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THE FIRST DETECTION OF IONIZED HELIUM IN THE LOCAL ISM: *EUVE* AND *IUE* SPECTROSCOPY OF THE HOT DA WHITE DWARF GD 246

STÉPHANE VENNES,[1,2] JEAN DUPUIS,[1] TODD RUMPH,[3] JEREMY DRAKE,[1] AND STUART BOWYER[1,2,3]
Center for EUV Astrophysics, 2150 Kittredge Street, University of California at Berkeley, Berkeley, CA 94720

AND

PIERRE CHAYER[1,2] AND GILLES FONTAINE[1]
Département de Physique, Université de Montréal, CP 6128, Montréal, PQ, Canada, H3C 3J7
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ABSTRACT

We report observations of the extreme ultraviolet spectrum of the hot degenerate star GD 246 (WD 2309+105) obtained with the *Extreme Ultraviolet Explorer* (*EUVE*). Our initial attempt at modeling the photospheric emission from the white dwarf reveals a relatively uncontaminated pure H spectrum in the range $\lambda \geq 200$ Å, allowing a study of interstellar continuum absorption features in the line of sight of GD 246. Modeling of the He I autoionization transition (~ 206 Å) discussed by Rumph, Bowyer, & Vennes (1993), and the EUV continuum ($200 \leq \lambda \leq 260$ Å) using the white dwarf as a source of background radiation provides measurements of both neutral and, for the first time, *singly ionized* He column densities in the local interstellar medium (LISM). We estimate the He ionization fraction He II/(He I + He II) $\approx 25\%$ with a total He column of $1.40\text{–}1.65 \times 10^{18}$ cm^{-2}. We have measured and compared H I column densities from the saturated Lyα ISM absorption in *IUE* high-dispersion spectroscopy and from EUV continuum absorption: the two measurements are in good agreement with a total H column of $1.2\text{–}1.6 \times 10^{19}$ cm^{-2}. We discuss some implications for the nature of the LISM, particularly in the context of current models of the EUV radiation field.

Subject headings: ISM: abundances — ISM: structure — ultraviolet: stars — white dwarfs

1. INTRODUCTION

Extreme ultraviolet (EUV, loosely defined as the range $100 \leq \lambda \leq 911$ Å) astronomy will play an essential role in the study of hot white dwarf stars. In the EUV wavelength regime, hot white dwarfs exhibit numerous heavy element spectral features which can provide powerful diagnostics for their temperatures, surface gravities, and chemical compositions. EUV spectroscopy of white dwarfs was pioneered with an observation of HZ 43 obtained during a sounding rocket flight (Malina, Bowyer, & Basri 1982), and later with *EXOSAT* (HZ 43, Feige 24, and Sirius B; Paerels et al. 1986a; Paerels et al. 1986b; Paerels et al. 1988), and with *Voyager* (G191-B2B, GD 153, and HZ 43; Holberg 1984). EUV all-sky surveys by the *Extreme Ultraviolet Explorer* (*EUVE*) (Bowyer & Malina 1991) and the *ROSAT* Wide Field Camera (WFC) (e.g., Pounds et al. 1993) now offer a wealth of photometric information about the hot end of the white dwarf luminosity function. However, the interpretation of EUV spectra and photometry is intimately related to our currently rather uncertain understanding of the local interstellar medium (LISM). Indeed, various interpretations of *EXOSAT* photometry of hot white dwarf stars (Jordan et al. 1987; Paerels & Heise 1989; Koester 1989; Vennes 1992; Vennes & Fontaine 1992) illustrated the important, but potentially confusing, effect of ISM absorption.

