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ULTRAVIOLET SPECTRUM SYNTHESIS OF THE HELIUM WHITE DWARF ROSS 640

P. L. COTTRELL AND JESSE L. GREENSTEIN
Palomar Observatory, California Institute of Technology
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ABSTRACT

The ultraviolet spectrum of the helium-rich white dwarf Ross 640 has been used to derive Mg, Si, and Fe abundances by a spectrum synthesis technique. The visible spectrum provides a Ca abundance and another estimate of the Mg abundance. The values obtained were: Mg/He $= 6.8 \times 10^{-8}$; Si/He $= 3.2 \times 10^{-8}$; Ca/He $= 7.6 \times 10^{-10}$; Fe/He $= 2.0 \times 10^{-9}$. These are far below the solar abundances, and the metals have different ratios relative to the Sun. The estimated cooling and diffusion times for Ross 640 predict that no metals should be observed. Our abundances indicate the operation of diffusion processes (Mg/Ca $\gg$ cosmic ratio) within a helium-rich atmosphere, provided some mechanism exists to deposit metals in the observable layers. However, no firm conclusion can yet be reached as to whether the metals have somehow been convectively mixed into the atmosphere or accreted from the interstellar medium.

Subject headings: stars: abundances — stars: atmospheres — stars: individual — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

With the emergence of space astronomy it is now possible to observe stellar photospheres below the atmospheric limit ($\lambda \approx 3000$ Å). In this region there are many low-excitation potential lines of the abundant elements (e.g., C, N, Fe, Mg, Si) from which one could hope to derive individual elemental abundances. For stars with solar abundances this wavelength interval is so heavily line blanketed as to make detailed abundance analyses impossible. However, for very hot ($T_e > 30{,}000$ K) stars (for which most of the flux is in the ultraviolet) and for cooler objects ($T_e < 10{,}000$ K) with low metal abundances (whose visible line spectrum is extremely weak), the data acquired in this spectral region may provide a significant amount of (or possibly the only) information on individual elements.

Many cool ($T_e < 10{,}000$ K) white dwarfs fall into the latter category and have provided the impetus to analyze in detail the He white dwarf Ross 640. This object has very few features in its visible spectrum—Ca II, H and K, and Mg I, $\lambda\lambda$3830, 5175, and a weak Hα feature. Similar objects in this class are GD 40 and G111-54 (for discussion and sources of this data see Vauclair, Vauclair, and Greenstein 1979, hereafter VVG). In order that we understand the final stages of a white dwarf's evolution we must obtain abundance data for these cool white dwarfs. Comparison of these data with current evolutionary theories will provide a basis for acceptance or revision. One major question for present theories is why *any* metals exist in the atmospheres of cool white dwarfs. Diffusion theories (Alcock and Illarianov 1980; Fontaine and Michaud 1979; VVG) would predict that all metals should have settled out of their atmospheres on time scales much less than the lifetime of the white dwarf. Thus, one has to consider situations where the metals can be retained in the atmosphere, possibly by episodes of convective mixing or accretion from the interstellar medium.

The above authors discuss these mechanisms extensively, and also the effect that turbulence and magnetic fields have on the diffusion rate within the atmosphere. The most promising process appears to be accretion followed by thermal diffusion within the atmosphere. The latter will result in the separation of elements depending on their ionization state: the higher the ionization state, the more quickly the element will be transported through the atmosphere. This will result in the ratio of heavy to light elements (e.g., Ca/Mg) being less than the solar value. Some theories predict a Mg/Ca ratio of $\sim$40 compared with the solar value of 14 (VVG). Both Fontaine and Michaud (1979) and VVG summarize our present knowledge of abundances in He white dwarfs and illustrate the critical need for more data. The present paper alleviates that situation a little by giving Mg, Si, and Fe abundances for Ross 640 using the UV (*IUE*) data and spectrum synthesis techniques.

