equations of diffusive equilibrium. Since the opacity of hydrogen is very small at EUV wavelengths, the presence of a small amount of helium in very deep layers in the star can be seen in the emerging EUV radiation, although no trace is visible in the optical region.

A simple version of such a model was first applied to the *ANS* observations of HZ 43 by Heise and Huizenga (1980). More realistic models, taking into account the real abundance profile as determined from the diffusion calculations have recently been published by Jordan and Koester (1986).

In these models the free parameter used to fit the EUV observations is no longer a He/H abundance, but the total hydrogen mass present on top of the helium. This parameter plays an increasingly important role in attempts to explain the origin and evolution of the various white dwarf spectral types (Sion 1984; Shipman, Liebert, and Green 1987; Liebert, Fontaine, and Wesemael 1987), as well as pulsation properties (Cox *et al.* 1987) or the importance of hydrogen burning in the late cooling phases (Iben and Tutukov 1984; Koester and Schönberner 1985).

From their time-dependent diffusion calculations, Vennes *et al.* (1988) conclude that in order to explain the *EXOSAT* data the hydrogen layers must be even thinner than they had assumed in their calculations ($\approx 10^{-7}$ and 10^{-10} $M_{\odot}$). Estimating the He abundance at an (EUV) optical depth of one from an equilibrium abundance profile they arrive at H layer masses in the range 10^{-13} to 10^{-15} $M_{\odot}$. While this should give the correct order of magnitude, there are some obvious problems associated with this procedure. The emerging stellar flux, especially in the EUV, originates from a wide range in geometrical depth with greatly varying He abundance. On the other hand, the observational abundances they use for comparison have all been determined assuming homogeneous model atmospheres.

In this paper we therefore study whether the *EXOSAT* observations analyzed in Paper I in terms of homogeneous atmospheres could also be explained assuming a stratified structure.

[1] Based on observations extracted from the *EXOSAT* data archives of ESOC/Darmstadt.
[2] *Louisiana State Observatory Contribution* No. 214.

II. OBSERVATIONS

The present sample includes 11 DA white dwarfs, which have been observed in at least two filters in the LE experiment (Al/P and Lexan 3000). The data for nine objects have been extracted from the *EXOSAT* archive of ESOC/Darmstadt, and reduced using the facilities at Darmstadt and additional software developed at the Astronomisches Institut in Tübingen as described in Paper I. For G191-B2B, the only case where larger differences appear in the deduced count rate, we took the values from Paerels and Heise (1989). In addition the observations of CD $-38°10980$ and PG 1659+440 as given by Paerels and Heise (1989) were included in the analysis. The observed count rates are given in the referenced papers.

III. MODEL ATMOSPHERES

Atmospheric models with stratified He/H abundances were calculated by Jordan and Koester (1986). In that paper and in Dziembowski and Koester (1981) we showed that the equations of diffusive equilibrium can be combined into one single differential equation defining the He/H abundance ratio as a function of pressure in the atmosphere. This equation can be solved analytically in the case of a constant degree of ionization of helium (either 1 or 2, depending on effective temperature; hydrogen is always ionized). In the more general case the solution must be obtained numerically; however, Lemke (1979) showed that the differences are negligible. For the present study we therefore adopt the simpler case of constant ionization.

The only parameter entering the calculations in addition to effective temperature and surface gravity ($\log g = 8$ assumed as in Paper I) is the pressure P_{g0} in the transition zone, where $n(\mathrm{H}) = n(\mathrm{He})$, which is connected in a simple way to the total mass of the hydrogen layer M_H (Jordan and Koester 1986, but note a typographical error in the formula given there. The correct relation is $M_\mathrm{H} \approx 5 \times 10^{-23} P_{g0}$). In all models the transition zone—as defined by $0.01 < \mathrm{He/H}$ (by numbers) < 100—extends over roughly 4 pressure scale heights, demonstrating the necessity to include the true equilibrium profile as opposed to a simple step function (e.g., Heise and Huizenga 1980; Muchmore 1982, 1984; Price and Shipman 1985).

Preliminary tests showed that the hydrogen masses used in Jordan and Koester (1986) were still too small to explain most of the *EXOSAT* observations. We therefore extended the grid to $P_{g0} = 10$, corresponding roughly to $M_\mathrm{H} \approx 5 \times 10^{-13}\ M_\odot$. Atmospheric structures and synthetic spectra were calculated using the methods developed by the Kiel group over the past decade (e.g., Koester, Schulz, and Weidemann 1979). Convection zones are present in several models especially at the lower effective temperatures as discussed by Jordan and Koester (1986). However, for those models needed in the analysis below, these convection zones do not reach the transition regions and thus probably do not lead to any mixing.