The properties of the LISM are still largely unknown. Cox & Reynolds (1987) review the evidence that the Sun is embedded within a cooler ($T \approx 10^4$), predominantly neutral, and denser [n(H I) ≈ 0.1 cm^{-3}] medium (the "local fluff"), which is surrounded by a hot ($T \approx 10^6$) and tenuous [n(H) ≈ 0.001 cm^{-3}] medium. The local fluff is generally believed to extend in various directions up to a few parsecs, or $n_H \approx 1\text{–}2 \times 10^{18}$ (Bruhweiler & Vidal-Madjar 1987)[4]. Of major significance is the fractional ionization of H and He. The detailed analysis of backscattered solar emission lines by Bertaux et al. (1985) favored, with some equivocation, significant H ionization relative to He in the local fluf—a result which could not be reconciled with the estimated stellar (Reynolds 1986; Bruhweiler & Cheng 1988) or evaporative boundary layer (Slavin 1989) contributions to the ionizing EUV radiation field. After including the effects of the surrounding hot interstellar substrata, Cheng & Bruhweiler (1990) predicted an integrated ionization fraction of $X_H \approx 17\%$ and $X_{He} \approx 30\%$. The first spectroscopic measurement of both H I and He I columns was made with a sounding rocket experiment conducted by Green, Jelinsky, & Bowyer (1990), who refuted suggestions for partial ionization of either H or He in the line of sight of the DA white dwarf G191-B2B. The recent *Hopkins Ultraviolet Telescope* (*HUT*) observations of this object (Kimble et al. 1993) seemed to favor partial ionization of He relative to H, in possible agreement with the Cheng & Bruhweiler (1990) model predictions. However, their measurement is based solely on the ratio of He I to H I, and the ionization ratio determined for each element was *model-dependent*.

The more comprehensive wavelength coverage of the *EUVE* offers the capability of *direct*, model-independent measurement of both neutral and ionized He columns. Our program of EUV spectroscopic investigations of white dwarf stars offers, then, a unique opportunity to probe the nature of the LISM. In this *Letter*, we present spectroscopic observations of the hot DA

[1] Guest Observer, NASA *Extreme Ultraviolet Explorer*.
[2] Guest Observer, NASA *International Ultraviolet Explorer*.
[3] Also with the Astronomy Department, University of California at Berkeley.

[4] In the following, column density units are assumed to be cm^{-2}.

white dwarf GD 246 (WD 2309+105) obtained with the *Extreme Ultraviolet Explorer* (§ 2). We present in § 3.1 our preliminary model atmosphere interpretation of the EUV spectrum of this object and our measurements of He and H absorption in the LISM. We establish that a clear distinction can be made between photospheric and ISM He absorption features in white dwarf spectra. In so doing, we present the first direct evidence for substantial ionization of He in the LISM. We complete our analysis of H I absorption in the LISM using *IUE* high-dispersion spectroscopy of the Lyα range (§ 3.2). Finally, we discuss briefly the implications of these observations for the LISM structure itself and for the study of hot white dwarf stars (§ 4).

2. EXTREME ULTRAVIOLET OBSERVATIONS

The hot DA white dwarf GD 246 (Giclas, Burnham, & Thomas 1965) is among the brightest objects of its class, and it was a logical candidate for detection at short wavelengths. The first detections in that range were made with the High Resolution Imager (HRI) of the *Einstein Observatory* (Petre, Shipman, & Canizares 1983, 1986) and with the Low Energy (LE) telescope of the *EXOSAT Observatory* (Heise 1985; Paerels & Heise 1989). Holberg, Wesemael, & Basile (1986) determined its effective temperature and gravity by using a model atmosphere simulation of Lyα absorption and *IUE* low-dispersion observations; they found $T_{\rm eff} = 53{,}600 \pm 2940$ K, and $\log g = 7.64 \pm 0.45$. Trace elements were convincingly detected in *EXOSAT* photometric measurements through an important EUV/soft X-ray flux deficiency (see Vennes & Fontaine 1992). The DA star GD 246 is among the brightest objects detected in the *EUVE* and *ROSAT* WFC all-sky surveys and is consequently one of the prime targets of investigation with the *EUVE* spectrometers.

