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WHITE DWARFS AND THE INTERSTELLAR MEDIUM

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ABSTRACT

Radiation emanating from hot ($T > 40{,}000$ K) white dwarfs can create large volumes of ionized material containing substantial column densities of highly ionized species, in particular Si IV and C IV. The ions N V and O VI can also be produced by hot, hydrogen-rich white dwarfs. These ionization spheres may be detectable around the nearby dwarfs. The relatively high space motions of these stars coupled with long recombination times in the interstellar medium suggest that a white dwarf leaves a region of ionized material—a fossil Strömgren trail (FST)—that marks its progress through the galaxy. White dwarfs create a patchy substrate of ionized gas in the galactic plane and lead to extended ionized regions out of the plane. The spatial frequency of hot white dwarfs indicates that they contribute a radiative energy comparable to that provided by nondegenerate stars and by supernovae and capable of affecting the ionization balance of the interstellar medium.

Subject headings: interstellar: matter — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

This *Letter* addresses the photoionization of hydrogen and heavy elements by hydrogen-rich and helium-rich white dwarfs in the interstellar medium. Ultraviolet spectroscopy with the *International Ultraviolet Explorer* (*IUE*) has revealed narrow absorption features in C IV, and sometimes Si IV, and N V in the spectra of three nearby hot white dwarf stars (Bruhweiler and Kondo 1981; Dupree and Raymond 1982; Sion and Guinan 1983). These lines have local standard of rest (LSR) radial velocities less than 20 km s^{-1}, consistent with material in the local interstellar medium, and in one case substantially (~ 50 km s^{-1}) distinct from the target stars. Such observations suggest that the highly ionized species may be direct evidence for photoionization of the ambient interstellar medium surrounding white dwarfs.

Many classes of nondegenerate stars have been evaluated as sources of photoionization of hydrogen or heavy elements in the interstellar medium: O and B stars (Torres-Peimbert, Lazcano-Araujo, and Peimbert 1974; Black *et al.* 1980; Cowie, Taylor, and York 1981); "ultraviolet stars," assumed to be hot pre–white dwarfs (Hills 1972, 1974); and planetary nebulae (Terzian 1974).

White dwarfs differ from these sources in two ways that can affect the ionization of the interstellar medium. For the same effective temperature, hydrogen-rich white dwarfs have an energy distribution with a greater proportion of flux at high energies than nondegenerate stars. This enables highly ionized interstellar species to be produced. Second, most recent surveys (Green 1980; see also Liebert 1980) and calculations (Koester 1978) suggest that hot white dwarfs have a substantially higher local spatial density than the nondegenerate hot stars; moreover, the scale height of white dwarfs is larger than that of nondegenerates—allowing their radiation to escape the galactic plane—as noted previously by Hills (1972).

II. MODEL CALCULATIONS

The ionization balance in an isothermal ($T = 10^4$ K) photoionized region of constant density was evaluated using our modification of a code discussed in Black *et al.* (1980). The incident radiation field originates from a white dwarf of $1.27 \times 10^{-2}\ R_{\odot}$ radius as prescribed by the pure hydrogen and helium models of Wesemael *et al.* (1980) and Wesemael (1981). Theoretical flux distributions (Fig. 1) show that substantial radiation emerges from hydrogen models above the photoionization edges of highly ionized species. However, the helium model exhibits discontinuities and a flux deficit at high frequencies that results from helium absorption. The precipitous drop at the ionization edge of He II at $\lambda 228$ (1.2×10^{16} Hz) implies a lack of photons able to produce N V and O VI.

The equilibrium was evaluated for all ionization stages of interest for the elements H, He, C, N, O, and Si where sources of atomic data and atomic processes (photoionization, radiative recombination, and charge transfer) were cited in Black *et al.* (1980). Charge transfer with hydrogen was included for all stages of nitrogen using rates of Butler and Raymond (1980), and rates for low-temperature dielectronic recombination were incor-

