1995ApJ...443..274S

THE ASTROPHYSICAL JOURNAL, 443:274–280, 1995 April 10
© 1995. The American Astronomical Society. All rights reserved. Printed in U.S.A.

# ON THE NATURE OF THE SPECTRAL FEATURES IN PECULIAR "DQ" WHITE DWARFS[1]

GARY D. SCHMIDT
Steward Observatory, University of Arizona, Tucson, AZ 85721; gschmidt@as.arizona.edu

P. BERGERON
Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec, Canada H3C 3J7; bergeron@astro.umontreal.ca

AND

BRUCE FEGLEY, JR.
Department of Earth and Planetary Sciences, Campus Box 1169, Washington University, One Brookings Drive, St. Louis, MO 63130-4899; bfegley@planet.win.net

*Received 1994 August 19; accepted 1994 October 19*

## ABSTRACT

Spectropolarimetric measurements are presented for the DQ white dwarfs ESO 439−162, LHS 1126, and G225−68, whose spectroscopic features in the optical have been interpreted in the past as pressure-shifted or magnetically shifted $C_2$ Swan bands. The results convincingly demonstrate that none of these objects is strongly magnetic, with upper limits of 30, 3, and 2 MG, respectively. Since Bergeron et al. have recently ruled out the pressure-shift interpretation for LHS 1126 as well, we discuss alternative physical mechanisms for displacing the Swan bands. Although possibilities for explaining the observed shifts may exist, a comparison of the optical spectra (and that of a similar DQ star, LP 77−57) indicates that the locations and shapes of the profiles in all four objects are virtually identical. This last result suggests instead that a different molecular species could be responsible. A detailed chemical equilibrium analysis of H/He/C mixtures under the physical conditions encountered in the atmospheres of these peculiar objects reveals that $C_2H$ is a molecule preferentially formed in the photospheric regions. The nature and evolution of these objects are discussed.

*Subject headings:* polarization — stars: abundances — stars: atmospheres — stars: magnetic fields — white dwarfs

## 1. INTRODUCTION

Recently, Bergeron et al. (1994b, hereafter B94; see also Greenstein & Liebert 1990) called attention to four cool white dwarfs, each of which shows a series of broad absorption features in the spectral region ∼4200–5600 Å: ESO 439−162, LHS 1126,[2] G225−68,[3] and LP 77−57.[4] In none of the objects do the features accurately match laboratory wavelengths of any known atomic or molecular species. Nevertheless, the stars are classified as type DQ due to their remarkable spectral resemblance to white dwarfs showing the Swan bands of $C_2$. In all four objects shifts of $\sim 400$ cm$^{-1}$ ($\sim 100$ Å) to the blue of their rest wavelengths are required. The possibility that high atmsopheric pressures are responsible for shifting the bands from their normal locations in LHS 1126 was proposed by Liebert & Dahn (1983) and emphasized by Greenstein & Liebert (1990). This idea was refuted by B94, however, who interpreted the strong infrared flux deficiency observed in LHS 1126 as the result of collision-induced absorptions by molecular hydrogen due to collisions with helium; the pressure in the continuum-forming region of their best-fitting model [$T_{\rm eff} = 5400$ K, $\log g = 7.85$, and $N({\rm He})/N({\rm H}) \sim 6$] is actually relatively low, and about a factor of 3 smaller than in the coolest DQ stars whose $C_2$ bands appear at rest.

An alternative explanation, magnetic displacements of the $C_2$ features in fields of $\sim 10^8$ G, has been suggested for ESO 439−162 by Ruiz & Maza (1988) and for LP 77−57 by Hintzen et al. (1989). This interpretation is motivated by a similarity in appearance to the overwhelming absorption trough in LP 790−29, which Liebert et al. (1978) attributed to magnetically distorted Swan bands. LP 790−29 is strongly polarized, so it is reasonable that its shifts of ∼180 Å are magnetic in origin. However, no polarimetry has been reported for ESO 439−162 or LP 77−57, and solid broadband nulls have been recorded for G225−68 and LHS 1126 (Angel, Borra, & Landstreet 1981; Liebert & Stockman 1980). Spectropolarimetry quoted by B94 also argued strongly against the magnetic interpretation for LHS 1126. In this paper we present those data, as well as new optical spectropolarimetry of two of the other peculiar stars. Our null results convincingly rule out the suggestion that the observed features in these objects are carbon features shifted by a magnetic field.

