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DETECTION OF TRACE HELIUM IN G104-27, A 26,000 K DA WHITE DWARF

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ABSTRACT

The presence of a weak He I $\lambda 4471$ feature has been detected in high signal-to-noise ratio spectra of the previously well-studied DA white dwarf G104-27 (WD 0612+177, EG 46). Trace He I in such a moderately hot DA star places G104-27 within the apparently sparse class of DAB white dwarfs. Model atmosphere fits to the Hγ and Hβ and Lyα profiles of G104-27 yield an effective temperature and surface gravity of $T_{\text{eff}} = 26{,}000 \pm 500$ K and $\log g = 8.12 \pm 0.15$. The use of homogeneous H-He model atmospheres to fit the equivalent width of the He I $\lambda 4471$ feature leads to a He abundance of $\log (\text{He/H}) = -2.56 \pm 0.26$. Alternately, it is estimated that a corresponding stratified atmosphere would have a hydrogen envelope mass of $\log (M_{\text{H}}/M_{\odot}) = -16.6 \pm 0.3$. Both atmospheres are consistent with the existing upper limit on the soft X-ray flux from G104-27. The implications of the presence of He in G104-27 are briefly discussed.

Subject headings: stars: atmospheres — stars: individual (G104-27) — stars: white dwarfs — ultraviolet: spectra

1. INTRODUCTION

The great majority of all white dwarfs are observed to fall into two spectroscopic classes, the hydrogen-rich DA stars and the helium-rich DB and DO stars. This apparently fundamental difference between H-rich and He-rich degenerates, however, really reflects only the composition of the thin photospheres, where the high surface gravities of white dwarfs lead to rapid chemical stratification. A central issue in the field of degenerate stars remains the nature of evolutionary relationships between these two classes of white dwarfs, as well as the closely related issue of the thickness of the hydrogen envelopes in DA white dwarfs. Current models of the origin of DA white dwarfs from the later stages of planetary nebulae central star evolution (Iben & Tutukov 1984) yield massive hydrogen envelopes, $\log (\dot{M}_{\text{H}}/M_{\odot}) \sim -4$. Were all DA stars characterized by such "thick" envelopes, H-rich and He-rich white dwarfs would constitute distinct cooling sequences, separated at birth (e.g., see Shipman 1989a, b). An alternate view (Fontaine & Wesemael 1987) favors much smaller hydrogen envelopes, $\log (M_{\text{H}}/M_{\odot}) \sim -11$ to -16, in DA white dwarfs and is based on the suggestion that the interplay between diffusion and convection leads to the shifts in composition observed along the white dwarf cooling sequence. This scenario does not require two separate channels of white dwarf evolution.

In the study of all these phenomena, those relatively rare stars of mixed composition are of obvious importance. The best studied such stars are the DBA white dwarfs (Shipman, Liebert, & Green 1987). These He-rich objects exhibit trace H at abundances of $\log (\text{H/He}) = -3$ to -5. Shipman et al. estimate that perhaps 25% of all DB stars may contain H at these levels. DAB stars, on the other hand, are considerably less frequent. Only three are previously known, and analyses have been published for only one, GD 323 (Liebert et al. 1984; Koester 1989a, 1991). In DAB stars the roles of H and He are reversed and He I is a trace component in a hydrogen-dominated atmosphere. If some DA white dwarfs actually do convert to DB white dwarfs in the vicinity of $\sim$30,000 K, as population statistics seem to indicate, then the presence of trace He in a DA in this temperature range is of great interest.

