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ATMOSPHERIC ANALYSIS OF THE CARBON WHITE DWARF G227−5

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ABSTRACT

Observations and a model atmosphere analysis of the spectrum of the white dwarf G227−5 (=1728+56) are reported. This star's spectrum is dominated by lines of C I, but weaker features attributed to H I and He I are also found. With the gravity fixed at log $g = 8$, the following atmospheric parameters are derived: $T_{\rm eff} = 12{,}500 \pm 500$ K, and the number abundances C:He = $(3 \pm 1) \times 10^{-3}$ and H:He = $(2 \pm 1) \times 10^{-4}$. With these relatively high values of C:He and $T_{\rm eff}$, it appears that G227−5 represents a new type of white dwarf defined by the presence of C I lines in its spectrum and that it can be interpreted as being an object near the maximum of the carbon abundance vs. $T_{\rm eff}$ curve predicted for carbon being brought to the surface by the convective zone penetrating downward into a carbon abundance gradient.

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

I. INTRODUCTION

Carbon has been known to exist in the atmospheres of the C_2, λ4670, or DQ white dwarfs for over a quarter of a century (cf. Greenstein and Matthews 1957). Some earlier analyses of a handful of these objects (Grenfell 1974; Bues 1973) established that these stars have helium-dominated atmospheres with only traces of carbon present. However, it has not been until relatively recently that the phenomenon of carbon in white dwarf atmospheres has been studied systematically. The two developments contributing to renewed interest are (1) the detection of strong ultraviolet C I lines using the *IUE* satellite on the hotter DC stars (Weidemann, Koester, and Vauclair 1980, 1981; Vauclair, Weidemann, and Koester 1981, 1982; Wegner 1981*a*, *b*; 1983*a*, *b*) and (2) use of high signal-to-noise ratio digital detectors in the visual (e.g., Wegner and Yackovich 1982; Wegner 1983*c*) with the result that weak carbon features are found in the spectra of many of the He-rich degenerates.

Furthermore, the reexamination of the DC white dwarfs has yielded a handful of hotter objects that show the visual neutral carbon lines. Some of these include G268−40, G47−18 (Koester, Weidemann, and Zeidler-K.T. 1982; Wegner and Yackovich 1984), G35−26 (Liebert 1983), and LP 93−21 (Greenstein *et al.* 1977). However, careful examination of the spectra of the hotter DB stars (Wickramasinghe 1983; Shipman 1984; Wegner and Nelan 1984) that have a range of effective temperatures extending down to the upper temperature limit of these objects with carbon, show no evidence for carbon in their atmospheres, indicating that the presence of carbon terminates somewhere in the vicinity of $T_{\rm eff} >$ 13,000 K.

From these studies of the DB stars and additional investigations of cool DC white dwarfs, Wegner (1983*a*, *b*) concluded that carbon in white dwarf atmospheres is mostly limited to 13,000 K $> T_{\rm eff} >$ 6,000 K. Furthermore, even the lowest carbon abundances found are too high to be explained by available accretion theories (Wegner and Yackovich 1983, 1984), but a range in $T_{\rm eff}$ for the occurrence of carbon suggests that in some way, that element is brought to the surface layers of the white dwarfs by convection.

Consequently, the discovery that the relatively hot white dwarf G227−5 has a visual spectrum which is dominated by neutral carbon (Wegner 1983*c*) is of considerable interest for checking ideas on the origin of carbon in white dwarf atmospheres. It is near the expected upper $T_{\rm eff}$ limit for these stars and the predicted maximum of carbon if it is brought to the surface by convection. The present investigation reports additional visual spectroscopic observations of G227−5 and provides a spectrum synthesis analysis of its atmosphere.

II. OBSERVATIONS

The earliest published spectral type for G227−5 is DC (Hintzen and Strittmatter 1974), and it has more recently been described as a DBQ4 (Greenstein 1984). However, the presence of neutral carbon lines in this star's spectrum was discovered independently from examination of a sample of DB stars at Palomar in 1981 employing an SIT (Oke 1983) which were being studied by the Kiel group and reexamination of all DC white dwarfs with the Kitt Peak IIDS in 1982 (Wegner and Yackovich 1982; Wegner 1983*c*). We subsequently decided to study this object jointly.