The observations are briefly summarized in § 2. In § 3 we tender strong arguments against magnetism as the explanation for the shifted features. Alternative possibilities are explored in § 4, and ramifications and suggestions for future study are discussed in § 5.

## 2. OBSERVATIONS

Observations of the peculiar DQ stars were obtained during 1993–1994 utilizing the Steward Observatory 2.3 m telescope and CCD spectropolarimeter described by Schmidt, Stock-

[1] A portion of the data presented here was obtained with the facilities of Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2] = WD 0038−226, G266−157, LTT 375, LFT 65, LP 825−669, L651−57.

[3] = WD 1633+572, LP 101−16, GL 630.1B, LHS 422.

[4] = WD 2351+650.



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



TABLE 1

OBSERVING SUMMARY

| Object | Spectral Type | $m_V$ | UT Date | Telescope | $\lambda\lambda$ | Resolution | $\langle V \rangle$ |
|---|---|---|---|---|---|---|---|
| LHS 1126 ........... | DQ?10 | 14.5 | 1993 Aug 23 | 2.3 m | 4680–6810 | 12 Å | −0.04% ± 0.03% |
| G225−68 ........... | DQ8 | 15.0 | 1993 Oct 8 | 2.3 m | 4670–6800 | 12 Å | −0.01% ± 0.03% |
| | | | 1994 May 15–16 | 2.3 m | 4150–7480 | 19 Å | −0.02% ± 0.02% |
| ESO 439−162...... | DQ | 18.8 | 1994 Feb 16 | 2.3 m | 4160–7480 | 19 Å | −0.11% ± 0.40% |
| | | | 1994 May 15 | 2.3 m | 4150–7480 | 19 Å | +0.50% ± 0.43% |
| LP 790−29 ......... | DQP9 | 16.0 | 1994 May 7–8 | 4.0 m | 4160–7460 | 19 Å | +5.43% ± 0.04% |

man, & Smith (1992) configured for circular polarimetry. The observing summary in Table 1 notes a variety of occasions and different instrumental setups. Observing procedures were as outlined by Schmidt et al., using nightly flux standards calibrated by Massey et al. (1988) and known circularly polarized stars observed each run to verify instrument performance. The value of circular polarization summed over the observed spectrum is noted in the table; for each star the results are the co-addition of more than one observation of the Stokes parameter $V$, and the statistical agreement between measurements was used in determining the uncertainty $\sigma_V$. Also noted are new observations of LP 790−29, obtained with the 4 m Mayall telescope of Kitt Peak National Observatory in the same manner. The polarization and flux spectra for these stars are presented in Figures 1 and 2. Obvious in the spectra displayed in Figure 1 is a principal feature at $\lambda$5000, which has generally been assigned to the (0, 0) transition of the $C_2$ Swan bands, displaced from its zero-field location.

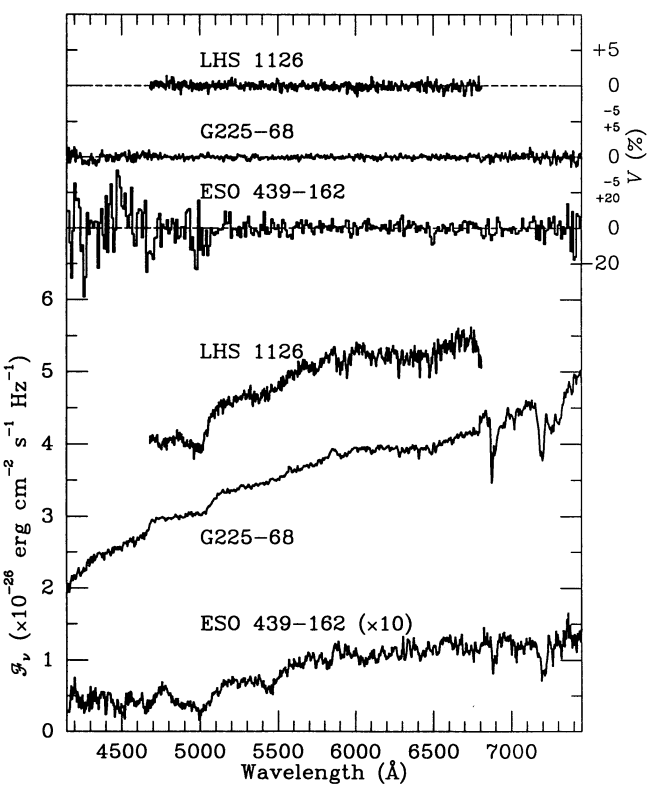


FIG. 1.—Total flux and circular polarization ($V$) spectra of LHS 1126, G225−68, and ESO 439−162 obtained in a search for magnetic fields. The lack of significant circular polarization in either the lines or continuum places an upper limit (3 $\sigma$) on the mean longitudinal ("effective") field strength of $B_e \lesssim 3$, 2, and 30 MG for the three stars, respectively. This falls far short of what is required to explain the absorption features near $\lambda$5000 as $C_2$ Swan bands shifted by $\sim$600 cm$^{-1}$ ($\sim$150 Å) from their normal locations.