EUVE incorporates three spectrometers (Bowyer & Malina 1991) covering essentially the entire extreme ultraviolet range in their respective first-order ranges: 70–190 Å (short-wavelength, SW), 140–380 Å (medium-wavelength, MW), and 280–760 Å (long-wavelength, LW). GD 246 was observed with *EUVE* in pointed mode during calibration periods from 1992 August 19 to August 21 and from 1992 September 27 to September 28. It was detected in all three spectrometers with effective exposure times of 104,102 s (SW), 84,475 s (MW), and 104,102 s (LW). However, the LW detection is entirely the result of second- and third-order overlaps. The August 19 spectrum in raw units can be obtained through the *EUVE* Public Archive releases. The spectra were extracted with the EUVE Guest Observer Center Software (EGOCS) developed within the IRAF environment. They are background-subtracted and corrected for spacecraft aspect. The Al edge of the MW Al/C filter near 170.2 Å (Vallerga, Vedder, & Siegmund 1992) provides an accurate marker for the MW scale. The wavelength solution from the preflight calibration was corrected for small residual errors relative to the filter Al edge (-2.9 and -0.4 Å, respectively) before we co-added the spectra.

We present in Figure 1 the MW co-added spectrum in units of flux (photons cm^{-2} s^{-1} Å^{-1}) versus wavelength (Å) together with a model appropriate to GD 246 (§ 3). Because in this particular observation the MW spectral range is essentially free from higher order contaminations, we simply divided the raw spectrum by the preflight calibration effective areas and by the effective exposure times. The spectrum clearly displays the autoionization resonance feature of He I near 206 Å discussed in Rumph et al. (1993) as well as what appears to be a photo-

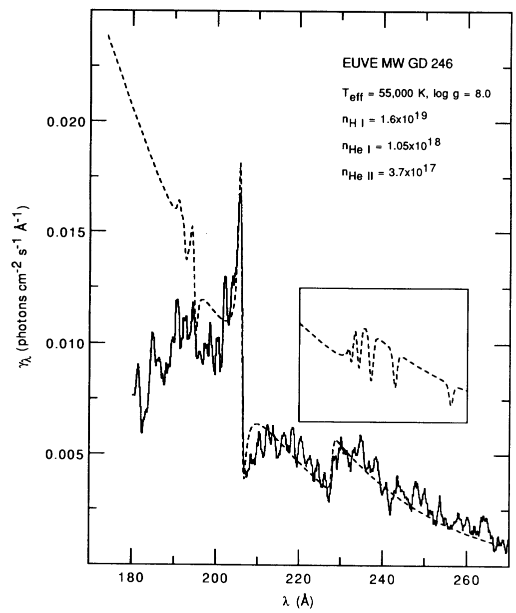

FIG. 1.—Pure H synthetic spectrum adjusted to the observed EUV spectrum of GD 246 in the range $\lambda \geq 200$ Å (see § 3.1). *Inset:* Synthetic spectrum with a trace abundance of helium (He/H $= 2 \times 10^{-5}$) illustrating pressure broadening effects near the He II series limit in a model atmosphere.

ionization edge near 227–228 Å, which is most likely attributable to He II. The features at 206 Å and particularly at 227 Å were not detected in other calibration spectra with comparable signal-to-noise ratios; they are intrinsic to the source GD 246. These two spectral features provide the tools for the first direct measurement of the He ionization fraction in the LISM. We note the presence of complex features in the range $\lambda \leq 200$ Å that are probably due to photospheric heavy elements with $Z \geq 6$ which suggests some similarity with the *EXOSAT* EUV spectrum of Feige 24 (Paerels et al. 1986b; Vennes et al. 1989). This could constitute a *direct* and *unambiguous* evidence of the role played by radiative support of heavy elements in the photospheres of hot DA white dwarfs; this aspect of these observations will be discussed in a forthcoming publication.

