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DISCOVERY OF PHOTOSPHERIC HELIUM IN THE ULTRAMASSIVE DA WHITE DWARF GD 50[1]

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ABSTRACT

Extreme-ultraviolet (EUV) spectroscopy of the hot, hydrogen-rich white dwarf GD 50 reveals an unusual photospheric mixture of hydrogen and helium. This hot DA white dwarf is also remarkable for its mass ($\approx 1.2\ M_\odot$) near the Chandrasekhar limit. The spectra obtained with the *Extreme-Ultraviolet Explorer* (*EUVE*) show a prominent He II resonance line series and constrain its atmospheric parameters to $T_{\rm eff} = 40{,}300 \pm 100$ K and $n({\rm He})/n({\rm H}) = (2.4 \pm 0.1) \times 10^{-4}$ (assuming $\log g = 9.0$). We also constrain the local interstellar medium column densities of neutral helium and hydrogen to $n_{\rm He\,I} = 6 \times 10^{16}$ and $n_{\rm H\,I} = 9 \times 10^{17}$ cm^{-2}. The presence of helium in an isolated, massive DA white dwarf is paradoxical. We examine and rule out a couple of scenarios (radiative levitation, accretion from the ISM or a hypothetical companion), but we suggest that if massive white dwarfs do result from stellar mergers, large orbital angular momentum may be preserved and result in a large meridional circulation current, possibly dredging up helium from the envelope. Although we find evidence of large rotational velocity in EUV He II line profiles, we propose additional observational tests of the dredge-up model.

Subject headings: ISM: abundances — stars: abundances — stars: individual: GD 50 — ultraviolet: stars — white dwarfs

1. INTRODUCTION

The hot, hydrogen-rich white dwarf GD 50 (Giclas, Burnham, & Thomas 1965; Eggen 1968; Greenstein 1974) is one of the most massive of its class ($M = 1.2\ M_\odot$; Bergeron et al. 1991), and it was identified as a strong soft X-ray source during a pointed *Einstein* high-resolution imager (HRI) observation (Kahn et al. 1984). The HRI detection is consistent with thermal emission from deep, hot photospheric layers of a hydrogen-rich white dwarf. However, Kahn et al.'s and Vennes & Fontaine's (1992) analyses also show that for any reasonable upper limits ($n_{\rm H} \lesssim 10^{19}$ cm^{-2}) to the absorption in the local interstellar medium (ISM), the HRI count rate requires the presence of trace elements in the photosphere, a result confirmed using *ROSAT* data (Barstow et al. 1993). Diffusion theory in high-gravity atmospheres would predict no detectable traces of helium or heavier elements. For example, Vennes et al. (1988) conclude that the helium abundance in white dwarfs cooler than $\approx$40,000 K and with masses larger than 0.8 $M_\odot$ would not exceed 10^{-8}, and similarly Chayer, Fontaine, & Wesemael (1995) predict an abundance smaller than $\approx 10^{-8}$ for several heavier elements. Such low abundances leave virtually no spectroscopic traces in extreme-ultraviolet (EUV) or soft X-ray observations. The observed presence of trace contaminants in the high-gravity photosphere of GD 50 is peculiar, and the nature of these contaminants is unknown.

GD 50 was detected in the *Extreme-Ultraviolet Explorer* (*EUVE*) all-sky survey (=EUVE J0348−009; Bowyer et al. 1994), most surprisingly, in all four survey bandpasses between 100 and 600 Å. Detections at long wavelengths (>400 Å) impose remarkably low ISM hydrogen and helium column densities. Vennes et al. (1994) summarize the properties of the local ISM in the lines of sight of all objects detected in the 400 and 600 Å bandpasses and find that these detections impose a low neutral hydrogen column density of the order of $\approx 10^{18}$ cm^{-2}. Clearly, EUV spectroscopic observations are necessary to determine the nature of GD 50's peculiar atmosphere. In § 2 we describe *EUVE* survey and spectroscopic observations. We present a detailed LTE and non-LTE (NLTE) model atmosphere analysis in § 3. Finally, we discuss the results in § 4, and we propose additional observations required to solve GD 50's mysteries.