There are at least two other mechanisms that theoretically could disturb the layered equilibrium structure. Radiative support of He ions has been shown to be negligible (Vennes *et al.* 1988). Eddington-Sweet circulation currents, induced by rotation, are probably also negligible, because white dwarfs have empirically been found to be generally slow rotators (Greenstein and Peterson 1973; Pilachowski and Milkey 1987, 1984; Koester and Herrero 1988). The models used in this study must therefore be considered realistic models.

IV. ANALYSIS AND RESULTS

The analysis proceeds in a very similar way as in Paper I. The effective temperature of an object is taken from literature values (see Paper I, Paerels and Heise [1988] and Finley, Basri, and Bowyer [1989] for sources). The distance and the solid angle are determined from the visual magnitude V and the absolute magnitude of a $\log g = 8$ model of that temperature. The two *EXOSAT* broad-band observations are then sufficient to determine the remaining parameters M_H, the mass of the hydrogen layer, and N_H, the interstellar hydrogen column density. We have repeated this calculation for two temperature values at the high end and low end of the allowed ranges in order to show the effect of the temperature uncertainty. The uncertainties of the observed count rates usually have only a minor effect on the result. In the cases of CD $-38°10980$, GD 394, GD 391, and G191-B2B a solution at the low end of the literature range for T_eff is not possible even for pure hydrogen models. In these cases we give the value of the lowest temperature for each object that allows a consistent solution within our model grid. Table 1 gives the final results for M_H, N_H, and n_H, the average hydrogen density along the line of sight.

The low temperature solutions for the cool objects in Table 1 are marked with an asterisk. These objects all have well-

TABLE 1

HYDROGEN LAYER MASSES AND INTERSTELLAR HYDROGEN COLUMN DENSITIES FOR 11 DA WHITE DWARFS OBSERVED WITH *EXOSAT*

Object	T_eff	M_H	N_H	n_H
G191-B2B	68000	3.48×10^{-16}	$4.62 \times 10^{+18}$	0.044
(0501+527)	60000	4.74×10^{-16}	$3.56 \times 10^{+18}$	0.036
	55000	4.90×10^{-16}	$2.70 \times 10^{+18}$	0.029
HZ 43	60000	9.19×10^{-15}	$7.36 \times 10^{+18}$	0.044
(1314+293)	57000	1.21×10^{-14}	$6.59 \times 10^{+18}$	0.040
	54000	1.83×10^{-14}	$5.79 \times 10^{+18}$	0.036
GD 246	60000	4.80×10^{-15}	$2.26 \times 10^{+19}$	0.129
(2309+105)	55000	5.75×10^{-15}	$2.03 \times 10^{+19}$	0.120
	50000	6.79×10^{-15}	$1.94 \times 10^{+19}$	0.120
GD 257	60000	2.94×10^{-15}	$4.04 \times 10^{+19}$	0.115
(0548+000)	55000	5.12×10^{-15}	$4.05 \times 10^{+19}$	0.120
	50000	5.64×10^{-15}	$4.04 \times 10^{+19}$	0.125
GD 153	44000	8.07×10^{-15}	$1.04 \times 10^{+19}$	0.059
(1254+233)	42000	1.06×10^{-14}	$8.93 \times 10^{+18}$	0.052
	40000	1.88×10^{-14}	$7.00 \times 10^{+18}$	0.041
LB 1663	39000	7.15×10^{-15}	$1.70 \times 10^{+19}$	0.055
(0321−539)	37000	8.80×10^{-15}	$1.55 \times 10^{+19}$	0.052
	35000	1.46×10^{-14}	$1.31 \times 10^{+19}$	0.046
GD 659	39000	1.50×10^{-14}	$1.10 \times 10^{+19}$	0.068
(0050−332)	37000	2.28×10^{-14}	$9.78 \times 10^{+18}$	0.063
	*36000	3.35×10^{-14}	$8.93 \times 10^{+18}$	0.058
GD 394	37000	2.27×10^{-14}	$9.11 \times 10^{+18}$	0.044
(2111+498)	36000	3.25×10^{-14}	$8.30 \times 10^{+18}$	0.041
	*35500	4.24×10^{-14}	$7.72 \times 10^{+18}$	0.039
PG 1658+440	33000	1.40×10^{-14}	$8.75 \times 10^{+18}$	0.029
(1658+440)	31000	2.63×10^{-14}	$6.28 \times 10^{+18}$	0.022
	*30500	3.68×10^{-14}	$5.29 \times 10^{+18}$	0.018
GD 391	30500	7.19×10^{-15}	$2.98 \times 10^{+19}$	0.222
(2028+390)	27500	1.08×10^{-14}	$2.54 \times 10^{+19}$	0.210
	*25500	2.59×10^{-14}	$1.90 \times 10^{+19}$	0.168
CD −38°10980	25300	3.23×10^{-14}	$1.59 \times 10^{+19}$	0.420
(1620−391)	25000	4.20×10^{-14}	$1.02 \times 10^{+19}$	0.273
	*24900	2.51×10^{-14}	$2.41 \times 10^{+18}$	0.065