3. PHOTOSPHERIC EMISSION AND INTERSTELLAR ABSORPTION

We model the far-UV (FUV) and EUV spectrum of GD 246 using a grid of model atmospheres developed for the study of H-rich white dwarfs in the optical, ultraviolet, and X-ray spectral ranges. The grid covers a range of effective temperature of $18{,}000 \leq T_{\rm eff} \leq 65{,}000$ K, a range of gravity of $7 \leq \log g \leq 9$, and various chemical compositions. In the present work we assume a pure H composition and then explore the effect of a trace abundance of He in the EUV spectrum. These restrictions will be relaxed after a comprehensive analysis of our new *IUE* and *EUVE* spectroscopy has been completed.

We adopt for the current analysis a reference model appropriate for the entire EUV and FUV spectral range with the following characteristics: $T_{\rm eff} = 55{,}000$ K, $\log g = 8.0$, and a pure H composition. This model is particularly appropriate to simulate the photospheric Lyα absorption (§ 3.2). We have determined that variations of surface gravity in the range $7.0 \leq \log g < 9.0$ have little influence on the predicted EUV flux for $\lambda \geq 200$ Å (§ 3.1). All models are normalized at $m_V = 13.07$.

3.1. *Modeling of the EUV Spectrum of GD 246*

Looking again at Figure 1, one can see that the He I autoionization transition at 206 Å and the He II photoionization edge at 227 Å clearly stand out. The pure H model is inappropriate for $\lambda \leq 200$ Å because it does not include photospheric heavy elements, but this does not affect our analysis of ISM features. We first model the shape of the He I autoionization transition, using the cross section ($\sigma_{\rm He\,I}$) provided by Rumph, Bowyer, & Vennes (1993), by adjusting two parameters, the He I column ($n_{\rm He\,I}$) and a normalization factor (A), in the function

$$Ae^{-n_{\rm He\,I}\sigma_{\rm He\,I}} . \qquad (1)$$

We have determined that the dominant source of errors is the choice of the width of the spectral resolution function. Allowing the FWHM to vary between 0.7 and 1.0 Å, we obtain $n_{\rm He\,I} = 1.05\text{–}1.25 \times 10^{18}$. An additional uncertainty may arise from spectral lines from heavy elements which could possibly blend with the He I autoionization transition. The depth of the He II photoionization edge is not subject to such errors because it is derived from a much wider spectral range and it is independent of spectral resolution. Because He II would be the dominant He ion in the high-temperature photosphere of GD 246, we have considered the possibility that photospheric He could be responsible for this feature. However, after the He II ground state line series is modeled with the Inglis-Teller formalism to correctly describe the convergence of the series, it is clear that *no edge* would have been detected, but instead a line series converging in a pseudo-continuum near 232 Å would be observed (see Fig. 1, *inset*). In general, the representation of a photoionization edge is not a correct physical description in a white dwarf photosphere (see Vennes 1992, Fig. 1). We conclude that the He II edge arises entirely from the ISM and we obtain $n_{\rm He\,II} = 3.5\text{–}4.0 \times 10^{17}$. Finally, we have used the *absolute* flux level in the range 230–260 Å from our reference model and a fixed He I column to estimate the H I column. By increasing $n_{\rm He\,I}$ from 1.05×10^{18} to 1.25×10^{18} we find that the corresponding H column $n_{\rm H\,I}$ decreases from 1.60×10^{19} to 1.25×10^{19}. This H I column measurement should be contrasted with our analysis of Lyα absorption in the ISM presented in § 3.2. We illustrate in Figure 1 one acceptable solution with the following parameters: $T_{\rm eff} = 55{,}000$ K, $\log g = 8.0$, $n_{\rm H\,I} = 1.60 \times 10^{19}$, $n_{\rm He\,I} = 1.05 \times 10^{18}$, and $n_{\rm He\,II} = 3.7 \times 10^{17}$.