The task of determining the He content of DA stars is not easy. At higher temperatures, He II, and sometimes He I, has been detected in a number of very hot DAO white dwarfs (Holberg et al. 1989; Napiwotzki & Schöberner 1991). At optical wavelengths, DA stars are regarded as having chemically pure H photospheres due to the lack of observed He lines. By current standards, however, existing observed limits are generally not very stringent. For example, Shipman (1972) quotes observational limits on He I $\lambda 4471$ in DA stars at < 1 Å equivalent width. From this, he derives He abundances of $\log (\text{He/H}) < -2$. Tytler & Rubenstein (1989) have presented results from very high S/N spectra of subluminous stars, some of which exhibit weak He I features. Stars which exhibit these features, however, either appear to be subdwarfs misclassified as DA stars or very cool DA white dwarfs. The presence of He at much lower levels has been *inferred* from soft X-ray observations of DA white dwarfs. Kahn et al. (1984) first showed that a source of soft X-ray opacity, in addition to pure H, was required to explain the soft X-ray observations of DA white dwarfs. Since then, there have been several studies (Petre, Shipman, & Canizares 1986; Jordan et al. 1987; Paerels & Heise 1989) which have confirmed this situation with many additional observations. Some observers have also argued for the existence of a positive correlation between T_{eff} and He abundance. These studies all relied on homogeneous (chemically mixed) model atmospheres to estimate He abundances of 10^{-6} to 10^{-3} in DA stars over the temperature range

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25,000–60,000 K. Models in which H and He are chemically stratified have also been applied to these data (Koester 1989b; Vennes, Fontaine, & Wesemael 1989). Stratified atmospheres, which are expected to occur if no forces operate to counteract gravitational sedimentation, can be parameterized by the effective thickness, or mass, of the overlying H envelope. These independent studies conclude that DA soft X-ray observations are equally well interpreted in terms of stratified atmospheres having H envelope masses of log $(M_H/M_\odot)$ − 13 to −16.

In this *Letter* we present a high S/N optical spectrum of G104-27 (WD 0612+177, EG 46, LTT 11818, L1244-26) which reveals the presence of a weak He I λ4471 feature. The Hγ and Hβ profiles from this same spectrum are used in conjunction with an *IUE* Lyα profile to obtain an estimate of the temperature and gravity of G104-27. The observed equivalent width can be matched by adjusting the He/H ratio in a homogeneous atmosphere, or by adjusting the hydrogen layer mass in a statified atmosphere. These estimates are in turn compared with the limits on these quantities which can be obtained with an existing *EXOSAT* upper limit on the observed soft X-ray flux. We discuss the nature of G104-27 and its implications for our understanding of the composition and structure of white dwarf atmospheres.

2. OBSERVATIONS AND ANALYSES

High S/N optical spectra of G104-27 were obtained on 1989 February 16 and 17 with the Steward Observatory 2.3 m telescope. Three spectra were acquired, each with S/N ∼ 90; two were at a grating setting covering the wavelength range 3975–4750 Å, and the third covered the wavelength range 4325–5100 Å. All employed a 1200 line mm^{-1} grating with a TI 800 × 800 CCD and achieved spectral resolutions of ∼2 Å. In each instance, a weak feature was clearly present at the expected location of He I λ4471. The third observation, at a different grating position, was obtained to eliminate the possibility of a flat-fielding artifact and to search for the He I λ5015 feature. Observations of other DA white dwarfs at comparable S/N, using the same instrumental configuration, produced no similar features on either night. In Figure 1 we show a co-added spectrum of G104-27 including all data from both nights and covering the region of the Balmer-β and Balmer-γ profiles. The mean equivalent width of the He I λ4471 feature from all three spectra is 296 ± 30 mÅ. On individual spectra, the He I λ4471 had respective equivalent widths of 366 ± 40, 319 ± 30, and 204 ± 30 mÅ. The third spectrum also contained a possible detection of He I λ5015 at 167 ± 60 mÅ. This latter feature, however, resides uncomfortably near the noise level in this portion of the composite spectrum.

In order to make an improved estimate of the temperature and gravity of G104-27, we jointly analyzed the Hγ and Hβ profiles in Figure 1, together with an *IUE* Lyman-α profile derived from existing large- and small-aperture SWP spectra of G104-27. Two large-aperture spectra (SWP 24321 and 36004) and two small-aperture spectra (SWP 32198 and 36004) were co-added in the manner described in Holberg, Wesemael, & Basile (1986). This joint analysis employed a grid of pure hydrogen, plane-parallel, line-blanketed, LTE model atmospheres, in which detailed H I Lyman and Balmer profiles are computed. These models are extensions of those described in Wesemael et al. (1980) and are discussed in more detail in Holberg, Wesemael, & Basile (1986). The joint analysis of both profiles is similar to that described in Holberg et al. (1985).