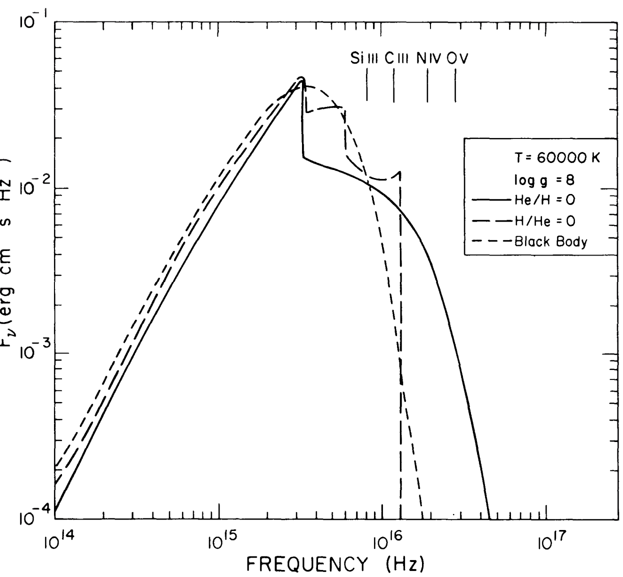

FIG. 1.—Two theoretical flux distributions from white dwarf model atmospheres as calculated by Wesemael *et al.* (1980) and Wesemael (1981).The photoionization edges of Si III, C III, N IV, and O V occur between 33 and 113 eV (375–110 Å) and are marked. A 60,000 K blackbody curve is also shown.

TABLE 1

INTERSTELLAR COLUMN DENSITIES[a] FROM A HYDROGEN MODEL
(White Dwarf: T = 60,000 K; log g = 8.0)

	n_H (cm^{-3})				
SPECIES	0.01	0.1	1	10	10^2
H I..........	6.6(+15)	2.0(+16)	5.5(+16)	1.3(+17)	2.8(+17)
He I	4.0(+14)	1.2(+15)	3.2(+15)	7.0(+15)	1.3(+16)
He II	1.0(+16)	3.2(+16)	9.1(+16)	2.4(+17)	5.6(+17)
C IV	7.8(+12)	2.5(+13)	7.7(+13)	2.4(+14)	7.5(+14)
Si IV	4.4(+11)	1.4(+12)	4.4(+12)	1.4(+13)	4.3(+13)
N V	1.2(+12)	3.7(+12)	1.2(+13)	3.8(+13)	1.2(+14)
O VI	1.4(+12)	5.6(+12)	2.0(+13)	6.5(+13)	2.1(+14)
r_{tr} (pc)[b] ...	6.8	2.1	0.63	0.18	0.05
r_S (pc)[c] ...	30.8	6.6	1.43	0.31	0.07

[a]At transition region.
[b]Radius of transition region where the fraction of neutral hydrogen is 10%.
[c]Strömgren radius.

porated from Storey (1981); solar abundances (Withbroe 1971) were assumed. The abundance of each species is computed as a function of distance from the white dwarf by assuming balance between the rates of photoionization, radiative and dielectronic recombination, and charge transfer at each point. Attenuation of the ionizing radiation by H and He with distance from the source is included; diffuse radiation in the nebula is not considered. The column density of each species is evaluated and given in Tables 1 and 2 for models of hydrogen-rich and helium-rich objects. Highly ionized species of interest lie within the tabulated transition region radius, r_{tr} (pc).

The hydrogen-rich model atmosphere produces species of higher ionization state than those produced by the helium-rich models; the relative ionization of high species increases with the temperature of the source. For a given stellar model, the ionic concentrations are similar, although the column density depends upon the value of the assumed hydrogen density. Trace abundances of heavy elements would modify the emergent spectrum, but such models have not been published; intermediate ionization fractions would be expected.

III. COMPARISON WITH OBSERVATIONS

Four hot white dwarfs have been observed at high resolution with the *IUE*. Feige 24 showed low-velocity interstellar components of log C IV > 13.4 (cm^{-2}) and log Si IV ≳ 12.7 (cm^{-2}) (Dupree and Raymond 1982),

TABLE 2

INTERSTELLAR COLUMN DENSITIES[a] FROM A HELIUM MODEL
(White Dwarf: T = 60,000 K; log g = 8.0)

	n_H (cm^{-3})				
SPECIES	0.01	0.1	1	10	10^2
H I	1.0(+16)	2.8(+16)	7.4(+16)	1.7(+17)	3.2(+17)
He I	1.3(+15)	3.6(+15)	9.3(+15)	2.1(+16)	3.6(+16)
He II	2.6(+16)	7.9(+16)	2.3(+17)	6.3(+17)	1.6(+18)
C IV	1.2(+13)	3.8(+13)	1.2(+14)	4.0(+14)	1.3(+15)
Si IV	8.0(+11)	2.5(+12)	8.0(+12)	2.5(+13)	7.9(+13)
N V	1.4(+07)	6.9(+07)	3.4(+08)	1.6(+09)	7.6(+09)
O VI	4.0(−03)	8.4(−02)	1.7(+00)	3.3(+01)	5.7(+02)
r_{tr} (pc) ...	9.59	2.88	0.84	0.230	0.057
r_S (pc) ...	34.25	7.38	1.59	0.342	0.074

