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HOT WHITE DWARFS AS SOFT X-RAY SOURCES. II. THE SPACE DENSITY OF HOT WHITE DWARFS DETERMINED FROM SOFT X-RAY SURVEYS

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ABSTRACT

New limits on the space density n of hot white dwarfs are obtained from the soft X-ray survey of Levine *et al.* and from recent theoretical work on hot, high-gravity atmospheres. The observed count rate yields $n \lesssim 3.3 \times 10^{-7}$ pc^{-3} at $T_e \geq 70{,}000$ K, for an assumed white dwarf mass $M = 0.6\ M_\odot$ and a uniform average interstellar neutral hydrogen density $n_{\rm H} = 0.15$ cm^{-3}. Within the uncertainties in both the theoretical expectations and the observed upper limits, this result is compatible with the predictions of white dwarf cooling theory including neutrino processes. The observed space density at $T_e \geq 70{,}000$ K, however, cannot be used to rule out evolution without neutrino energy losses.
Subject headings: neutrinos — stars: stellar statistics — stars: white dwarfs — X-rays: sources

I. INTRODUCTION

In a previous paper (Wesemael 1978, hereafter referred to as Paper I), we investigated the possibility of using soft X-ray surveys to place limits on the space density of hot white dwarfs. Since hot white dwarfs have been shown not to radiate like blackbodies at wavelengths shortward of the Lyman edge (Shipman 1976, 1979*b*; Auer and Shipman 1977), a small grid of hot, high-gravity, hydrogen-rich atmospheres was computed for the purpose of obtaining accurate thermal soft X-ray luminosities for these hot objects. This grid, together with the soft X-ray survey of Vanderhill *et al.* (1975), was then used to place limits on the space density of white dwarfs above $T_e = 100{,}000$ K. The effects of changes in stellar mass and helium abundance, and of the departures from the zero-temperature mass-radius relationship were crudely investigated, and it was pointed out that, at that effective temperature, the available data suggested the occurrence of neutrino processes during the evolutionary phases preceding the white dwarf stage.

The aim of the present paper is to reinvestigate the limits of Paper I in the context of some recent observational and theoretical developments. The major improvement to the analysis of Paper I is the use of the soft X-ray survey of Levine *et al.* (1976, 1977), which extends down to ultrasoft energies ($E \sim 90$ eV). In addition, the recent theoretical work on the atmospheres of hot, high-gravity stars by Wesemael *et al.* (1980) provides a homogeneous grid of model atmospheres which can be used to investigate the sensitivity of our results to different assumptions. Moreover, the work of Lamb, Van Horn, and Winget (1980, hereafter LVHW) on the evolution of cooling white dwarfs, together with the earlier investigations of Vila (1967), Koester (1972), Shaviv and Kovetz (1976), and others, can be used to obtain accurate estimates of the cooling times of hot white dwarfs; the white dwarf masses chosen in these most recent calculations ($0.6\ M_\odot$ and $0.8\ M_\odot$) bracket the masses of the DA white dwarfs recently determined from photometric data. Finally, our knowledge of the structure of the interstellar medium (ISM) continues to improve. In particular, the data recently collected by Cash, Bowyer, and Lampton (1979) suggest that, despite the apparently chaotic and patchy structure of the ISM, the neutral hydrogen density within 100 pc of the Sun is most likely $\lesssim 0.1$ cm^{-3}. This has some bearing on this problem, since the typical distance over which our vision extends when considering thermal X-ray emission from white dwarfs at $T_e \sim 70{,}000$ K is ~ 100–200 pc. A reliable estimate of the ISM neutral hydrogen density in that distance range thus could give further weight to the upper limits obtained near that effective temperature.

This paper is organized as follows: in § II, we discuss in detail our method of analysis. We review both the observational material and the theoretical calculations which form the basis of this investigation, and outline our procedure. We present and discuss our results in § III. The main conclusions of this paper are then summarized in § IV.