This object is a good candidate for a detailed investigation because of extensive analyses in other spectral regions. Oke (1974) has obtained multichannel scans; Liebert (1977) has used spectrum synthesis methods to interpret the visual spectra which he obtained. Liebert used a model atmosphere with an effective temperature (T_e) of 8500 K and a gravity, log g, of 8.0. Earlier analyses have been performed by

Wegner (1972) and Hammond (1974), but the Liebert (1977) work appears to be the most careful analysis to date. He obtained the following abundance ratios (or upper limits): H/He $= 3 \times 10^{-4}$, Na/He $< 7.0 \times 10^{-10}$, Mg/He $= 3.0 \times 10^{-8}$, Si/He $< 1.0 \times 10^{-7}$, Ca/He $= 4.0 \times 10^{-10}$, and Fe/He $\lesssim 2.5 \times 10^{-9}$. A résumé of the known metal/helium ratios in other stars is in Greenstein (1979); an improved table will be included in our forthcoming study of GD 401 (Cottrell and Greenstein 1980).

The present paper derives abundances (§III) for Mg, Ca, Si and Fe using the UV observations (§ II) and the data of Liebert (1977). The spectrum synthesis method is described in § III. Finally, we discuss the abundances in terms of current theories (§ IV).

II. OBSERVATIONS

The data to be used in the abundance analysis is from two sources. The UV data covering the wavelength interval $\lambda\lambda$2000–3000 were obtained with the *International Ultraviolet Explorer* (*IUE*) by Greenstein and Oke in 1978 May and December. In Figure 1 we show the *IUE* data averaged over ~3 points to provide better statistics, combined with the multichannel spectrophotometric (MCSP) observations from $\lambda\lambda$3000–10,000 (Oke 1974). The UV observations are shown in Figure 2 (*dots*) with individual data points plotted rather than averages. This figure will be discussed in greater detail in the next section (§ III).

Since two *IUE* observations were obtained separated by 7 months, it is instructive to study the differences between two independently reduced measurements. For this purpose, 32 five-point means of $\log_{10} f_\nu$ were compared; the means differed systematically by -0.010 ± 0.006, and had a dispersion of ± 0.033. An individual measurement of $\log_{10} f_\nu$ would have $5^{1/2} \times 2^{-1/2} \times 0.033$, or ± 0.052 as its dispersion. The three-point means we used are good to 0.030 or about 7%, except in the line cores.

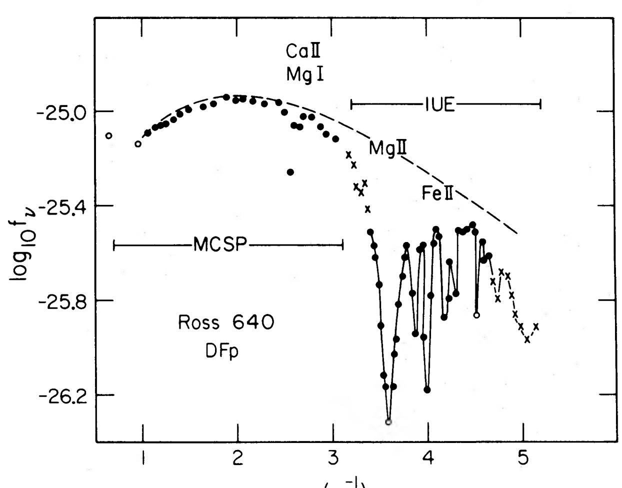

FIG. 1.—*IUE* (for $\nu \gtrsim 3.2$) and multichannel scan (for $1 < \nu < 3$) observations for Ross 640. The continuum flux for a T_e, $\log g$ = (8800, 8) model is shown by the dashed line. Filled circles are MCSP (open, poor data). In the UV filled circles are means over five *IUE* pixels, approximately 22 Å (crosses are uncertain; open circles, single bottom pixels in strong lines).