3.2. Lyα *Absorption in the LISM*

The broad unsaturated Lyα absorption in a very hot ($T_e \geq$ 40,000–50,000 K) H-rich white dwarf photosphere provides a quasi-featureless background source of radiation for measurements of Lyα ISM absorption. Low-resolution ultraviolet spectroscopy with *IUE* ($\Delta = 6$ Å resolution) blends the ISM and photospheric components and does not allow a clear separation of their respective effects. To remedy this situation, we have acquired four well-exposed *IUE* high-dispersion spectra of GD 246 on (UT) 1992 December 20, 21, 22 and 1993 January 13 (SWP 46544, 46546, 46560, 46723). All four spectra were co-added, for a total exposure time of 26 hr 5 minutes, with the RDAF software from Goddard Space Flight Center (cf. *IUE* RDAF User's Tutorial Manual, version 7.2). The geocoronal emission lies well within the saturated line core and was simply removed. We show in Figure 2 the resulting spectrum (smoothed with a four-point boxcar) with the best model

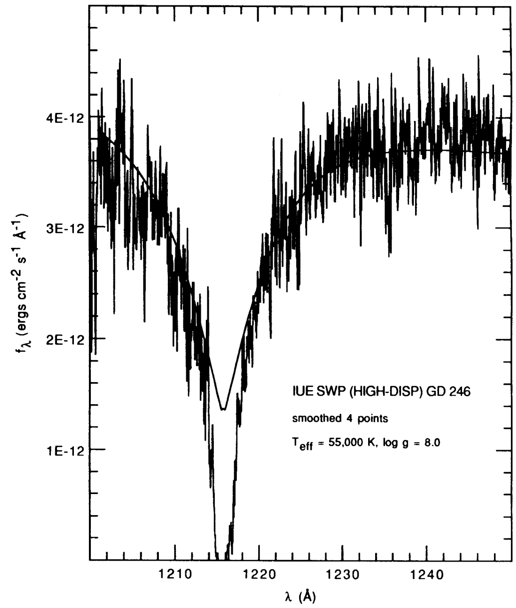

FIG. 2.—High-dispersion (*IUE*) FUV spectrum of GD 246 near Lyα, with a synthetic spectrum adjusted to the photospheric Lyα wings in GD 246, emphasizing the presence of a saturated ISM absorption core (see § 3.2).

fit to the Lyα wings excluding the line core ($T_{\rm eff} = 55{,}000$ K, $\log g = 8.0$). Clearly, the saturated Lyα core originates in the LISM. We have measured the equivalent width of the feature from the normalized ISM Lyα profile; this profile was obtained by dividing the measured spectrum by the model. The error in the equivalent width is dominated by uncertainty in the stellar flux close to the line center. The wings of the geocoronal Lyα emission partly contaminated the line core; and the background-subtraction algorithm, performed with the standard extraction, produces negative flux near the rapidly rising emission feature. By varying the degree of correction applied to the line core flux, we conservatively estimate the ISM Lyα equivalent width to be in the range $W_{\rm Ly\alpha\,ISM} = 2.5\text{–}3.1$ Å. Such a strong line develops in the square-root part of the curve of growth, and we follow a methodology developed in early sounding rocket measurements of Lyα absorption in the ISM (Morton 1967; Carruthers 1969) in which the relationship between Lyα equivalent width and H I column density is given by

$$W_{\rm Ly\alpha\,ISM} = 7.3 \times 10^{-10} n_{\rm H\,I}^{1/2} . \qquad (2)$$

This leads to our value of the H I column density in the line of sight of GD 246, measured with *IUE*, of $n_{\rm H\,I\,ISM} = 1.2\text{–}1.8 \times 10^{19}$.