II. METHOD OF ANALYSIS

a) *The Observational Material*

i) *The Soft X-ray Survey*

We use the results of the soft X-ray survey of Levine *et al.* (1976, 1977). This survey was carried out in the range 90 eV $\lesssim E \lesssim 280$ eV, and was designed to have a significant effective area at the low-energy end. We use the data of Levine *et al.* in the following three pulse-height intervals: 90–150 eV, 150–240 eV, and 240–310 eV. For these channels, the effective collecting area as a function of energy was obtained from Levine *et al.* (1977).

No evidence for ultrasoft, pointlike sources was found in the data. Any point source yielding a countrate of 5 counts s^{-1} in any of the three energy channels would have been recognized as a discrete source (Rappaport 1978), and we use this number for our subsequent analysis (see § II*c*.) The survey covered about 8% of the sky.

ii) *The Neutral Hydrogen Density in the ISM*

Cash, Bowyer, and Lampton (1979) recently summarized the determinations of the interstellar neutral hydrogen density within 100 pc from the Sun. Their data clearly exhibit the patchy structure of the ISM and seem to confirm, at least qualitatively, the elaborate theoretical picture of McKee and Ostriker (1977). A fit to the variation of the H I column density with distance yields an average hydrogen density of $n_H \approx 0.06$ cm^{-3} within 100 pc. This is an important result since, at the sensitivity of the survey of Levine *et al.*, 100 pc is roughly the distance to which a white dwarf like WD 1314 + 29 ≡ HZ 43 would be detected at soft X-ray wavelengths. At larger distances, the survey of Bohlin, Savage, and Drake (1978) indicates somewhat higher average number densities of H I. Their best estimate for the mean number density of neutral hydrogen in the intercloud medium is $n_H \approx 0.16$ cm^{-3}, whereas they estimate the mean neutral gas density for clouds and the intercloud medium at $n_H \approx 0.86$ cm^{-3}.

In order to study the influence of the ISM neutral hydrogen density distribution on the results of our analysis, we have adopted three distinct models. In the first case, we have used a uniform average neutral hydrogen density along the line of sight. Our choice of densities ranges from $n_H = 10^{-2}$ cm^{-3} to $n_H = 1.0$ cm^{-3} (model 1). In the second case, we have assumed a two-region model of the ISM, with average number densities $n_H = 0.1$ cm^{-3} within 100 pc and $n_H = 1.0$ cm^{-3} outside of 100 pc (model 2). Finally, we have adopted a two-component model of the ISM, consisting of a low-density ($n_H = 0.16$ cm^{-3}) intercloud medium with higher-density ($n_H \approx 10$ cm^{-3}) clouds embedded within it. We assume a typical cloud radius of $R_c = 5$ pc. The 21 cm study of Radhakrishnan and Goss (1972) and the statistical analysis of Hobbs (1974) both argue for a mean distance between clouds along the line of sight of ~ 200–300 pc. Because this distance is comparable to the typical distance sampled with the soft X-ray detectors, we assume, for illustrative purposes, that there is, on the average, only roughly one cloud along the line of sight to the white dwarf (model 3).

b) The Theoretical Material

i) *The Model Atmosphere Calculations*

Most thermal soft X-ray fluxes used in this analysis are taken from the grid of hot, high-gravity, unblanketed pure hydrogen atmospheres of Wesemael *et al.* (1980). In a few cases, additional models were computed specifically for the present work. The pure hydrogen composition is appropriate for the DA white dwarfs, which represent about two-thirds of the total white dwarf sample. The evidence from visual observations implies