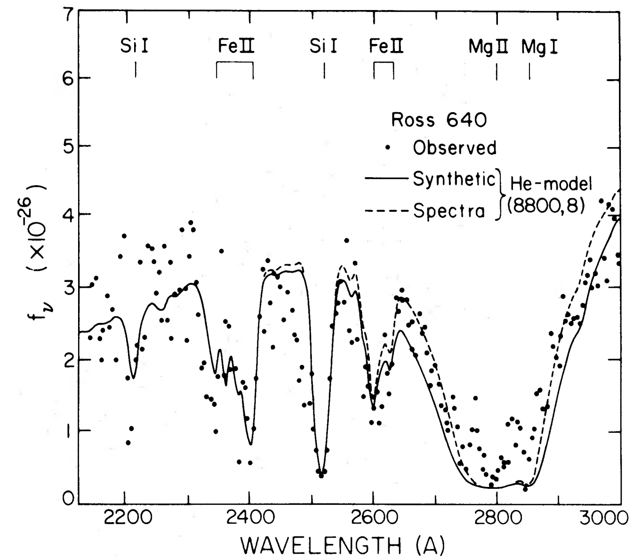

FIG. 2.—*IUE* observations of Ross 640 with two synthetic spectra superposed; filled circles, individual pixels, 4.5 Å spacing, about 8 Å resolution. Both computations have the same atmospheric parameters except for their Mg abundance, with metal abundances as given in Table 2, except for Mg, where the solid and dashed lines have 0.1 dex higher and lower Mg abundances, respectively.

The relatively high-resolution (FWHM ≈ 8 Å) visual data is from Figure 3 of Liebert (1977). A portion of it ($\lambda\lambda$3700–4300) is included in our Figure 3 and compared with two synthetic spectra, which are described in § III.

III. SPECTRUM SYNTHESIS

Only a few elements are represented (Fig. 1) in the UV region of metal-deficient white dwarfs. These data are of relatively low resolution so that many overlapping lines of a number of multiplets of several elements are represented. Thus spectrum synthesis provides an ideal technique for the abundance analysis. This method has been used previously in the interpretation of white dwarf spectra (e.g., Wehrse 1977; Cottrell, Bessell, and Wickramasinghe 1977). In this section we describe our basic synthesis technique, the sources of atomic data, and then synthesize the Ross 640 spectrum in the wavelength intervals $\lambda\lambda$2000–3000 and $\lambda\lambda$3700–4300.

a) *Technique*

The basic method used in this analysis has been developed by Cottrell and described in Cottrell and Norris (1978) and Cottrell (1978). The two wavelength intervals require two line lists to be constructed.

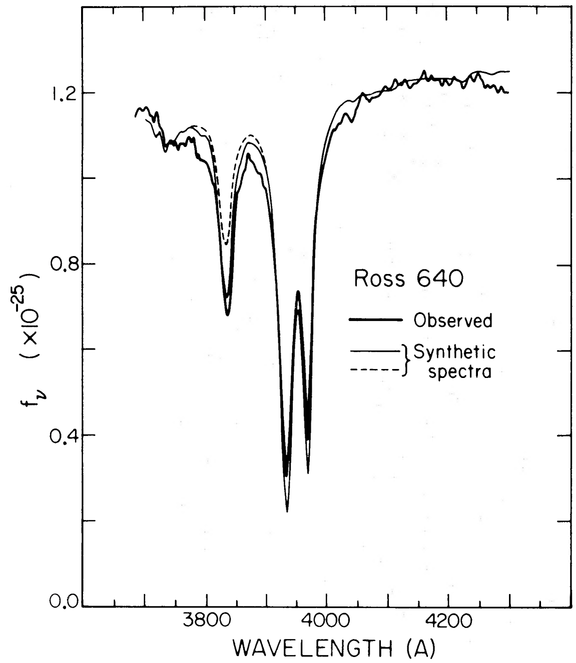

FIG. 3.—Observed Liebert 1977 and synthetic spectra for Ross 640 in the wavelength interval λλ3700–4300. The metal abundances are those described in Fig. 2.

Between λλ3700 and 4300 approximately 100 lines of Mg, Ca, and Fe were included. These were a subset of the line list constructed by Cottrell in the analysis of the heavily line-blanketed white dwarf LP 701–29 (Cottrell, Bessell, and Wickramasinghe 1977). For the UV data, the wavelengths, the excitation potentials, and *gf*-values were taken from Kurucz and Peytremann (1975) for the atomic species listed in Table 1. The total number of lines included was ~140.