2. EUV PHOTOMETRY AND SPECTROSCOPY

The *EUVE* all-sky survey scanned the hot white dwarf GD 50 from 1992 August 14 through August 20. Bowyer et al. (1994) estimate count rates of $C_{100\,\text{Å}} = 0.41 \pm 0.02$, $C_{200\,\text{Å}} = 0.31 \pm 0.02$, $C_{400\,\text{Å}} = 0.22 \pm 0.02$, and $C_{600\,\text{Å}} = 0.51 \pm 0.04$ s^{-1}. As demonstrated by Vennes et al. (1994), instrumental effects render count rate extractions difficult for survey data in the 400 and 600 Å bandpasses, and corrections of +40% and +10% to the 400 and 600 Å count rates, respectively, are necessary. The adopted count rates are $C_{400\,\text{Å}} = 0.31 \pm 0.06$ and $C_{600\,\text{Å}} = 0.56 \pm 0.11$ s^{-1}. Following these detections, we scheduled *EUVE* spectroscopic observations of GD 50 between 1994 December 12 and 14. We obtained exposures of 69,635 s in the short-wavelength (SW; 70–170 Å), 67,042 s in the medium-wavelength (MW; 140–340 Å), and 63,486 s in the long-wavelength (LW; 280–680 Å) spectrometers. Details of the *EUVE* data reduction are given in Dupuis et al. (1995). We present in Figure 1 the *EUVE* spectrum between 80 and 540 Å. From this observation, the source of opacity detected with the *Einstein* HRI becomes quite evident.

3. MODEL ATMOSPHERE ANALYSIS

The EUV spectrum shows the prominent He II ground-state line series, presumably arising in GD 50's photosphere, and the He I photoionization edge from the ISM. Napiwotzki et al. (1993) show that NLTE effects in mixed hydrogen/helium white dwarf atmospheres are most notable in the He II EUV continuum. Therefore, we have computed a grid of NLTE H/He model atmospheres using an extended version of Mi-

[1] Based on observations obtained with NASA's *Extreme Ultraviolet Explorer*.

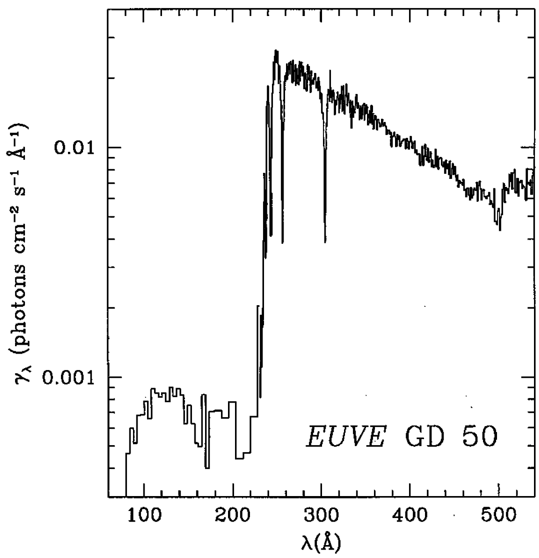

FIG. 1.—EUV spectroscopy of the hot DA white dwarf GD 50 in photons cm^{-2} s^{-1} Å^{-1} vs. wavelength (Å). Note the He II ground-state line series and the He I photoionization edge (see analysis in § 3). The flux scale is logarithmic. The data are binned to half a resolution element above 230 Å, and to improve signal-to-noise ratio the data are binned to seven resolution elements below 230 Å.

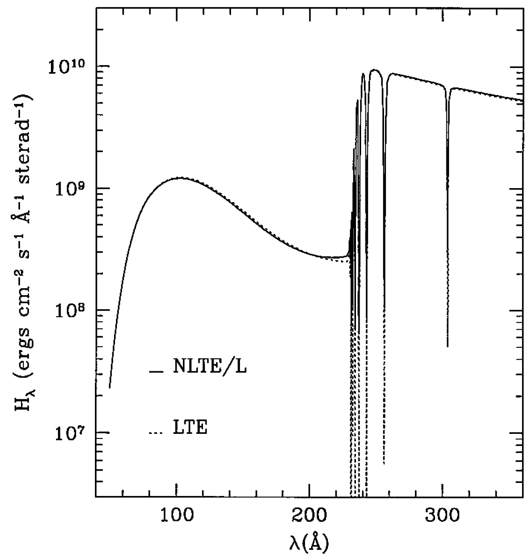

FIG. 2.—Comparison between LTE (*dotted line*) and NLTE (*solid line*) EUV spectral synthesis of a mixed hydrogen/helium model at $T_{\rm eff}$ = 40,300 K, log g = 9.0, and He/H = 2.4 × 10^{-4}. The simulation demonstrates the adequacy of the LTE assumption for GD 50's stellar parameters.