$$N(\mathrm{He})/N(\mathrm{H}) < 10^{-2}$$

for the DA stars, from the absence of He I lines in the spectrum (Shipman 1972). For the few hot DA white dwarfs for which ultraviolet observations have been obtained and abundance analyses performed, the limits are more stringent: $N(\mathrm{He})/N(\mathrm{H}) \lesssim 10^{-4}$ for HZ 43 ≡ WD 1314 + 29 (Auer and Shipman 1977; Wesselius and Koester 1978; Malina, Bowyer, and Paresce 1978) and $3 \times 10^{-5} < N(\mathrm{He})/N(\mathrm{H}) < 3 \times 10^{-3}$ for Feige 24 ≡ WD 0232+03 (Shipman 1979*b*). This deficiency of elements heavier than hydrogen is consistent with our general understanding of the gravitational settling process in the photospheres of these stars. In the hotter objects, however, theoretical considerations suggest that radiation pressure could disrupt the settling process and bring some heavy elements to the surface (Vauclair, Vauclair, and Greenstein 1979). These authors suggest a search for the ultraviolet C III λ1175, C IV λ1549, and N V λ1240 features to confirm the presence of metals in the photospheres of hot DA white dwarfs. In one case, Greenstein and Oke (1979) obtained IUE spectra of WD 1314+29 ≡ HZ 43, and report that "no other definite lines (besides Lα) are seen in the spectrum," while Heap *et al.* (1978) reported some possible structure near 1720 Å (N IV) in earlier spectra of the same object. There is thus, at present, no evidence for the presence of metals in the atmospheres of hot DA white dwarfs, and we adopt the pure hydrogen composition for our analysis.

ii) *The Evolutionary Calculations*

We use the recent white dwarf cooling evolutionary calculations of LVHW. These calculations extend the previous analysis of Lamb and Van Horn (1975), which was restricted to pure carbon models at $M = M_\odot$. Most of the newer calculations also adopt a pure carbon composition throughout the core and the envelope, and we use these models for the bulk of our analysis. A few models also include a layered (C/He/H) envelope composition profile which we expect to be more representative of the true structure of DA white dwarfs. These computations (restricted to models at $M = 0.6\ M_\odot$) provide us with an estimate of the effect of the residual hydrogen envelope on the stellar radius.

The investigations of Shipman (1972, 1977, 1979*a*), Shipman and Sass (1980), and Koester, Weidemann, and Schulz (1979) all indicate that the mean mass of the DA white dwarfs is in the range $M \sim 0.6$–$0.8\ M_\odot$. To test the sensitivity of our results to the assumed average DA mass, calculations were performed both for $M = 0.6\ M_\odot$ and $M = 0.8\ M_\odot$.

The space density of white dwarfs with luminosities larger than L can be written in terms of the white dwarf birthrate $\chi(t)$ (which we assume to be independent of the stellar mass) as (see also Koester 1978)

$$n(L) = n(L_0) + \int_{\tau(L_0)}^{\tau(L)} \chi(t)dt\ , \tag{1a}$$

where L_0 is some reference stellar luminosity and $\tau(L_0)$ and $\tau(L)$ are the cooling times down to L_0 and L, respectively. *For a constant white dwarf birthrate in that luminosity (time) interval*, we can rewrite equation (1a) as

$$n(L) = n(L_0) + \chi[\tau(L) - \tau(L_0)]\ . \tag{1b}$$

For $L \ll L_0$, $\tau(L) \gg \tau(L_0)$ so that equation (1b), with $n(L_0) \approx 0$, yields $\chi = n(L)/\tau(L)$. The white dwarf birthrate has been determined in that way by Weidemann (1977), using published cooling tracks and the standard Eggen and Greenstein white dwarf sample for $M_{\rm bol} \leq 13$. His result is $\chi = 2 \times 10^{-12}$ pc^{-3} yr^{-1}, uncertain by a factor ~ 2. This result is in agreement with that obtained from Green's (1980) recent value for the space density of blue degenerates with $M_v \leq 12.75$, namely, $(1.43 \pm 0.28) \times 10^{-3}$ pc^{-2}; the use of Green's space density yields $\chi = 1.4 \times 10^{-12}$ pc^{-3} yr^{-1}.