The latter line list, together with the solar model of Bell *et al.* (1966), was then used to synthesize a solar spectrum and incidentally to check the *gf*-values of

TABLE 1

SPECIES INCLUDED IN ULTRAVIOLET LINE LIST

Element	Ionization Stage	UV Multiplets
Mg	I	1
Mg	II	1, 2, 3
Si	I	1, 2, 3
Fe	II	1–6, 32–36, 60–64

Kurucz and Peytremann (1975). With only a small number of lines included, one could not expect to obtain a detailed fit. We found that our adopted *gf*-values, damping constants, and abundances[1] gave a realistic fit to the solar UV spectrum obtained by Kohl, Parkinson, and Kurucz (1978).

The white dwarf model atmosphere ($T_e = 8800$ K, $\log g = 8.0$, with the metals and hydrogen down by 10^4 relative to helium) used in this analysis is from J. Liebert (1979, private communication), computed by him for his analysis of Ross 640 (Liebert 1977). Although this was his preferred temperature, he used the more commonly accepted effective temperature of 8500 K and tabulated that model in his paper. However, since the 8800 K model provides a little more UV flux and still fits the visual and red data well (see the continuum fluxes [*dashed line*] in Fig. 1), we selected the hotter model. The conclusions of this paper are not changed by this assumption. Uncertainty arises in He-rich white dwarf models (which have extremely high gas pressures, $P_g \approx 10^9$ dynes cm^{-2}) from pressure ionization effects and the paucity of data on the He$^-$ opacity. The latter (according to current thinking) is the dominant source of continuous opacity in metal-deficient He-rich atmospheres. This uncertainty is well illustrated in Figure 4 where Liebert's (1977) T_e = 8500 K, $\log g = 8.0$ model, which has both metals and hydrogen down by ~10^4 relative to helium, is compared with the model computed with the same

[1] Our solar abundances are those of Kurucz (1970).

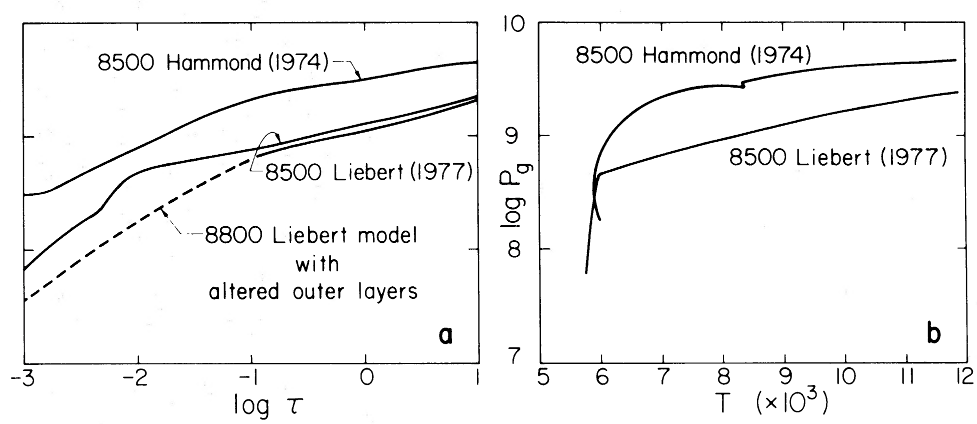

FIG. 4.—Comparison of the (8500, 8) model atmospheres of Hammond 1974 and Liebert 1977: (*a*) $\log P_g$ vs. $\log \tau$; also shown is Liebert's (8800, 8) model (*solid line*) with its modified outer layers (*dashed line*) (see text); (*b*) $\log P_g$ vs. temperature T.

parameters by Hammond (1974). The large differences (factors of 3 to 5) give some indication of the preliminary nature of our theory of plasmas at very high pressures.

Finally, for the broadening of the lines in this star we have assumed that it can be represented by van der Waals interactions, with helium as the perturbing species. The interaction parameters (C_6) have been taken from Wegner (1972).

b) Abundance Analysis

Using the above technique, synthetic spectra were computed for a range of Mg, Si, Ca, and Fe abundances. The fluxes were computed at 5 Å wavelength intervals. Such a coarse grid was possible because of the enormous line broadening at high gas pressures in transparent He-rich atmospheres. The fluxes computed were subsequently convolved with a Gaussian whose FWHM was 10 Å for the UV data and 8 Å for the interval $\lambda\lambda$3700–4300.