## 3. FAILURE OF A MAGNETIC INTERPRETATION

In general, the presence of a magnetic field may be inferred from Zeeman-displaced $\sigma$ components of an absorption line or through magnetic dichroism in the continuum opacity which gives rise to different brightness temperatures for opposing senses of polarization. Both yield circular polarization in a longitudinal magnetic field. For LP 790−29, the effect appears predominantly in the continuum (Liebert et al. 1978 and Fig. 2), where one of the largest polarizations among magnetic white dwarfs is seen ($V \sim 8\%$). In contrast, our measurements for the three peculiar stars reveal no polarization of significance anywhere in the spectrum. Scaling with continuum polarization from a value of $\sim$200 MG for LP 790−29 (Bues 1993), crude upper limits (3 $\sigma$) to the disk-averaged longitudinal component $B_e$ for LHS 1126, G225−68, and ESO 439−162, are 3, 2, and 30 MG, respectively.

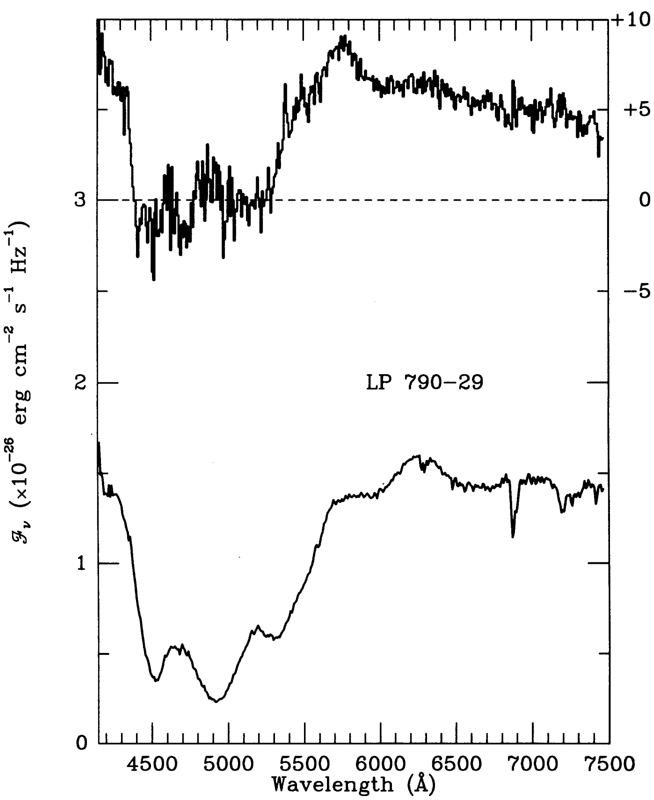


FIG. 2.—New spectrophotometry and circular spectropolarimetry of the strongly polarized white dwarf LP 790−29. Interpretation of the features as magnetically displaced $C_2$ Swan bands indicates a polar field strength of $\sim$200 MG.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



Additional evidence against magnetic displacements in the peculiar stars is presented in Figure 3. Here we compare in a single plot the spectral region surrounding the $C_2$ Swan bands for several cool white dwarfs of interest: L879−14 (Wegner & Yackovich 1984) and BPM 27606 (adapted from Wickramasinghe & Bessel 1979) illustrate two "normal" DQ stars of widely different line strengths, with BPM 27606 representing the DQ white dwarf with the strongest known $C_2$ features. G99−37 is a magnetic DQ white dwarf of comparatively weak field, $B_s \approx 3.6$ MG (Angel & Landstreet 1974). The spectrum is taken from Wesemael et al. (1993). G99−37 is also the only known DQ star to exhibit a CH feature at 4300 Å. In these three objects, the $C_2$ origin of the features is uncontested. The spectrum of the magnetic star LP 790−29 from Figure 2 is reproduced at the bottom of the plot and is discussed below. The middle four spectra portray the stars of interest here: G225−68 (data from Fig. 1), LHS 1126 (from Wesemael et al.),