In the present work, care must be exercised in choosing L_0 since the condition $\tau(L) \gg \tau(L_0)$ is usually not satisfied for values of L of interest to us. We adopt here for L_0 the luminosity where $\epsilon_F/kT \sim 1$ at the center of the white dwarf. In the above expression, ϵ_F and kT are the Fermi energy and thermal energy per electron, respectively. The above expression thus defines in physical terms the onset of degeneracy at the center of the white dwarf. For the model at $M = 0.6\ M_\odot$, this occurs at $\log(L_0/L_\odot) \approx 2.2$. Although we favor this definition of L_0, some calculations were also performed with the alternate value of L_0 used by Koester (1978), namely, $\log(L_0/L_\odot) \equiv 1.0$. For all models considered here, $\epsilon_F/kT \sim 1$ at the center is reached before $\log(L/L_\odot) = 1$, and thus the theoretical space densities obtained with Koester's definition of L_0 will be smaller than those obtained with our own. We believe, quite subjectively, that these choices bracket any reasonable value of L_0 and may represent roughly the range of uncertainty in that number.

c) *The Space Density of Hot White Dwarfs*

One of the most significant conclusions which can be drawn from the work of Vanderhill *et al.* (1975) and Levine *et al.* (1976, 1977) is that it is extremely likely that the soft X-ray background is truly diffuse.[1] The lower limit to the source density in a discrete-source model of the background is $n > 0.2$ pc^{-3}, a number comparable to the total density of known stellar objects (Levine *et al.* 1977).

We thus use, in our analysis, the upper limits on individual sources that stand out against the diffuse background. We introduce N, the 3 σ upper limit on the number of photons cm^{-2} s^{-1} detected from an individual source in a particular energy channel. Then, for any isolated white dwarf,

$$4\pi(R^2/D^2)\int_0^\infty (H_\nu/h\nu)A_\nu \exp[-n_{\rm H}\sigma_e(\nu)D]d\nu \leq N\ , \quad (2)$$

where R is the stellar radius, D the distance to the star, H_ν the emergent Eddington flux (ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}, such that $\int_0^\infty H_\nu d\nu = \sigma T_e^4/4\pi$), $n_{\rm H}$ the neutral interstellar hydrogen density, and $\sigma_e(\nu)$ the hydrogen absorption cross section. At the low energies considered here, Hayakawa (1973) gives

$$\sigma_e(E) = 6 \times 10^{-23}(E/1\ {\rm keV})^{-3}\ {\rm cm}^{-2}\ . \quad (3)$$

In equation (2), A_ν is the energy-dependent effective area of the particular channel considered.

For each stellar model used, the surface gravity is determined consistently from the stellar mass and radius, as given by the evolutionary calculations of LVHW. The stellar radius thus incorporates automatically the departures from the zero-temperature mass-radius relationship which are encountered at high effective temperatures. The fluxes of Wesemael *et al.* (1980) are then interpolated in surface gravity, and also in frequency to perform the integration of equation (2). An iterative procedure is adopted to determine the value of D consistent with the chosen values of R, H_ν, A_ν, and N. A guess at the value of D is first made, and equation (2) is then solved for the correction to the initial value of D. The procedure is repeated until the desired accuracy is achieved.

The white dwarf space density n follows then from

$$n < (4\pi D^3 f/3)^{-1}\ , \quad (4)$$

where f is the fraction of the sky surveyed.