The final derived abundances are given in Table 2 and compared with Liebert's (1977) determinations. In Figures 2 and 3 we illustrate some of our synthetic spectra, superposed on the UV (*IUE*) and visual (Liebert 1977) data, respectively. Although the errors associated with the fit to the data are approximately a factor of 2 (i.e., $\sim$0.3 dex), there are other uncertainties, one of which has already been illustrated in Figure 4, which should be mentioned. One assumption of this analysis is the use of simple broadening theory at high gas pressures ($\sim 10^9$ dynes cm^{-2}). Liebert (1977) discussed in depth the problem of the correct interaction parameters to be used in his analysis of the line profiles in the spectra of Ross 640. We refer the reader to this work for more details. Another area of uncertainty is the UV damping constants and *gf*-values.

We will now return to our discussion of the synthetic spectra. The fit to the visual data is extremely good, although the abundances derived differ slightly from those determined by Liebert (1977). In the UV the fit is not as precise, especially in the core of the Mg II lines near λ2800, where the observations have sharper line cores than the computations. We cannot explain some finer details, like the apparent dip at λ2740. However, the dip at λ2852 is real and is caused by Mg I. To investigate this divergence we considered the hypothesis that the models do not have realistic surface layers and that the gas pressure declines more rapidly than indicated by Liebert's (1977) model. Some physical basis for this may be derived from a discussion by Wesemael (1979). If an He-rich white dwarf accreted interstellar material, the accreted H would float on top of the He, since it is difficult to conceive of a situation (except possibly an extremely strong convective mixing process), in which the H could be mixed into deeper layers. As indicated by Wesemael (1979), the hydrogen (as H^-) would have a larger atmospheric opacity (κ_c) than helium (as He^-), which in turn would reduce the gas pressure (via the equation of hydrostatic equilibrium, $P_g \propto 1/\kappa_c$). Using the above reasoning as a basis for making the changes, we reduced the gas pressure of the outer layers as shown by the dashed line in Figure 4*a*. No other changes were made to the model atmospheres. The resulting synthetic spectrum is shown in Figure 5 where it is compared with the spectrum computed with the same abundances but the "normal" atmospheric structure. The desired effect of producing sharper cores was not fully attained; the overall effect was just to predict weaker features. To produce lines of equivalent strength one would have to increase the abundance of Mg by $\sim$0.2 dex. Were the surface temperature lowered, the line cores might sharpen further in a composite atmosphere because of the higher H opacity for a given gas pressure. The Mg I would also be enhanced. Further work with a steeper drop in P_g and T at the surface should await justification from model-atmosphere calculations. Part of our inability to get a detailed fit may arise in the data, which has lower signal-to-noise ratio in the deep cores of the Mg lines, relative to the wings, We prefer the abundance indicated by the broad wings, formed deep within the atmosphere, both to minimize the effect of uncertainties in the surface layers and poorer data in the cores of strong features.

TABLE 2

DERIVED ABUNDANCES

ELEMENT[a]	ABUNDANCE CG	ABUNDANCE Liebert	ABUNDANCE/SOLAR
Mg	6.8×10^{-8}	3.0×10^{-8}	25×10^{-4}
Si	3.2×10^{-8}	$<1.0 \times 10^{-7}$	10×10^{-4}
Ca	7.6×10^{-10}	4.0×10^{-10}	4.0×10^{-4}
Fe	2.0×10^{-9}	$\lesssim 2.5 \times 10^{-9}$	0.6×10^{-4}

[a] The abundances are by number relative to He.

NOTE.—Using Liebert's 1977 model; $n(H) = 1.5 \times 10^{-4}$ and $n(He) = 1.0$ relative to the total number of atoms.