defined solutions at the assumed "best effective temperature." However, lowering the temperature very slightly below our lowest value, but within the range allowed by optical or UV observations, demands increasingly larger H layer masses and the solutions are no longer well defined due to the increasingly smaller influence of the helium contribution. In these cases, a pure H atmosphere could be compatible with the observations, if the effective temperature is lower than assumed.

V. DISCUSSION

The analysis demonstrates that an alternative explanation of the *EXOSAT* data on DA white dwarfs in terms of stratified atmospheres is indeed possible. The values for the hydrogen layer mass are in the range 3×10^{-16} to 5×10^{-14} as estimated by Vennes *et al.* (1988) and as is expected from a simple estimate of the hydrogen topacity at these temperatures. Although there is no single-valued relation to $T_{\rm eff}$, a tendency for thinner H layers at the hot and thicker at the cool end of the sequence is apparent, with the notable exception of HZ 43. This is very reminiscent of the relation between He abundances and $T_{\rm eff}$ noted by Petre *et al.* and Jordan *et al.* (1987) from interpretations with homogeneous atmospheres. If both interpretations are possible, how can we decide, which one is correct?

i. A major problem with the interpretation of white dwarf *EXOSAT* data has been that the derived interstellar column densities for some objects were relatively high. The required column densities are unfortunately even higher for the solutions obtained with stratified atmospheres. Most values for $n_{\rm H}$ are around or below 0.1 cm^{-3}, which seems to be typical for the immediate solar neighborhood within 5 pc (Landsman *et al.* 1984). For the average density within 100 pc Paresce (1984) gives a value of 0.07 cm^{-3}, although in some directions it may be much higher.

However, at least for HZ 43 and GD 153 the results are in severe conflict with *Voyager* observations in the range shortward of the Lyman edge (Holberg 1987; Jordan *et al.* 1987; Paerels and Heise 1989). Incidentally, both objects are in the direction of the galactic north pole.

Paerels and Heise (1989) propose that this discrepancy can be resolved by assuming that hydrogen along the line of sight of HZ 43 is largely ionized. The *Voyager* observations detect the small residual neutral hydrogen in the 500 to 900 Å range, whereas *EXOSAT* is sensitive to the neutral He absorption below 500 Å, which can be parameterized by assuming a higher, equivalent neutral hydrogen column density.

A careful referee has noted that the interstellar neutral hydrogen column densities in Table 1 are much larger than for homogeneous atmospheres (Jordan *et al.* 1987), even for objects with fairly thick hydrogen layers such as GD 659 and GD 394. The spectrum of an infinitely thick hydrogen atmosphere must of course be identical to one with zero helium content.

However, as soon as the helium becomes apparent in the emerging spectrum, the effects are significantly different depending on whether the atmosphere is homogeneous or stratified. It is not possible to find a stratified model that reproduces the spectrum of a homogeneous atmosphere with He/H $= 10^{-5}$ in the region above and below the He II 228 absorption edge, although for $\lambda > 500$ Å the spectra are almost identical.