III. RESULTS

We have summarized our results in Figures 1–3 and Table 1. Figure 1 shows the calculated upper limits on the space density of hot white dwarfs above $T_e = 70{,}000$ K as a function of average interstellar neutral hydrogen density. A white dwarf mass of $M = 0.6\ M_\odot$, with a radius $R = 0.01540\ R_\odot$, has been assumed. The limits for the three energy channels of Levine *et al.* (1976, 1977) are shown, together with the theoretical estimates obtained from the cooling time at 0.6 $M_\odot$ and Weidemann's (1977) white dwarf birthrate. The evolutionary calculations include neutrino energy losses. The theoretical estimates shown are labeled n_ν^W, for the value obtained with $L_0 = L|_{\epsilon/kT\sim 1}$, and n_ν^K for that obtained with $L_0 = 10\ L_\odot$, as used by Koester (1978). The evolutionary calculations of Vila (1967) at 0.6 $M_\odot$ indicate that the cooling time, measured from the epoch of maximum effective temperature, down to $T_e \approx 70{,}000$ K is a factor ~ 4 longer in the absence of neutrino cooling than when neutrino processes are operating. This is in agreement with the factor ~ 3.2 which can be obtained from Koester's (1978) analysis. The shortening of the cooling time down to $T_e = 70{,}000$ K due to neutrino processes is thus less severe than the estimate used by Henry *et al.* (1976) and in Paper I for cooling down to $T_e \gtrsim 100{,}000$ K.

Figure 1 shows that the observational limits on n, used at face value, can be reconciled with the theoretical estimate based on the evolutionary calculations of LVHW and the definition of L_0 favored in this work if $n_{\rm H} \gtrsim 1.0$ cm^{-3}. The limits obtained with Koester's value of L_0 are less stringent and, in that case, we find that the condition $n_{\rm H} \gtrsim 0.4$ cm^{-3} is required to bring theoretical

[1] A similar conclusion was reached by Stern and Bowyer (1980), although they cannot rule out, on the basis of their analysis, substantial contributions from stellar coronae to the low-energy extreme-ultraviolet background.

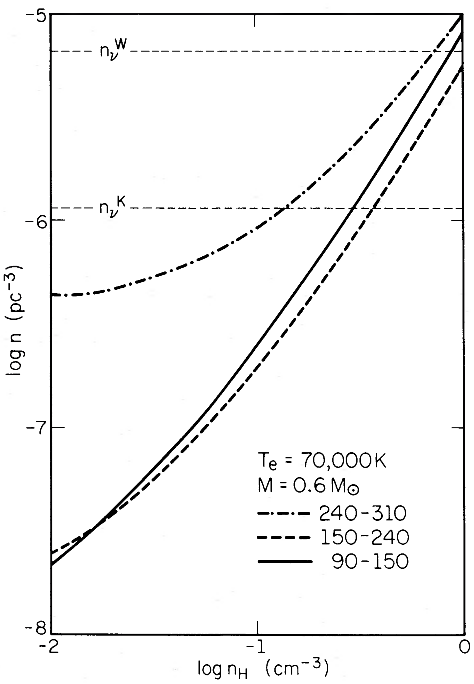

FIG. 1.—Upper limits on the space density of hot white dwarfs above $T_e = 70{,}000$ K as a function of average interstellar neutral hydrogen density. The curves are labeled by the energy channel (in eV). The theoretical predictions, obtained with the cooling times of LVHW and the zero point of this work and of Koester (1978), are marked $n_\nu{}^W$ and $n_\nu{}^K$, respectively. The adopted stellar mass and radius are $M = 0.6\ M_\odot$ and $R = 0.01540\ R_\odot$.

predictions and observational results into agreement. Although these hydrogen densities appear large compared to those generally characterizing the local ($D \lesssim 100$ pc) ISM, they depend rather critically on our assumption of a uniform distribution of interstellar hydrogen.

Noteworthy in Figure 1 is the fact that, at $T_e = 70{,}000$ K, the uncertainties in the zero point L_0 preclude an unambiguous distinction between evolution with and without neutrino energy losses. At that effective temperature, the difference in theoretical space densities would be a factor ~ 4, as discussed above, a difference comparable to the uncertainty due to the choice of zero point (a factor ~ 5.5, with the choices of L_0 used in this work).