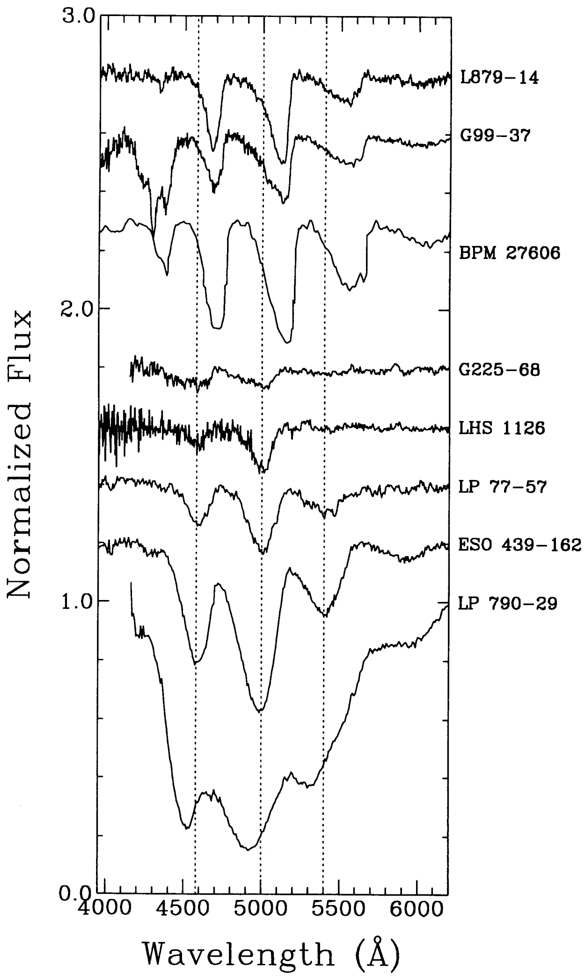


FIG. 3.—Comparison of the spectral region surrounding the Swan bands for (top to bottom): three "normal" DQ white dwarfs, the four peculiar stars studied here, and the strongly magnetic white dwarf LP 790−29. All spectra are normalized to a continuum set to unity and offset for clarity. Because of the strength of the $C_2$ bands in BPM 27606, its spectrum has been shrunk vertically by a factor of 2. Note also the presence of the CH feature at ~4300 Å in the spectrum of G99−37. Dotted lines drawn at wavelengths of λλ4575, 5000, and 5400 accurately denote minima of the major absorption features in *each* of the four peculiar stars. Displacements of ~150 Å and differences in the shapes of the line profiles of the peculiar stars compared to normal DQ stars are evident.

LP 77−57 (adapted from Hintzen et al. 1989), and ESO 439−162 (from Ruiz & Maza 1988). For the purpose of the comparison, the higher signal-to-noise ratio and/or extended wavelength coverage of these previously published spectra of LHS 1126 and ESO 439−162 were preferred to those displayed in Figure 1. We note, however, that both sets of spectra are consistent and that there is no evidence for any obvious spectroscopic variations.

Several interesting features emerge from an intercomparison of the four middle spectra. Most noteworthy is the extreme similarity in the location, symmetry, and overall shape of the profiles in *all four objects*. This has already been pointed out by B94 in the spectra of LHS 1126 and ESO 439−162. The strengths of the features vary considerably from star to star, however. In G225−68, only the two leftmost components are visible in our spectrum, while at least three components are detected in the three remaining objects (all three components in LHS 1126 are clearly visible on an expanded scale; see, e.g., Greenstein & Liebert 1990, Fig. 6*b*). ESO 439−162 even shows a fourth component around 5900 Å. The analogy drawn between these stars and normal DQ stars is understandable. However, give the strong field on LP 790−29, a magnetic interpretation of the peculiar stars demands that the field strengths on *all four must be* (*a*) *large, and* (*b*) *identical.* Both requirements are ruled out by our spectropolarimetry above, and we conclude that a different explanation for the optical features must be pursued. We further propose that these four stars form a physically distinct group of objects and that they define a new spectral class.