We show in Figure 2 the resulting contours in effective temperature and surface gravity space which correspond to 1 σ and 3 σ χ^2 fits to both profiles. Using a temperature determined primarily from the Lyman-α profile and a gravity determined primarily from the Hγ and Hβ profiles, we adopt a single best-fitting model defined by T_{eff} = 26,000 ± 500 K and log g = 8.12 ± 0.15. Also included in Figure 2 are the locations of previously published estimates of T_{eff} and log g from optical photometry. The effective temperatures from Shipman (1979), Koester, Schulz, & Weidemann (1979), and Guseinov, Novruzova, & Rustamov (1983) are in reasonably good agreement with our results. The major discrepancies are in gravity. However, estimates of this quantity based solely on photometric colors are frequently unreliable in this temperature range.

We have also estimated the homogeneous He/H ratio required to match the strength of λ4471. We find log (He/H) = −2.56 ± 0.26, where the quoted uncertainty includes an allowance for uncertainties in the observed equivalent width as

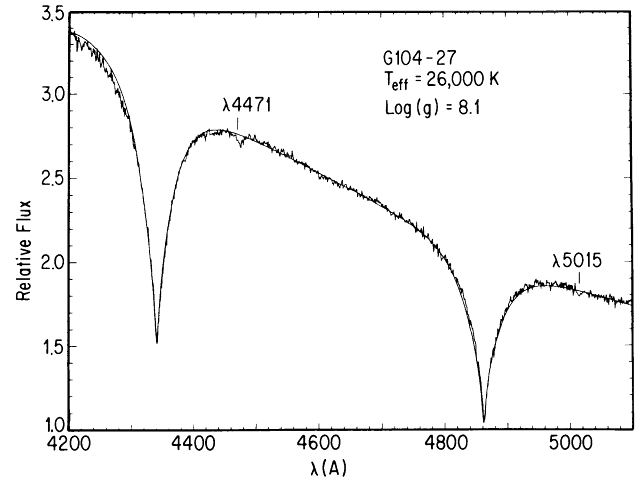

FIG. 1.—The observed spectrum of G104-27 in the region of the Hβ and Hγ lines. The comparison model (T_{eff} = 26,000 K and log g = 8.1) is derived from a joint analysis of the Lyα, Hβ, and Hγ profiles (see Fig. 2). The locations of the weak He I λλ4471 and 5015 features are indicated.

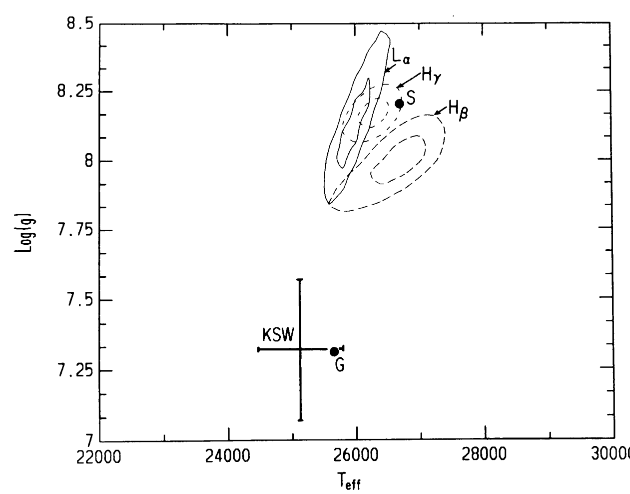

FIG. 2.—A joint analysis of the Lyα, Hβ, and Hγ profiles of EG 46. Contours at 1 and 3 σ of equal χ^2 are shown for each profile. Previous estimates of the temperature and gravity of EG 46 are shown; KSW = Koester, Schulz, & Weidemann (1979), S = Shipman (1979), and G = Guseinov, Novruzova, & Rustamov (1983).

well as in T_{eff} and log g. A match to the equivalent width of the possible λ5015 feature would require an abundance a factor of 3.5 higher than that quoted above; however, because the width of λ4471 is based on the co-addition of three independent scans, we adopt here the helium abundance based on the λ4471 line only. Note that the presence of a weak He I line could also be reproduced in terms of a stratified atmosphere. On the basis of Koester's (1989a, Table 3) criterion for the visibility of helium lines in stratified models near 25,000 K, we estimate the hydrogen envelope mass in G104-27 to be log $(M_{\mathrm{H}}/M_{\odot}) \sim -16.6 \pm 0.3$, if a stratified model is appropriate for this star.