Figure 1 (as well as the following figures) also shows that the upper limits obtained from the low-energy channels (90–150 eV and 150–240 eV) are considerably more stringent than those obtained with the high-energy channel (240–310 eV). This arises because the emergent thermal flux from the white dwarf photosphere increases steeply with increasing wavelength in that temperature and energy range ($H_\lambda \propto \lambda^4$ at $T_e = 70{,}000$ K in the range 100–280 eV).

As a byproduct of the evolutionary calculations of LVHW, it is possible to estimate the changes induced in the space density n by the adoption of a layered envelope composition profile. The evolutionary calculations show that the stellar radius of the layered model is $\sim 4\%$ larger than that of the homogeneous, pure ^{12}C model at $T_e = 70{,}000$ K. At $n_H = 0.1$ cm^{-3}, this induces a change $\Delta(\log n) = -0.03$. The influence of the more realistic layered composition is thus negligible for the domain of effective temperatures considered here, and we restrict the rest of our discussion to homogeneous, pure ^{12}C models.

Figure 2 shows the observational upper limits on the space density of hot white dwarfs at $T_e = 90{,}000$ K. We have assumed again $M = 0.6\ M_\odot$ and, in this case, $R = 0.01773\ R_\odot$. Also shown is the theoretical estimate $n_\nu{}^W$, obtained from the cooling times of LVHW. We do not show any results for $n_\nu{}^K$, since at $T_e = 90{,}000$ K, we find $\log (L/L_\odot) = 1.26$, a value larger than Koester's theoretical zero point. We point out, however, that at this effective temperature the object is already degenerate at the center ($\epsilon_F/kT \sim 35$) so that there is little doubt, in our opinion, that this object should be identified with a white dwarf.

When compared to Figure 1, Figure 2 clearly exhibits the very steep dependence of the thermal soft X-ray flux on the effective temperature. In the temperature range $70{,}000\ \text{K} \lesssim T_e \lesssim 100{,}000$ K, we find that the soft X-ray flux integrated over the bandpass 160 eV–280 eV (which corresponds to the bandpass over which the effective area of the first energy channel drops to $1/e$ of its maximum value) varies as $\sim T_e{}^{7.5}$. Thus a small increase in T_e will dramatically reduce the observed upper limits, whereas the cooling time varies more slowly with effective temperature. Our observational limits on n are thus more stringent at $T_e = 90{,}000$ K and, in particular, fall all below the theoretical estimate based on calculations including neutrino energy losses.

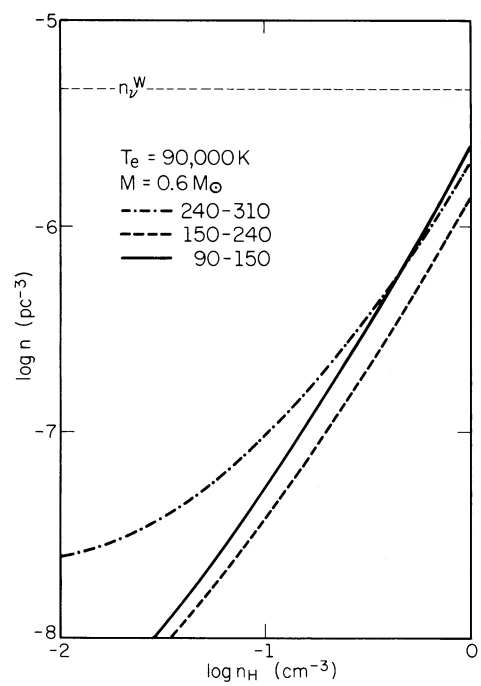

FIG. 2.—Same as Fig. 1 but for $T_e = 90{,}000$ K and $R = 0.01773\ R_\odot$.