halas, Heasley, & Auer's (1975) NLTE model atmosphere code: both H I and He II statistical equilibria assume nine NLTE levels coupled by 36 line transitions described with Doppler profiles; neutral helium is approximated with two levels, and all continuum transitions are included. Schöning & Butler (1989) considered broadening parameters for the He II ground-state line series to be of no astrophysical interest; therefore, we used the approximate theory of Auer & Mihalas (1972) to compute detailed EUV synthetic spectra. The analysis of GD 50 constitutes the first description of the complete He II ground-state line series in an astrophysical plasma.

Preempting the results presented below, in Figure 2 we compare NLTE and LTE synthetic spectra at $T_{\rm eff}$ = 40,300 K, log g = 9, and He/H = 2.4 × 10^{-4}. The comparison shows that the He II ground-state departure from LTE is negligible, except for line cores, in high-mass white dwarfs similar to GD 50. We now analyze *EUVE* spectroscopic data using homogeneous LTE line-blanketed model atmospheres (see Vennes & Fontaine 1992). By fixing the surface gravity at log g = 9, we simultaneously constrain the effective temperature and the helium abundance, as well as the neutral helium and hydrogen column densities in the local ISM (formal error only):

$$\begin{aligned} T_{\rm eff} &= 40{,}300 \pm 100\ {\rm K}, \\ {\rm He/H} &= 2.4 \pm 0.1 \times 10^{-4}, \\ \log n_{\rm He\,I} &= 16.72 \pm 0.08, \\ \log n_{\rm H\,I} &= 17.94 \pm 0.02. \end{aligned} \tag{1}$$

These results are consistent with *EUVE* photometric measurements. Using the 400 and 600 Å bandpasses, we obtain (assuming log g = 9 and $n_{\rm He\,I}/n_{\rm H\,I}$ = 0.07)

$$\begin{aligned} T_{\rm eff} &= 43{,}000 \pm 5{,}000\ {\rm K}, \\ \log n_{\rm H\,I} &= 17.5 \pm 0.5. \end{aligned} \tag{2}$$

Adopting $T_{\rm eff}$ = 40,300 K from the spectroscopic results (eq. [1]) and using the 100 and 200 Å survey bandpasses (assuming again log g = 9 and $n_{\rm He\,I}/n_{\rm H\,I}$ = 0.07), we obtain

$$\begin{aligned} {\rm He/H} &= 2.5 \pm 0.5 \times 10^{-4}, \\ \log n_{\rm H\,I} &= 18.15 \pm 0.35. \end{aligned} \tag{3}$$

The results based on EUV spectroscopy (eq. [1]) are of course more accurate than results based on survey data (eqs. [2] and [3]). We present in Figure 3 (*upper panel*) the EUV spectrum between 225 and 315 Å and a model spectrum adjusted to GD 50's spectrum using parameters from equation (1) and degraded to the instrument resolution (~1 Å).

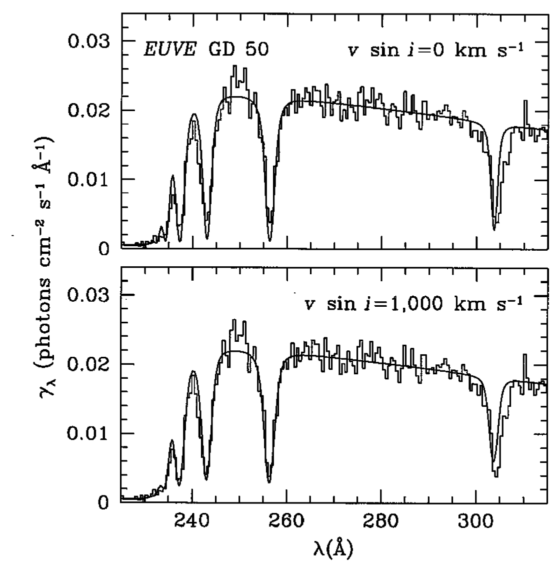

FIG. 3.—*Upper panel*: *EUVE* spectroscopy of the He II ground-state line series and best model fit ($T_{\rm eff}$ = 40,300 ± 100 K and He/H = 2.4 ± 0.1 × 10^{-4}) assuming log g = 9.0. *Lower panel*: Same as in upper panel, but using a model including rotational broadening (v sin i = 1000 km s^{-1}).