Spectroscopic observations of G227−5 which clearly revealed the presence of the C I lines and employed in this study were obtained by G. W. 1982 May 25, using the Kitt Peak 2.1 m telescope and the Image Intensified Dissector Scanner (IIDS) attached to the Gold Spectrograph. A 300 lines mm^{-1} grating in first order was employed, and the resulting scan covers most of the visual spectrum (λλ3300–6900) with a resolution of about 17 Å.

An additional scan of G227−5 was secured 1983 November 11 and 12, using the same IIDS system attached to the Kitt Peak 4 m telescope, but employing an 831 lines mm^{-1} in second order and a $CuSO_4$ order separation filter. This scan

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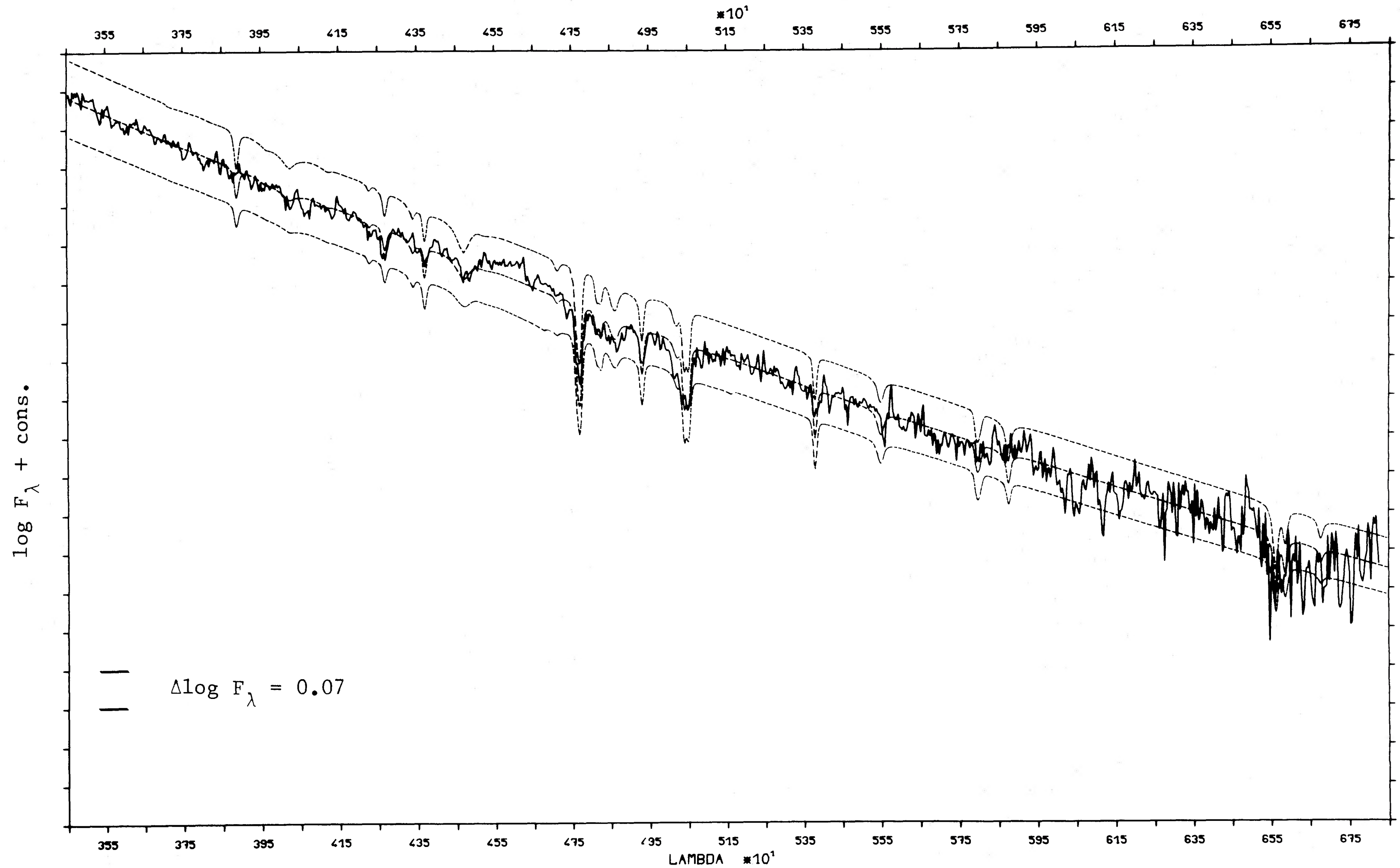