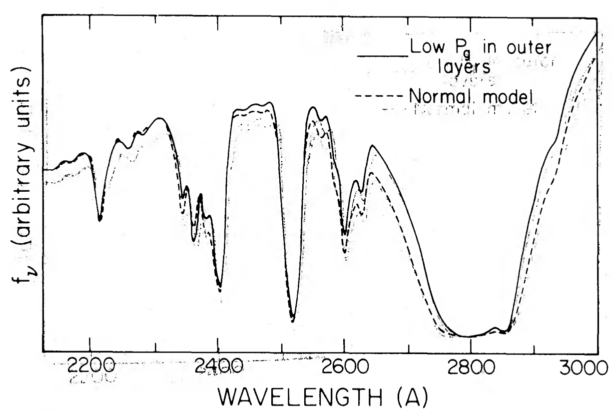

FIG. 5.—Comparison of synthetic spectra computed with the normal model (*dashed line*) and a model which has modified pressures in its outer layers (*solid line*), as shown in Fig. 4.

Taking the abundances given in Table 2 at face value, we will endeavor to relate them to current white dwarf theories, as has been outlined in § I. The Mg/Ca ratio is the most useful, but the results for v Ma 2 are unfortunately subject to the uncertainty concerning λ3835 of Mg I, blended with Fe I.

IV. DISCUSSION

The abundances given in Table 2 indicate that the elements Mg, Si, Ca, and Fe are not represented in anything like their solar ratios. Not only are metals deficient by a large amount ($\sim 10^3$ for Mg), but there is a range in the deficiencies (Fe is underabundant by more than 10^4). The metal deficiency, however, is not as great as one would expect from white dwarf evolutionary calculations which propose that all the metals should have settled out of the atmospheres during the white dwarf cooling time (e.g., see Fontaine and Michaud 1979). We are therefore beset with a problem. How did Ross 640 acquire (or produce) metals in these proportions? Some explanations (e.g., differential settling by thermal diffusion) have already been alluded to in § I, but we will now put them in perspective using observational results for Ross 640 and the other cool He-rich white dwarfs, which have T_e between 7000 and 15,000 K. These objects have been discussed most recently by VVG and Wehrse and Liebert (1980). Of all those considered, only Ross 640 and van Maanen 2 (Wegner 1972) have sufficiently detailed abundance data for enough elements to test the settling-process theory. For GD 40 the analysis of the UV Mg II lines has not yet been completed and, thus, the Ca/He abundance is the only ratio available. Preliminary results by Cottrell and Greenstein (1980) indicate that GD 401 has Ca/He = 6.0×10^{-9} and Mg/He $\lesssim 1 \times 10^{-8}$. No other lines have been positively identified in the visible spectrum of GD 401.

VVG and Fontaine and Michaud (1979) have used their thermal diffusion models to predict that the Mg/Ca ratio should be greater than the cosmic ratio (~ 14) in the He-rich white dwarfs. Table 3 shows this ratio. Using this alone, only two of the three objects support their hypothesis that diffusion is operating in their atmospheres. For GD 401, the overabundance of Ca relative to Mg might indicate accretion of interstellar material with noncosmic abundances. Fontaine and Michaud (1979) proposed that dispersion in the Mg/Ca ratio may be due to variations in turbulence within the atmospheres with increased turbulence retarding the settling process. Alternatively, VVG suggested that a range in Mg/Ca ratio could arise from different accretion rates.

TABLE 3

Mg/Ca RATIOS

Elements	Cosmic	Ross 640	van Maanen 2	GD 401
Mg/Ca	14	89	20	≲0.4

From observational data accumulated to date, one must conclude that it is not possible to derive any firm prediction whether convective mixing or accretion of interstellar material is the process by which these He-rich white dwarfs acquire the metals seen in their atmospheres. In fact, as we speculate for GD 401, region-to-region abundance variations in the interstellar medium (which may be accreted onto these white dwarfs), could be reflected in the abundance spread seen in the atmospheres of cool white dwarfs. With only three sufficiently well-studied objects, and with the uncertainties in the theory of the final stages of white dwarf evolution, we seem still to be at an early stage of interpretation of the origin of the metals in the atmospheres of cool He-rich white dwarfs.

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P. L. COTTRELL: Department of Astronomy, R. L. Moore Hall, University of Texas, Austin TX 78712

JESSE L. GREENSTEIN: Department of Astronomy 105-24, California Institute of Technology, Pasadena, CA 91125