[a]At transition region.

and an upper limit to the equivalent width of N V (25 mÅ) corresponding to log N V < 13.1. Results in Table 2 show that column densities in this range can be achieved for hydrogen densities of 0.1 (cm^{-3}) or larger. A model more specific to Feige 24 with $R_* = 0.0239\ R_\odot$ (Shipman 1979) yields log C IV (cm^{-2}) of 13.66 and 13.78 for T_e = 60,000 K and 70,000 K, respectively, with $n_H = 0.1$ cm^{-3}, in satisfactory agreement with observations. The Si IV column density is predicted as 12.42 dex or 12.51 dex for models of 60,000 K and 70,000 K, respectively, for $n_H = 0.1$ cm^{-3}; these values are low, but commensurate with the observed values considering the noisy spectrum. The column density of N V is predicted to equal 12.8 dex and 13.0 dex for the same conditions; these values are consistent with the observed upper limit.

Another hot, hydrogen-rich white dwarf, G191 − B2B possesses sharp resonance absorption lines of N V, C IV, and Si IV in its ultraviolet spectrum which Bruhweiler and Kondo (1981) have assigned to an expanding wind around the white dwarf. The observed minimum column densities (cm^{-2}), 12.95 dex, 13.66 dex, and 13.59 dex for Si IV, C IV, and N V, respectively, agree with the calculated values in Table 1 for densities n_H (cm^{-3}) between 0.1 and 1; values of the column density derived from the doublet ratio are 2–5 times higher requiring higher cloud densities $n_H \sim 10$ cm^{-3}.

HZ 43 is a hot white dwarf classified optically as hydrogen-rich. It displays no high-temperature species to an upper limit of 50 mÅ for each transition (Malina, Basri, and Bowyer 1981). Translating this into column densities on the linear part of the curve of growth, we find upper limits (cm^{-2}) for C IV, Si IV, and N V of 13.08 dex, 13.04 dex, and 13.38 dex respectively. For a hydrogen model atmosphere at 60,000 K as a photoionizing source, these values suggest a region with $n_H <$ 0.03 cm^{-3}. EUV spectrophotometry of HZ 43 by Malina, Bowyer, and Basri (1982) may show a helium absorption edge at λ225 which, if interstellar, requires a He II column density (cm^{-2}) of 17.4–17.8 dex. This density is higher by an order of magnitude than the value we predict in a photoionized region. Alternately, if the He II absorption is a stellar feature, and there is a trace amount of helium in the photosphere, the far-ultraviolet flux from the white dwarf will be decreased over a pure hydrogen model. With appropriate models, the interstellar absorption spectrum might be used to probe the stellar EUV radiation field. Trace abundances of helium were found for several other DA white dwarfs by Kahn *et al.* (1984). Calculations for a pure helium model (Table 2) are an extreme case, but show the requisite observed upper limit of C IV for $n_H < 0.01$ cm^{-3}; the absence of Si IV and N V also agrees with our calculations.

Sion and Guinan (1983), observing the helium-rich white dwarf, HD 149499B, found sharp absorption lines of C IV, but none from N V or Si IV. They concluded that the C IV is of photospheric origin, an argument based on its velocity coincidence with He II (λ1640) and separation of 23 ± 8 km s^{-1} from interstellar species of low excitation. The velocity separation might conceivably be explained by the dispersion among individual cloud velocities or by expansion of gas heated by the white dwarf. Our calculations for a helium-rich model (Table 2) show that the observed column densities (cm^{-2}) of C IV (> 13.3 dex), Si IV (< 12.64 dex), and N V (< 12.99 dex) can be produced by photoionization of an interstellar region of 3 pc radius, around the white dwarf, with a hydrogen density between 0.03 and 0.3 cm^{-3}.