FIG. 1.—Comparison of observed G227−5 spectrum (*full line*, log F_λ) with theoretical models of 12,000, 12,500, and 13,000 K (*dashed lines*, from top). The 12,000 and 13,000 K models have been shifted arbitrarily. Abundances are C:He = 4×10^{-3}; H:He = 1×10^{-4}.

has a smaller wavelength coverage ($\lambda\lambda$4300–5100), but a higher resolution of about 2.3 Å.

The data were converted to true stellar flux using the reduction programs provided at the Kitt Peak National Observatory. This consists of sky subtraction, division of each spectral scan by that from a quartz lamp, correcting for the instrument's sensitivity using standard stars, and taking out the effects of atmospheric absorption by adopting the mean extinction for Kitt Peak.

III. MODEL ATMOSPHERES

a) Description of the Models

The model atmosphere calculations used for this analysis of G227−5 are a higher temperature extension of the He-rich model grid employed by Koester, Weidemann, and Zeidler-K.T. (1982) and Zeidler-K.T. (1983) for the interpretation of DC and C_2 white dwarfs. The basic methods are described in Koester, Schulz, and Weidemann (1979) and Koester (1980).

Convection is included in the present calculations, employing Böhm-Vitense's (1958) mixing length approximation with $l/H_p = 1$. The line blanketing of He and the strongest ultraviolet C I and C II lines is taken into account. The temperature structure of the flux constant model is used to compute synthetic spectra in the range 3,000–8,000 Å, including the absorption of approximately 50 atomic lines of He, H, C I, and C II and about 60 molecular bands of C_2.

After computing a preliminary grid of models with $\log g = 8$ and $T_{\rm eff}$ ranging from 10,000 K to 15,000 K, the final fit was achieved by constructing models having $T_{\rm eff}$ = 12,000, 12,500, and 13,000 K and varying the C and H abundances relative to He. All other elements were neglected since they do not show up in the star's spectrum and because with the high C abundance found below. He and C will entirely dominate as opacity and electron contributors in the atmosphere.

b) Results of the Atmospheric Analysis

Effective Temperature.—Figure 1 shows the complete IIDS spectrum of G227−5 compared to three carbon-rich model spectra with $T_{\rm eff}$ = 12,000, 12,500, and 13,000 K. The $T_{\rm eff}$ = 12,500 K achieves a good fit to the overall continuum slope, which is also confirmed by Palomar multichannel observations (Oke 1983). Therefore we adopt $T_{\rm eff} = 12{,}500 \pm 500$ K as a preliminary temperature estimate. Oke, Weidemann, and Koester (1984) assigned the much higher temperature of