EXOSAT observed, but failed to detect, G104-27 at soft X-ray wavelengths (Paerels & Heise 1989). To match the 3 σ upper limit to the count rate in the LE4 and Al/P filters, Paerels and Heise required a homogeneous atmosphere with log (He/H) > -4.2. Pearels and Heise used a slightly different, less constrained T_{eff} for G104-27. If we repeat their analysis for the same count rate, we obtain log (He/H) > -3.8, a result clearly consistent with our He I λ4471 result. Furthermore, Vennes, Fontaine, & Wesemael (1989) have already estimated, for G104-27, the corresponding H envelope mass required for stratified models to fit the soft X-ray data, namely log $(M_{\mathrm{H}}/M_{\odot}) < -14.3$.

3. THE NATURE OF G104-27

The fits to the observed Lyman-α and Balmer profiles which lead to our estimates of the temperature and gravity of G104-27 show no evidence of any peculiarities. We can also use these estimates of T_{eff} and log g, along with a parallax of $\pi = 0''.0238 \pm 0''.0031$ (Harrington & Dahn 1980), to estimate the mass, radius, and bolometric luminosity of G104-27; $M/M_{\odot} = 0.63 \pm 0.20$, $R/R_{\odot} = 0.0131 \pm 0.0017$, and log $(L/L_{\odot}) = -1.15 \pm 0.12$. Thus, the mass and radius place G104-27 near the standard white dwarf mass-radius relation (Hamada & Salpeter 1960). G104-27 therefore appears to be unusual only in that it exhibits trace He in the optical.

In a widely quoted result, Paerels & Heise (1989) plot He abundance as a function of effective temperature for the bulk of all DA white dwarfs observed with *EXOSAT* and *Einstein*. Of the 21 stars plotted, G104-27 and one other star (PHL 380) stand out as having only *lower limits* to their He abundance. This occurs because G104-27 is bright enough and hot enough to have been detected with *EXOSAT*, but was not. The conclusion therefore is that G104-27 must possess a source of soft X-ray opacity which can suppress the observed flux.

As we have shown, He is clearly present in sufficient quantity to supply this opacity. To our knowledge this is the first clear *spectroscopic* demonstration of He in sufficient quantity to be responsible for the soft X-ray opacity. In several objects, the observed soft X-ray opacity could well be supplied by metals as in Feige 24 (Vennes et al. 1989), and we might remain largely unaware of it. It will, of course, be of great interest to see whether more sensitive *ROSAT* soft X-ray observations might succeed in detecting G104-27. Specific predictions of *ROSAT* count rates (Barstow 1990) based on the atmospheric parameters presented here suggest that such a detection is not expected. Should G104-27 be detected, this could have important implications for our current understanding of DA atmospheres.