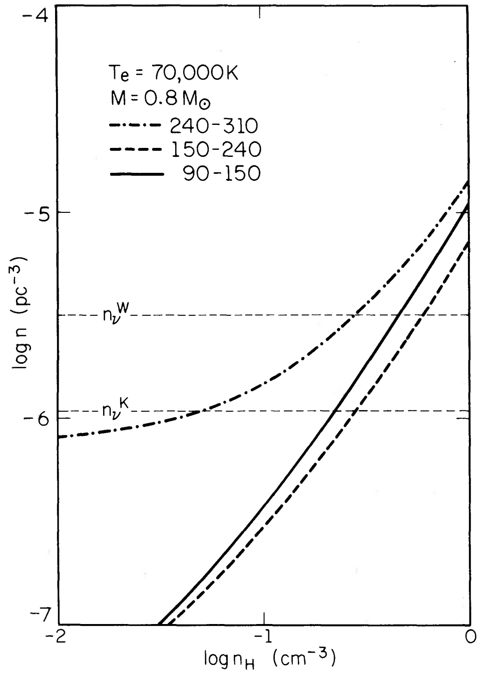

FIG. 3.—Same as Fig. 1 but for $M = 0.8\ M_\odot$ and $R = 0.01103\ R_\odot$.

To test the sensitivity of our results to the assumed mean mass of the DA white dwarfs, additional calculations were performed with the 0.8 $M_\odot$ model. The results at $T_e = 70{,}000$ K ($R = 0.01103\ R_\odot$) are shown in Figure 3. Because the increase in mass is accompanied by a decrease in the stellar radius, the observational limits are less stringent in the high-mass case. Furthermore, because the neutrino energy losses are density-dependent, evolution through the hot phases is accelerated in the 0.8 $M_\odot$ so that, at $T_e = 70{,}000$ K, the age of the 0.8 $M_\odot$ model is a factor ~ 2 smaller than that of the 0.6 $M_\odot$ model, thus reducing the expected space densities. In this high-mass case, the observational limits at $T_e = 70{,}000$ K can be accommodated if $n_H \gtrsim 0.25$ cm^{-3} within 150 pc from the Sun ($n_H \gtrsim 0.65$ cm^{-3} within ~ 100 pc if n_ν^W is used). Again, both lower limits on n_H are obtained within the framework of our uniform density ISM model.

Because these conclusions are sensitive to the patchy and poorly known structure of the ISM, it is important to investigate the sensitivity of our limits to the adopted ISM model. Our results for several models (numbered 1–3) are shown in Table 1. Model 1 is that used in Figures 1–3 with a variable value of the average interstellar neutral hydrogen density n_H. For the sake of definiteness, model 1 in Table 1 has $n_H = 0.15$ cm^{-3}. Model 2 is the two-region model; the adopted densities of neutral hydrogen used in the two regions are given in § II*a*(ii) and in the footnote to Table 1. Finally, model 3 is the two-component model. We assume that there is only one large-scale cloud on the line of sight, and that the line of sight crosses the cloud along a cord of average length $l \approx 4R_c/\pi = 1.27R_c$. A comparable optical depth would be obtained if our line of sight crossed, say, three or four smaller-scale patches (thickness ~ 1–2 pc, $n_H \sim 10$ cm^{-3}), of the kind described by Cash, Bowyer, and Lampton (1979).

Table 1 shows that, in model 2, the high-density component of the ISM beyond 100 pc severely limits our vision beyond that distance. This is especially important in the model at $T_e = 90{,}000$ K, since the original distance sampled in model 1 was ~ 430 pc; in model 2, the large column density beyond 100 pc reduces sharply the distance sampled and increases the limit of model 1 by a factor ~ 6. The adoption of a two-phase model of the ISM also reduces the space densities compared to the values obtained with an "average" interstellar neutral hydrogen density, as in model 1. Examination of Table 1 thus reveals that the observational limits on the space density of hot white dwarfs could be uncertain by a factor 5–15, depending on the model of the ISM adopted.