Although the continuum shape is correctly predicted, a few characteristics of the spectrum are not well reproduced: the line cores in all lines except the first member of the series are predicted deeper than observed. Although NLTE model would indeed predict shallower lines than LTE models, the line profiles are indistinguishable after smoothing to the *EUVE* spectral resolution. We also note that the first member of the series (304 Å) is blueshifted by ~1 Å, while the other series members are well aligned. Moreover, the observed 304 Å line profile is totally at odds with the model. Unfortunately, strong He II geocoronal background may have severely corrupted the data near 304 Å, and we may have to restrict the analysis to higher members of the series. Interestingly, if we rotationally broaden the model to a velocity $v \sin i = 1000$ km s^{-1} (*lower panel*), most difficulties with the higher series members disappear; the line shapes, depths, and convergence of the line series are well reproduced. The true significance of this phenomenon may have to await detailed line profile calculations. In the following, we explore possible explanations for the peculiar EUV spectrum of GD 50.

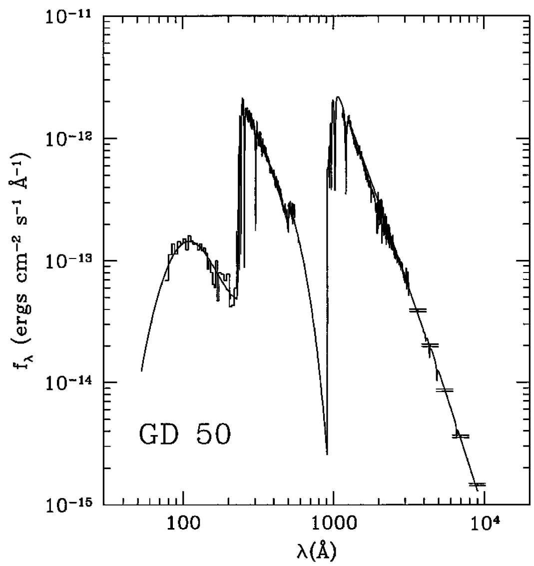

FIG. 4.—Ultraviolet and optical energy distribution of the hot DA white dwarf GD 50, including data from *EUVE* (75 Å ≤ λ ≤ 550 Å), *IUE* (1150 Å ≤ λ ≤ 3200 Å), and Landolt's (1992) *UBVRI* photometry, along with our best model fit (eq. [1]). The red photometry excludes the presence of a companion with $M_I \leq 14$.

4. DISCUSSION

We have uncovered a most peculiar abundance pattern in the photosphere of the massive white dwarf GD 50. We measured a large helium abundance of He/H = 2.4×10^{-4}, apparently not accompanied by a corresponding abundance of heavier elements (Vennes, Thejll, & Shipman 1991). The presence of helium in its photosphere and its effective temperature ($T_{\rm eff} \approx 40{,}000$ K) place GD 50 amid the so-called DB gap, a feature in the white dwarf luminosity function found between $T_{\rm eff} = 28{,}000$ and 45,000 K (Liebert et al. 1986; Thejll, Vennes, & Shipman 1991), where helium is, possibly with the exception of HS 0209+0832 ($T_{\rm eff} = 36{,}000$ K; Jordan et al. 1993), conspicuously absent from the photosphere of any objects within these bounds. As alluded to above, GD 50 is also one of the most massive white dwarfs with a surface gravity of $\log g = 9.0$ and an estimated mass of 1.2 $M_\odot$. Other DA white dwarfs were found to have masses close to the Chandrasekhar limit—for example, PG 0138+253 and the magnetic white dwarf PG 1658+440, with estimated masses above 1.2 $M_\odot$ (Schmidt et al. 1992). Both objects are bright EUV sources, and a spectroscopic study may help establish a relationship between helium abundance and surface gravity.