## 4. ON THE ORIGIN OF THE OBSERVED FEATURES

### 4.1. *Displaced Swan Bands*?

One of the arguments against magnetic field displacements—the dichotomy in position of the absorption features between the peculiar stars and their normal counterparts—applies to *any* mechanism involving simple shifts of the Swan bands. For continuous variables such as temperature, pressure, or even atmospheric composition, such a process would be expected to yield a continuous range of displacements. This is particularly relevant considering the huge range in line strength represented by the four stars. Even the bona fide DQ stars shown in Figure 3 span a temperature range 6300–7500 K and inferred carbon abundance of $N$(C)/$N$(He) $= 2 \times 10^{-6}$ to nearly $10^{-3}$, yet they exhibit $C_2$ features at virtually the same wavelengths (Grenfell 1974; Wegner & Yackovich 1984 and references therein). A viable $C_2$ interpretation must invoke a mechanism which is essentially quantized. Finally, profiles of the features in the peculiar stars are much more symmetric than in the common stars.

Despite these distinctions, the remarkable similarity to the Swan bands in number of features, spacing, and relative strength suggests that we begin by reinvestigating the $C_2$ molecule. The ensemble which is known as the Swan bands is a rotation-vibration sequence well-studied in comets. The lower electronic state, $a^3\pi_u$, is not the ground state of the molecule, but situated some 0.07 EV (600 cm$^{-1}$) above the lowest single state, $X^1\Sigma_g^+$. The five principal bands have heads at λλ4383, 4737, 5165, 5636, 6191 for $\Delta v = +2$ to $-2$, respectively, and are shaded to the blue.

Displacements of the bands could occur for absorption by molecules in high vibrational levels. Relative to the band minima in a normal DQ star like L879−14, the bands in the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



peculiar stars show displacements of approximately −95, −110, −145, and −180 Å for the features which can be measured ($\Delta v = +1$ to $-2$, respectively). In all cases, the magnitude and sense of the shifts could be explained by low-level states with vibrational quantum number $v'' \sim 4$. However, the required excitation of 6300 $cm^{-1}$ (Phillips 1948) above the ground vibrational level requires a temperature $T_{vib} \gtrsim 10{,}000$ K, well in excess of the photospheric temperatures of the stars. It is true that, because the molecule is homonuclear, nonelectronic (i.e., strictly rotation or vibration transitions) are forbidden, and, in the absence of collisions, level populations can be driven well out of thermal equilibrium (e.g., A'Hearn 1982). However, this situation, which prevails in the coma of a comet, is not likely to occur in a dense stellar atmosphere. A peculiar vibrational population would also be expected to yield unusual band strengths for the Swan series, since various bands in the sequence arise from different lower states. In fact, the relative equivalent widths are similar to the garden-variety DQ stars at the top of Figure 3.

An alternate possibility is absorption from excited states of rotation. The required degree of excitation, $J'' \sim 40$, corresponds to $\Delta E \sim 0.35$ eV, and thus is energetically more feasible than vibrational elevation. Populations of these levels become appreciable in a plasma at $T_{rot} \sim 5000$ K, similar to the photospheric temperatures of these stars. Moreover, because of the $2J + 1$ degeneracy of rotational levels, this mechanism has the added advantage of producing level populations which are not Boltzmann, but actually peak at a specific $J$-value. Thus they naturally give rise to more-or-less symmetric band composites (e.g., Herzberg 1950).

A final $C_2$ option stems from the rough coincidence between the magnitude of observed spectral shifts, $\sim$400 $cm^{-1}$, and the separation of the $a^3\Pi_u$ and ground $X^1\Sigma_g^+$ state. Absorptions directly from the ground state to the $d^3\Pi_g$ upper state of the Swan transitions would produce an ensemble whose electronic term is offset by approximately the required amount. These are spin-forbidden intercombination transitions, discussed generically in detail and specifically in passing by Gredel, van Dishoeck, & Black (1989). For such a mechanism to dominate the normal Swan bands, it would seem that the $a^3\Pi_u$ state would have to be closely coupled to the ground state by collisions, as might occur in a high-pressure atmosphere. The Mulliken bands near $\lambda$2300 and the Phillips group near $\lambda$8000—singlet transitions from the ground state—should then be extremely prominent.

Thus, it would appear that there are possibilities for explaining the optical absorption features of peculiar DQ stars while retaining a $C_2$ origin. However, given the likely thermal equilibrium in a dense white dwarf atmosphere, the difficulty is in envisioning a difference in the atmospheric conditions of these versus normal DQ stars which could give rise to such a fundamental distinction in the microphysics. An alternative origin is proposed below.