With this uncertainty in mind, it is now possible to draw some conclusions from the results of Figures 1–3. Within the uncertainties in both the theoretical zero-point and the structure of the ISM, the observed upper limits on the space density of white dwarfs above $T_e = 70{,}000$ K are found to be consistent with the theoretical estimates based on white dwarf cooling theories including neutrino energy losses. However, whether or not neutrino processes are indeed operative in the early white dwarf evolutionary phases cannot be decided on the basis of the present analysis.

The evidence provided by the calculations at $T_e = 90{,}000$ K, $M = 0.6\ M_\odot$ is less conclusive. It seems possible to bring theoretical expectations and observational results into agreement by stretching their respec-

TABLE 1

UPPER LIMITS ON THE SPACE DENSITY OF HOT WHITE DWARFS AS A FUNCTION OF ISM MODEL[a]

T_e (K)	M ($M_\odot$)	Model[b]	log n
70,000...........	0.6	1	−6.48
		2	−5.95
		3	−5.33
90,000...........	0.6	1	−7.18
		2	−6.34
		3	−6.40
70,000...........	0.8	1	−6.31
		2	−5.88
		3	−5.13

[a] All values of log n were determined from the (150–240 eV) energy channel.

[b] Definition of ISM models (see §II*a*(ii) for further details): (1) Uniform ISM with average density $n_H = 0.15$ cm^{-3}. (2) Two-region model with $n_H = 0.10$ cm^{-3} for $D < 100$ pc and $n_H = 1.0$ cm^{-3} for $D > 100$ pc. (3) Two-component model with one cloud of radius $R_c = 5$ pc and density $n_H = 10$ cm^{-3} along the line of sight. Estimated average distance traveled within the cloud, $l \sim 4R_c/\pi = 1.27R_c$. The intercloud medium has $n_H = 0.16$ cm^{-3}.

tive uncertainties in the right direction, although such a procedure would require some justification. The agreement would also be improved by adopting a somewhat higher white dwarf mass ($M \sim 0.8\ M_{\odot}$).

Although the structure of the ISM is the largest unknown in calculations of this kind, other sources of uncertainty should be mentioned. Geometrical effects due to the large-scale distribution of white dwarfs in the Galaxy have been ignored. Abundance variations in hot white dwarfs have also been neglected. As described in § II*b*, the evidence for a helium-free atmosphere even in the hottest DA white dwarfs ($T_e \gtrsim 50{,}000$ K) is very strong. In Paper I we showed that, as long as He/H $\lesssim 10^{-2}$, the thermal soft X-ray luminosities were quite insensitive to the exact helium content of the atmosphere. The importance of radiation pressure on CNO ions, however, deserves further consideration. If heavy ions, like oxygen, can be supported against gravitational settling, they could quench the thermal soft X-ray flux from hot DA white dwarfs. A search for lines of metallic ions in the UV spectra of hot DA white dwarfs would be invaluable, as suggested by Vauclair, Vauclair, and Greenstein (1979).[2]

[2] We note the recent detection of the C IV λ1549 transition in the ultraviolet spectrum of a few DO-like white dwarfs (Green and Liebert 1980). Helium and metal lines are also ubiquitous in the spectra of hot subdwarfs (Greenstein and Sargent 1974).

IV. CONCLUSIONS

We have determined new upper limits on the space density of hot hydrogen-rich white dwarfs above $T_e = 70{,}000$ K and $T_e = 90{,}000$ K from the ultrasoft X-ray survey of Levine *et al.* (1976, 1977) and from recent theoretical work on the atmospheres of hot, high-gravity stars. These limits have been compared with the theoretical predictions of white dwarf cooling calculations, including neutrino energy losses. Within the uncertainties in both the hot phases of pre-white dwarf evolution and the fluctuating nature of the interstellar medium, the observed upper limits are consistent with the prediction of white dwarf cooling theory. However, because of these uncertainties and because the difference in predicted space densities at $T_e = 70{,}000$ K between evolution with and without neutrino energy losses is small, the present results cannot be used to rule out evolution without neutrino energy losses.

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