Figure 4 presents the ultraviolet/optical energy distribution of GD 50. We have obtained two *IUE* spectra (LWP 9690 and SWP 29858) from the archives at Goddard Space Flight Center, and we complete the data set with *UBVRI* photometry from Landolt (1992). The complete energy distribution is perfectly well reproduced by our best model fit (eq. [1]) to the EUV data. We find no evidence of a companion. With a distance modulus of $m - M = 2.4$, we determine a limit of $M_I \geq 14$ to the I magnitude of a faint red companion, or a spectral type later than dM7–dM8. The absence of any apparent companion complicates the interpretation of the abundance pattern. Accretion from a close companion as in the case of the DAO+dM binary EUVE J1016−053 (Vennes et al. 1996) could have offered an explanation for the relatively large helium abundance in GD 50. The good match offered by homogeneous models allows us to exclude the presence of a thin hydrogen layer as an explanation for the high helium concentration; the EUV spectral shape (λ ≤ 228 Å, in particular) is totally at odds with spectral synthesis presented in Vennes & Fontaine (1992).

We examine various scenarios to explain the presence of helium in a high-gravity white dwarf. We have already ruled out selective radiation pressure (§ 1), but we still need to examine the possibility that a magnetic field may prevent separation of helium and hydrogen in the atmosphere. However, an upper limit to the longitudinal magnetic field in GD 50 of $B_e \leq 30$ kG has been recently established (Schmidt & Smith 1995). Such a low field cannot prevent separation in a high-gravity atmosphere (Michaud & Fontaine 1982). MacDonald & Vennes (1991) examine the effect of accretion from the ISM on the white dwarf luminosity function. The same mechanism may act as a source of helium and heavier elements in a DA photosphere. Using a simple diffusion model, the ratio of the measured abundance to the accretion flow abundance (solar) is

$$\frac{\mathrm{He/H}_*}{\mathrm{He/H}_\odot} = \frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm acc} + 4\pi R_*^2 \rho v_D}, \quad (4)$$

where R_* is the white dwarf radius and ρ and v_D are the density and diffusion velocity at the measurement location, respectively. The helium diffusion velocity at $\tau_{227\,\text{Å}} = \frac{2}{3}$ is $v_D \approx 0.09$ cm s^{-1}, and the local density is $\rho \approx 4 \times 10^{-7}$ g cm^{-3}. We have obtained a ratio of the measured abundance to solar abundance of 2.4×10^{-3}, resulting in an accretion rate of $\dot{M}_{\rm acc} \approx 3 \times 10^{-18}\, M_\odot$ yr^{-1}. Assuming a velocity in the ISM of 50 km s^{-1}, accretion at the Bondi-Hoyle rate requires a density of hydrogen in the ISM of 0.13 cm^{-3}. The very low *neutral* hydrogen column density measured in the line of sight of GD 50 results in an average density of $N_{\rm H\,I} = 0.01$ cm^{-3}, or approximately 1/10 the *total* (mostly ionized) hydrogen density required near GD 50. These requirements are reasonable, but we have to determine why accretion onto GD 50 is not inhibited while other DA stars like GD 153 and HZ 43 possess no evidence of this process (Dupuis et al. 1995). A final interpretation of the peculiar helium abundance requires high rotational velocity. We note that massive white dwarfs are often considered the product of a stellar merger; a fraction of the initial orbital angular momentum may be preserved in the merger, possibly resulting in a rotational velocity of the order of 1000 km s^{-1}. Fast rotation may induce a large meridional circulation current, thereby dredging up helium from the envelope if the hydrogen layer is sufficiently thin. The presence of photospheric helium would constitute a first spectroscopic signature of a stellar merger. Although we presented evidence of this phenomenon (Fig. 3), a description of meridional current in white dwarf envelopes does not exist. The helium surface abundance may also, in that context, be a function of the hydrogen layer thickness.

In summary, the peculiar abundance pattern observed in GD 50's photosphere may be related to its high surface gravity; EUV spectroscopic observations of other massive white dwarfs may confirm this relationship. High-dispersion optical spectroscopy of the Hα NLTE emission core may also constrain the rotational velocity and therefore indicate a model where helium dredge-up is induced by meridional circulation current.

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