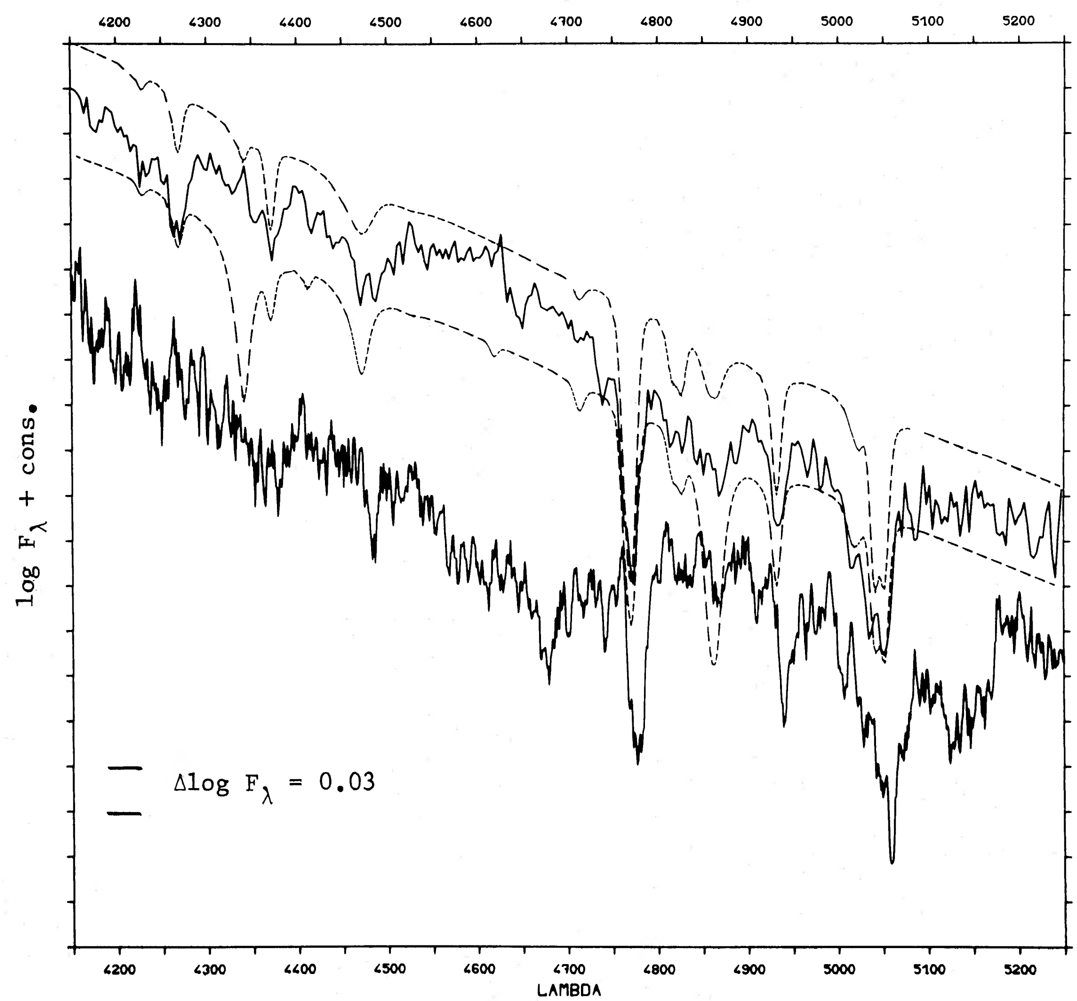

FIG. 2.—Enlarged part of the spectrum of G227−5, showing the strongest carbon features (*upper full line*, log F_λ). The parameters of the theoretical models (*dashed*) are $T_{\rm eff}$ = 12,500 K, $\log g = 8$, C:He = 4×10^{-3}, H:He = 1×10^{-4}. Also shown for comparison is the spectrum of the C I/C_2 star G268−40 (Koester, Weidemann, and Zeidler-K.T. 1982).

18,000 K to this star earlier using pure helium model atmospheres, which demonstrates that the object mimics a higher temperature continuum if pure He models are employed for the analysis.

Carbon Abundance.—The corresponding carbon abundance can be best determined from the strong C I lines: λλ4371, 5040/50, and 4765/75, which are temperature insensitive in the range 12,000–13,000 K. In the detailed comparison between the models and observation shown in Figure 2, the detailed agreement is not perfect, but the C abundance must certainly be in the range of $(3 \pm 1) \times 10^{-3}$ compared to He.

In most cases, the residual discrepancies between the theoretical and observed spectra can be attributed to noise (e.g., the feature near 4650 Å, which is absent from the more recent spectra taken with the Kitt Peak 4 m telescope), uncertainties in the damping constants (Γ_6), and the neglect of many weaker C I lines with unknown oscillator strengths. However, one possible exception to this should be noted.