We are unable, on the basis of our data, to distinguish between a stratified or homogeneously mixed atmosphere for G104-27. A stratified structure would be natural for a DA white dwarf. However, the fact that G104-27 resides near the red edge of the DB gap, in a region where DA stars could well transform into DB stars through convective mixing in the underlying helium envelope, suggests that the envelope stratification might be destroyed (Liebert, Fontaine, and Wesemael 1987). Of course accretion from the ISM could also leave observable traces of helium. Should this be the case, however, the required steady state accretion rate would be $\sim 6 \times 10^{-17}$ $M_{\odot}$ yr^{-1}. Note that an examination of the local ISM in the direction of G104-27 indicates a generally low H I density ($n_{\mathrm{H}} \sim 0.03$ cm^{-3}) along this line of sight. Such densities can be inferred from the H I maps of the local ISM of Paresce (1984) and Frisch & York (1983), where G104-27 is seen to lie well within the contour of 10^{19} cm^{-2} H I column density and well away from the cloud in Taurus. This conclusion is strengthened by careful comparisons with two other DA stars in the vicinity of G104-27 which *have* been detected in the soft X-ray. These are GD 71 ($l = 192^{\circ}.4$, $b = -4^{\circ}.7$, $D \sim 40$ pc) and WD 0631+107 ($l = 201^{\circ}.4$, $b = 1^{\circ}.0$, $D \sim 49$ pc), which conveniently bracket the location of G104-27 ($l = 193^{\circ}.5$, $b = 0^{\circ}.9$, $D = 42^{+6}_{-5}$ pc). Homogeneous He abundance estimates and soft X-ray H I columns are available for both stars. For GD 71, Paerels & Heise (1989) find log (He/H) < -4.5 and $N_{\mathrm{H}} = 3.5 \pm 0.5 \times 10^{18}$ cm^{-2}. For WD 0631+107, an *Einstein* soft X-ray source, Kidder (1990) finds log (He/H) $= -4.1 \pm 0.3$ and $N_{\mathrm{H}} = 3 \times 10^{18}$ cm^{-2}. WD 0631+107 and GD 71 are somewhat hotter than G104-27; $T_{\mathrm{eff}} = 27{,}700$ K and 33,000 K, respectively. In summary, we find that two DA white dwarfs in the immediate vicinity of G104-27 show no similar evidence of He I and in fact have soft X-ray He abundances significantly less than G104-27. If accretion were the source of He in G104-27, similar abundances might be expected for WD 0631+107 and GD 71. This observational evidence appears somewhat ambiguous, however, since the cool DZ6 white dwarf G105-B2B ($l = 201^{\circ}.3$, $b = -0^{\circ}.6$, $D \sim 53$ pc) also appears to lie in the general vicinity of G104-27. This star shows Ca II features, believed to be due to accretion of interstellar material (Sion, Kenyon, & Aannestad 1990).

To date only one DAB white dwarf has been described in the literature, GD 323. Spectra of two others, discovered as part of the Montreal-Cambridge-Tololo (MCT) Survey (Demers et al. 1986), are currently under analysis. Liebert et al. (1984) reported the results of a comprehensive study of GD 323. They found the overall energy distribution, from the optical to the UV, to be incompatible with the strengths of the H I Balmer and He I lines in the optical. Their analysis could find no single homogeneous model atmosphere capable of fitting all observations. They suggested that stratified atmospheres could perhaps resolve this dilemma. Koester (1989a, 1991) discusses continuing efforts to explain GD 323 in terms of such stratified models. He achieves a more satisfactory fit to the existing data with a stratified model having $T_{\mathrm{eff}} = 27{,}500 \pm 500$ K and a hydrogen envelope mass of log $(M_{\mathrm{H}}/M_{\odot}) = -17.3 \pm 0.1$, a first instance of stratified models clearly outperforming homogeneous models.

The relationship of G104-27 to GD 323 is unclear in spite of the fact they share a common spectroscopic designation. The other known DAB stars, GD 323 and the other two MCT stars, have been classified on the basis of spectra with modest (7–8 Å) spectral resolution and modest S/N. For example, the equivalent width of the He I λ4471 feature in GD 323 is 2.1 ± 0.4 Å. In contrast, the weak hybrid nature of G104-27 is only apparent at high spectral resolution and high S/N. It is also significant that G104-27 does not seem to share the incompatibilities between continuum and detailed spectral features evident in GD 323. Perhaps this is merely due to the significantly lower He abundance or alternately larger H envelope mass in G104-27 than in GD 323. A comprehensive analysis of all DAB stars with stratified models may shed light on these peculiarities.

Further investigations of G104-27 are clearly warranted. In addition to the previously mentioned possibility of a *ROSAT* detection, a search for metal lines, particularly Si III, is possible with *IUE* at high dispersion. The only existing high-dispersion spectrum is too weakly exposed to provide useful limits. Additional high S/N optical spectra would also be of use in a search for further He I features, particularly in the red. Finally, our investigation raises the unavoidable question of how many other DA stars in that temperature range may reveal weak He I features if observed at high dispersion and S/N ratio.

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