Hot white dwarfs produce substantial radiation at frequencies that photoionize highly ionized interstellar species. Provided that these hot stars are embedded in a sufficient amount of warm interstellar material, they can account for the existing detection, or absence, of highly ionized species. The lack of C IV absorption in a hot white dwarf spectrum implies a very low density medium within a few parsecs of the white dwarf, presumably the

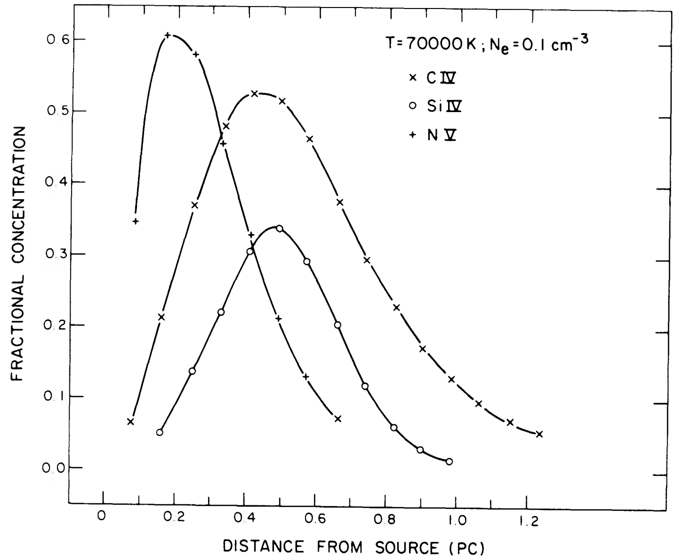

FIG. 2.—Fractional concentration of highly ionized species in the Strömgren sphere around a hydrogen-rich white dwarf with $R = 0.0127$ $R_{\odot}$. The Strömgren radius is 8.2 pc.

hot, low-density gas inferred from X-ray and O VI observations.

IV. EFFECTS OF WHITE DWARF IONIZATION

a) *Local Strömgren Spheres*

A single white dwarf can form an ionization bubble in its immediate surroundings (Fig. 2). Highly ionized species are closest to the source, but the hydrogen ionization zone (the Strömgren radius) extends to 8 pc. Since many hot white dwarfs are nearby, the apparent size of an ionization bubble can be large (diameter ~ 2°), and stars located behind the photoionized regions may exhibit C IV and Si IV absorption lines.

Optical identification of the discrete ionized regions associated with white dwarfs might be accomplished through their Hα emission signature since sufficient emission measure can exist for detection. For Feige 24, the radius of the fully ionized region (the transition zone radius) is 4.5 or 1.3 pc for electron densities of 0.1–1 cm^{-3} respectively. This yields a central emission measure of 0.1 or 2.7 pc cm^{-6}; the high-resolution measurements of Reynolds (1980) are sensitive to 1–2 pc cm^{-6}—making a detection or even an upper limit possible to constrain the value of the interstellar density close to the white dwarf. Durisen *et al.* (1976) previously speculated on such a region for HZ 43.

b) *Galactic Contribution*

i) *Total Ionizing Flux*

The space density of hot white dwarfs is estimated to be from 1.2×10^{-5} pc^{-3} (Koester 1978) to 3×10^{-4} pc^{-3} (Green 1980). They are clearly more abundant than other distributed sources of ionizing ultraviolet radiation such as O and B stars (5.2×10^{-6} pc^{-3}, Torres-Peimbert, Lazcano-Araujo, and Peimbert 1974), planetary nebulae (~ 5×10^{-8} pc^{-3}, Cahn and Kaler 1971), and cataclysmic variables ($1\text{–}7 \times 10^{-6}$ pc^{-3}, Lamb 1981). In addition, the hydrogen-ionizing photon production of white dwarfs rivals that of supernova explosions and their subsequent radiation, which are currently thought to provide much of the ionization in the interstellar medium.

About 30% of the kinetic energy of a Type II supernova eventually emerges as photons with energies greater than 13 eV (Chevalier, as quoted by McKee and Ostriker 1977). Thus for a total kinetic energy of 5×10^{50} ergs, the contribution of supernovae to the galactic ultraviolet is approximately 1.5×10^{50} ergs per 65–130 years depending on the estimate of the supernova frequency (Cox 1981). The ionizing flux provided by hot white dwarfs is evaluated by using Koester's (1978) semi-empirical spatial frequency, hydrogen-rich models of Wesemael *et al.* (1980), the mean radius of Shipman (1979), a scale height of 250 pc (Green 1980), and a galactic volume of $\pi(15 \text{ kpc})^2 \times 500$ pc. Depending on the amount of neutrino cooling (Koester 1978), the ionizing energy input by white dwarfs is $0.35\text{–}1.1 \times 10^{50}$ ergs in a 65 year interval, or $0.75\text{–}2 \times 10^{50}$ ergs in 130 years. These values are clearly commensurate with the supernova value in the galactic plane.