The λ4478 line is a blend of several C I two-electron transitions. This line should be present in G227−5, but was not included in the calculations because the f-values are unknown. Figure 2 shows that there is some additional absorption on the red wing of He I 4471 Å, which can probably be attributed to this C I feature.

The spectrum of G268−40 is shown for comparison in Figure 2. The C abundance in this object is similar to G227−5, but $T_{\rm eff}$ is 2,000 K lower (Koester, Weidemann, and Zeidler-K.T. 1982) giving rise to strong C_2 bands, which are absent in G227−5.

Helium Lines.—λ4471 of He I is certainly present and λ4026 is probably there. The theoretical spectra in Figures 1 and 2 demonstrate the dependence of He line strength on temperature and carbon abundance which comes through the He^- continuous opacity and the C abundance as an electron donor. Therefore it is important to calculate models and synthetic spectra consistently with the same elemental abundances. If this is done, the λ4471 strength is additional evidence for $T_{\rm eff} = 12{,}500$ K.

Hydrogen Abundance.—The spectrum clearly shows an absorption near the position of Hβ, a weak feature at Hα, and nothing at Hγ. In order to study the effect of a nonnegligible H content, synthetic spectra were calculated for different H:He ratios in the range of 10^{-4} to 10^{-3}. As shown in Figures 1 and 2, H:He $= (2 \pm 1) \times 10^{-4}$ is consistent with the observations; Hβ is indeed expected to be much weaker than Hα, and its invisibility can be explained by observational noise.

Liebert (1983) has noted a similar steep hydrogen line decrement in G35−26 which he attributed to neutral helium being the primary line broadening agent. Most probably, G35−26 is rather similar to G227−5, but with a somewhat lower temperature and hydrogen abundance.

IV. DISCUSSION

In view of the discovery of the high carbon abundance (C:He 10^{-3}) in G227−5 and other comparatively hot degenerates ($T_{\rm eff}$ 10,000 K): e.g., G47−18 (Koester, Weidemann, and Zeidler-K.T. 1982; Wegner and Yackovich 1984), G35−26 (Leibert 1983), and G268−40 (Koester, Weidemann, and Zeidler-K.T. 1982), which all seem to be related, a whole new class of white dwarfs that is defined by the presence of C I lines in the spectrum seems firmly established. By comparison, the classical carbon white dwarfs that show the Swan bands of C_2, variously called DQ, 4670, or C_2 white dwarfs (cf. Greenstein 1958), generally are cooler with $T_{\rm eff}$ in the range of 9,000–6,000 K and have lower C:He abundances of order 10^{-5} to 10^{-6} (Koester, Weidemann, and Zeidler-K.T. 1982; Wegner and Yackovich 1984).

A new spectroscopic designation for these stars seems unnecessary at the present. They can be incorporated by the new white dwarf spectral class scheme of Sion *et al.* (1983), most probably as type DBQA4. However, it should be noted that the visual spectrum of G227−5 does differ from any object described in the earlier white dwarf literature.

These hotter carbon white dwarfs might be the precursors of the cooler C_2 band objects. It now seems clear that the observed C:He abundances are too high to be explained by existing theories of accretion from the interstellar medium (cf. Wegner and Yackovich 1983, 1984), but the restricted range in $T_{\rm eff}$ where C appears in the atmospheres of the He-rich degenerates (Wegner 1983*a*, *b*) and the details of their carbon abundance with $T_{\rm eff}$ fit nicely with the carbon being dredged up by convection from the stars' deeper layers (Wegner and Yackovich 1983, 1984).

Furthermore, this supports the qualitative ideas proposed by Koester (1981) and Koester, Weidemann, and Zeidler-K.T. (1982) and the calculations of Fontaine *et al.* (1984), wherein an equilibrium diffusion profile is set up around the He/C transition and the carbon is dredged up when the He convection zone penetrates into the "tail" of the carbon profile. A major prediction of this dredging theory is that the highest C:He ratios occur for the effective temperature range near 10,000–12,000 K where the surface convection zone reaches maximum depth.