4. THE HELIUM AND HYDROGEN IONIZATION FRACTIONS IN THE LISM

We have established, with a study of extreme ultraviolet spectroscopy of a hot white dwarf star, the presence of singly ionized He in the LISM. The He ionization fraction, using our He I and He II column density measurements, is $f_{\rm He} =$ 23%–26%. If we use the total He column derived from our results ($n_{\rm He} = 1.40\text{–}1.65 \times 10^{18}$) to scale the total H column, assuming the cosmic abundance ratio H/He = 10, we obtain $n_{\rm H} = 1.40\text{–}1.65 \times 10^{19}$. Using the smallest value of $n_{\rm H\,I}$ measured with *IUE* and *EUVE* spectroscopy (1.2×10^{19}), in combination with the largest value for the total H column n_H cited above (1.65×10^{19}), we obtain an upper limit to the H ionization fraction of $f_H < 27\%$. We emphasize that this value relies heavily on the knowledge of the cosmic abundance ratio H/He.

What is the spatial distribution of the gas probed in the line of sight of the white dwarf GD 246? The photometric distance of this object is 65 ± 10 pc, and it lies midway to the south Galactic pole ($l \approx 88°$, $b \approx -44°$). Limited data suggest that neutral hydrogen is abundant at this Galactic longitude and a distance of 65 pc (see Paresce 1984). It is very likely that GD 246's line of sight intercepts a complex of several dense structures neighboring the local fluff and we may have established only their average properties. The study of closer EUV sources would help determine the distances and individual properties of these structures.

We may speculate about the morphology of the various structures in the line of sight of GD 246. They may be, for instance, similar in size and density to the local fluff with similar contribution to the integrated H and He ionization fractions. If, as suggested by Bruhweiler & Vidal-Madjar (1987), the total H column density of the local fluff is $1\text{–}2 \times 10^{18}$, it is largely transparent to EUV radiation in the He I continuum and we should expect the He ionization fraction to be fairly homogeneous. This suggests another experiment which would consist of comparing the He ionization fraction in different lines of sight. While we await additional data from *EUVE*, we may compare our results with the only other measurement available, the line of sight of G191-B2B (Green et al. 1990; Kimble et al. 1993). Kimble et al. quote an upper limit to the He ionization fraction, 30%, which is consistent with our measurement from GD 246 data. Substantial ionization of He may be a global property of the LISM. Lacking a firm measurement of the total H column, we cannot rule out the existence of a similar level of H ionization. However, the EUV flux in the LISM is believed to be orders of magnitude fainter in the H continuum than required to produce significant H ionization in the local fluff (Reynolds 1986) and, by extension, in similar structures. The identification of several hundred EUV sources in the LISM with the *EUVE* and *ROSAT* WFC all-sky surveys may alter this picture considerably. A number of sources were found to be much brighter than HZ 43 in the H I continuum and may modify the H ionization balance toward H II.

Is the presence of He II in the line of sight of GD 246 linked to the presence of C IV in the line of sight of Feige 24 (Dupree & Raymond 1982)? The C IV column density inferred from observations of the C IV doublet at 1550 Å in Feige 24 is $n_{C\,IV} > 4 \times 10^{13}$, implying that at least 5% of all carbon is found in the C IV state. The original assessment of Dupree & Raymond led to the conclusion that C IV is photoionized in a circumstellar shell excited by EUV radiation from Feige 24. Dupree & Raymond (1983) estimated that a DA white dwarf (T_{eff} = 60,000 K, $\log g = 8$) surrounded by a dense circumstellar shell [n(H) = 10 cm^{-3}] generates a C IV column of 2.4×10^{14} and an He II column of 2.4×10^{17}, in qualitative agreement with Dupree & Raymond (1982) and the present measurements. GD 246 shares similar stellar properties with Feige 24, and both objects may be surrounded by dense circumstellar shells producing most of the ionic species observed. A study of possible interactions between mass loss and accretion flow suggests an even more complicated picture (MacDonald 1992). At this point we cannot discriminate between circumstellar material and LISM gas.

We conclude by noting that the interpretation of EUV/soft X-ray photometry of hot white dwarf stars should now take into account a variable ionization fraction of He in the LISM.

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