ii) *Distributed Ion Species*

Ionized hydrogen (Reynolds 1977, 1980) and highly ionized species of O VI and C IV are now thought to pervade the Galaxy (Jenkins 1978; Cowie, Taylor, and York 1981), and the contribution of white dwarfs to these measures can be estimated. Electron column densities are evaluated from the column density of H^+ in our models by taking the Strömgren sphere appropriate for each $T_{\rm eff}$ and using the spatial frequencies of Koester (1978). Values of 0.2–0.5 pc $\rm cm^{-6}$ result for a 1 kpc path length. Inclusion of diffuse radiation in the models would nearly double those values. Reynolds (1977, 1981) measures 1–2 $\rm cm^{-6}$ pc toward the galactic pole.

The contribution of stars of space density $n_{\rm WD}$ ($\rm pc^{-3}$) for a given $T_{\rm eff}$ to the column density of an ionized species is: $2N \times (n_{\rm WD} \times L \times \pi r^2)$, where N ($\rm cm^{-2}$) is the column density of the species toward the source, L (pc) is the path length, and r (pc) is the radius of the transition region within which the ionized species occur. The quantities are evaluated for stars of a given effective temperature and then summed over all effective temperatures for hydrogen-rich white dwarfs. The predicted C IV column density ranges from 2 to 6×10^{13} ($\rm cm^{-2}$) for $n_{\rm H} = 0.01$ and $0.5\text{–}2 \times 10^{13}$ ($\rm cm^{-2}$) for $n_{\rm H} = 0.1$. These values are higher than the column density of 6×10^{12} ($\rm cm^{-2}$) inferred by Cowie *et al.* (1981) for a 1 kpc path length in the distributed C IV background.

An alternate calculation can be made by evaluating the probability of intersecting a chord of an appropriate ionization sphere along a line of sight and then computing the total column density for white dwarfs of all temperatures at an interstellar density of 0.1 $\rm cm^{-3}$. This gives a 15% chance of a 1 kpc line of sight having a C IV column density greater than 10^{11} $\rm cm^{-2}$. If the filling factor for warm, low-density gas is 40% (McKee and Ostriker 1977), then our estimate should be lowered; however, the extended trails, discussed in § IV*b* (iii), may well compensate.

An O VI column density of $1.3\text{–}5.4 \times 10^{12}$ $\rm cm^{-2}$ results for a 1 kpc path length in an ambient hydrogen density of 0.1 $\rm cm^{-3}$; higher values, $4.6\text{–}14 \times 10^{12}$, occur in a lower density (0.01 $\rm cm^{-3}$) medium. These predicted values are lower by an order of magnitude than the column density of 6×10^{13} ($\rm cm^{-2}$) found for O VI over a distance of 1 kpc (Jenkins 1978).

A static model of white dwarf photoionization appears able to account for the distributed sources of Hα and C IV, but an additional source of ionization is required for O VI.

iii) *Fossil Strömgren Trails (FSTs)*

The recombination time for highly ionized species such as C IV is long (~ 10^5 yr) at a density of 0.1 $\rm cm^{-3}$. Hydrogen and lowly ionized species recombine more slowly (~ 10^6 yr), so these ions will be present after the disappearance of the more highly ionized species. In addition, the space velocities of white dwarfs are generally high (~ 30 km $\rm s^{-1}$). Thus a remnant region of ionization could exist in the interstellar medium tracing the path of the star in space. These fossil Strömgren trails (FSTs) would create a patchy substrate of ionized material. Since many hot white dwarfs are nearby, the apparent extent of the FSTs can be substantial. In 10^6 years, Feige 24, which has an annual proper motion of 0$''$.084, leaves a trail of approximately 20° in length. Such estimates depend not only on our uncertain knowledge of the interstellar density but also on the recombination rate coefficients. If sufficient neutral hydrogen is present, charge exchange can rapidly destroy C IV. Recombination time scales of 10^6 years are commensurate with white dwarf cooling time scales (Koester 1978), suggesting that even a (now) cool white dwarf could exhibit an FST. Details of the recombination should be evaluated in a time-dependent situation.

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