Figure 3 compares the location of G227−5 in the $T_{\rm eff}$ versus log C:He diagram with that of other carbon white dwarfs for

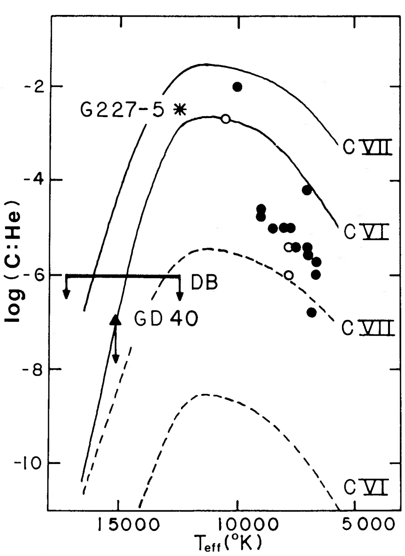

FIG. 3.—The position of G227−5, derived from this study (*), compared with those of some other carbon white dwarfs (●) reported in Wegner and Yackovich (1984) and (○) Koester, Weidemann, and Zeidler-K.T. (1982) and (▲) the DB star GD 40 (Shipman 1984) and preliminary *IUE* DB data (Wegner and Nelan 1984). The continuous and dashed curves give theoretical predictions of C:He surface abundances produced by the carbon abundance gradient and convective dredging from Fontaine *et al.* (1984) for 0.6 $M_\odot$ models with log $q = -4$ and -2 (*top and bottom set of curves*, respectively). These are based on the assumption that the equilibrium profiles are determined by either C VI or C VII diffusing in He III below the convection zone.

which atmospheric analyses are available and the upper limits for some DB stars (Wickramasinghe 1983; Shipman 1984; Wegner and Nelan 1984). These observational data are then compared with the C:He number ratios predicted by Fontaine *et al.* (1984) for equilibrium abundance profiles in a 0.6 $M_{\odot}$ white dwarf. The curves have been constructed assuming that the equilibrium profiles for carbon are governed by the cases of C VI and C VII diffusing in He III below the convection zone and adopting different He envelope masses, log $q(\mathrm{He}) = \log M(\mathrm{He})/M_{*} = -4$ and -2 (*top and bottom pairs of curves*, respectively). From the location of G227−5 in Figure 3, it appears that this white dwarf lies near the maximum carbon abundance predicted by Fontaine *et al.* (1984) for the carbon white dwarfs, giving a helium envelope mass of order $\log q = -4$. Due to the rapid decline in C:He foretold for $T_{\mathrm{eff}} > 13{,}000$ K, few carbon white dwarfs hotter than G227−5 are to be expected. It is interesting to note how the absence of observed C in the DB atmospheres appears to confirm the shape of the C:He curves as a function of T_{eff}.

V. CONCLUSIONS

This analysis of the spectrum of G227−5 has brought to light two new details about the carbon abundance in the helium-rich white dwarfs: First, the relatively high values of $T_{\mathrm{eff}} = 12{,}500$ K and number abundance $\mathrm{C:He} = 3 \times 10^{-3}$ found for this star added weight to earlier conclusions that higher atmospheric abundances tend to be more common among the hotter carbon white dwarfs (Wegner and Yackovich 1984). Second, G227−5 is an example of a recently discovered class of He-rich white dwarfs, defined by the presence of C I lines in the visible spectrum.

These results appear to fit in well with an interpretation of the carbon in the atmospheres of white dwarfs like G227−5 having been brought from the deeper layers of its atmosphere by the combined process of convection and the existence of a carbon abundance gradient with depth in the outer He envelope (cf. Koester, Weidemann, and Zeidler-K.T. 1982). Employing the theoretical results of Fontaine *et al.* (1984), G227−5 is an object near maximum C:He and has a helium envelope mass of near $\log q \sim -4$. If the occurrence of carbon is indeed due to the convective mixing of material from the processed carbon core of the white dwarf, further studies of elemental abundances in white dwarfs like G227−5 should yield further information on their envelope structure and the processes of stellar evaluation leading to their formation.

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