Other (minor) contributions to differences between the

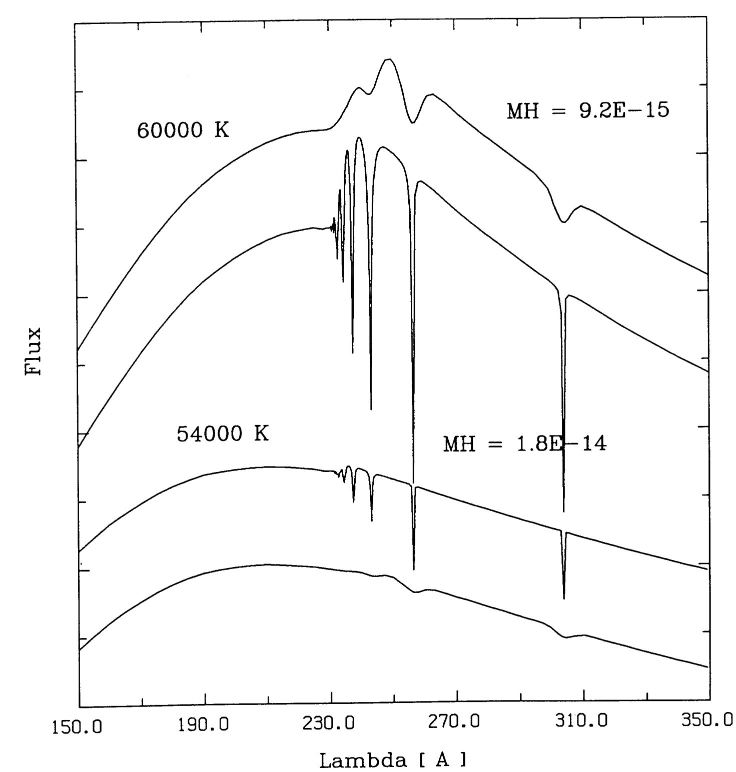

FIG. 1.—Theoretical EUV flux for two models reproducing the *EXOSAT* broad band filter counts (*second and third from top*). Also shown are the same spectra smoothed to a resolution of 6 Å (*top and bottom*). The vertical scale is a linear scale in F_λ with the correct zero point for the unsmoothed spectra. The smoothed spectra are shifted vertically.

results of this paper and Jordan *et al.* (1987) originate from changes in computational details. The treatment of the overlapping He II lines near the series limit has been improved, and the interstellar absorption has been calculated using the more recent data of Morrison and McCammon (1983) instead of Cruddace *et al.* (1974).

ii. Another problem with the *EXOSAT* observations has been the discrepancy between the EUV spectrum and the broad-band filter observations of HZ 43. In their table of the results from EUV photometry Paerels and Heise (1988) give for HZ 43 the He abundance derived from the nonvisibility of the He II λ228 edge without using the very accurate observations for five different filters.

These are in fact completely incompatible with the low He abundance they obtain as long as the temperature is confined to the interval obtained from optical and UV observations, as was demonstrated in Paper I. If the temperature is lowered to 50,000 K, the value favored by Heise *et al.* (1988) in their second paper on the EUV spectrum of HZ 43, we would indeed get a He abundance of 3×10^{-6} also from the filter data and homogeneous atmospheres (see Fig. 1 in Paper I) and the discrepancy between spectrum and broad-band filters disappears.

Interpretation with stratified atmospheres can remove this discrepancy at a higher temperature, more in accord with other observations. Figure 1 shows two theoretical EUV spectra at the high and low end of the temperature assumed for HZ 43 (57,000 ± 3000 K), which both reproduce the observed EUV filter fluxes. Also shown are the same spectra smoothed to match the resolution of the grating spectrum of 6 Å. In the hot model the absorption edge remains clearly visible, whereas in the cool model, which has a slightly larger H mass, it has disappeared, in part due to the strong overlapping of the high series members of the He II Lyman series. The lines are broader than in a homogeneous model because He is only present in regions of the atmosphere with higher pressures. At this resolution only the absorption lines near 250 and 300 Å remain visible, and an indication for such features can indeed be seen in the LEXAN 3000 spectrum in Figure 2 in Heise *et al.* (1988).

iii. Holberg *et al.* (1988) have pointed out that the He abundance of G191-B2B as determined from homogeneous models ($> 3 \times 10^{-3}$) would lead to visible He II lines λ1640 and λ4686, which are not observed. In a stratified model with $M_H \approx 5 \times 10^{-16}$ the predicted lines are compatible with their observational upper limits (Koester 1988).

We conclude that an explanation of the *EXOSAT* observations in terms of stratified atmospheric models is certainly possible as well as with homogeneous models. The balance of the arguments discussed above favors the first interpretation, but homogeneously mixed atmospheres cannot be ruled out, and a final decision is not possible with the present data. The strongest argument for the existence of stratified atmospheres with thin H layers remains for the time being the absence of any known physical mechanism that could prevent diffusion.

Note added in manuscript.—After the completion of this paper S. Vennes, G. Fontaine and F. Wesemael (private communication) presented results of a similar study at IAU Colloquium No. 114. For most objects they derive lower limits on the hydrogen layer mass, which are in agreement with our findings. In five of the six cases where they actually determine this parameter, it is in agreement with our result within the mutual error margins; in the remaining case the difference is also small.

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