### 4.2. *A Carbon and Hydrogen Compound?*

An important clue to the puzzle may reside in detailed abundance analyses of the four objects. Such an analysis of LHS 1126, the only object thoroughly studied thus far, has been presented by B94. Their results portray an atmosphere composed of comparable amounts of hydrogen and helium [$N(\mathrm{He})/N(\mathrm{H}) \sim 6$], a most unusual feature with respect to the ongoing analysis of Bergeron, Ruiz, & Leggett (1994a; see Ruiz, Bergeron, & Leggett 1993 for preliminary results of this investigation). That study reveals that cool white dwarf stars appear to have either hydrogen- or helium-dominated compositions. With the glaring exception of LHS 1126, no objects with intermediate composition were found. Although only partial data are available for the three other peculiar objects, preliminary analyses strongly suggest that, in addition to the observed peculiar features, helium-to-hydrogen ratios near unity may differentiate these objects from garden-variety white dwarfs. In contrast, normal DQ stars have well-established hydrogen-depleted atmospheres [$N(\mathrm{H})/H(\mathrm{He}) \lesssim 10^{-3}$; Wegner & Yackovich 1984]. In Table 2 we provide for reference a summary of measured atmospheric parameters for the peculiar and normal DQ stars considered here.

If hydrogen is present in the atmospheres of our peculiar objects, we also need to consider the possibility of carbon residing in various $C_nH_n$ compounds (e.g., CH, $CH_2$, $CH_3$, ..., $C_2H$, $C_2H_2$, ..., etc.). For example, G99−37 is a DQ star in which traces of hydrogen can be inferred from the presence of a spectroscopic CH $\lambda$4300 feature. Curiously, such a feature is not observed in any of our spectra. If we interpret the features observed in our objects as due to some carbon compound, the absence of CH $\lambda$4300 would seem to imply that the hydrogen abundance is much lower than that determined by B94. This is

TABLE 2

ATMOSPHERIC PARAMETERS

| Star | $T_{eff}$ (K) | log [$N(\mathrm{H})/N(\mathrm{He})$] | log [$N(\mathrm{C})/N(\mathrm{He})$] | Reference | $B$ (MG) | Reference |
|---|---|---|---|---|---|---|
| | | | Peculiar DQ | | | |
| LHS 1126 | 5400 ± 200 | −0.8 ± 0.2 | ... | 1 | <3 | 2 |
| G225−68 | ~6000 | ... | ... | 3 | <2 | 2 |
| ESO 439−162 | ~6300 | ... | ... | 4 | <30 | 2 |
| LP 77−57 | ~5000 | ... | ... | 5 | | |
| | | | Normal DQ | | | |
| LP 879−14 | 6600 | ≤ −2.7 | −5.7 | 6 | | |
| BPM 27606 | 7000 | ... | −4.2 | 6 | | |
| | | | Magnetic DQ | | | |
| G99−37 | 6300 | ... | −4 to −3 | 7, 8 | 3.6 | 8 |
| LP 790−29 | 7500 | ~ −5 | ~ −3 | 9 | ~200 | 9 |

REFERENCES.—(1) B94; (2) This paper; (3) Bergeron, Ruiz, & Leggett 1994a; (4) Ruiz & Maza 1988; (5) Hintzen et al. 1989; (6) Wegner & Yackovich 1984; (7) Grenfell 1974; (8) Bues & Pragal 1989; (9) Bues 1993.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



an oversimplified interpretation, however. The type(s) of molecule formed in the photospheric regions depends upon the elemental abundances, pressure, and temperature. For example, at the high temperatures found in the photospheres of white dwarfs, H/He/C mixtures will tend to form $CH_n$ molecules and radicals such as acetylene, $C_2H_2$, and its dissociation products. However, the high temperatures and low hydrogen abundance will discriminate against the formation of $CH_4$ and more complex saturated hydrocarbons. We explore this problem more quantitatively below.

The molecular equilibrium in our peculiar white dwarfs can be studied in detail using the sophisticated and robust thermochemical equilibrium code CONDOR used to calculate nebular condensation chemistry (Lodders & Fegley 1993) and chemistry in the deep atmospheres of Jupiter and Saturn (Fegley & Lodders 1994). It operates by simultaneously considering the constraints of chemical equilibrium, electroneutrality, and mass balance. The operation of the code as well as the database used are described in Fegley & Lodders (1994). Here we note only that the mass balance expressions for carbon and hydrogen consider several hundred molecules, radicals, and ions. At present the database for the CONDOR code can be used up to $T = 10{,}000$ K.

In the present calculations, we considered a mixture of H/He/C with all other elemental abundances set to negligibly low values. Both neutral equilibria and thermal ionization were considered in the calculations. In the only object well-studied so far, LHS 1126, the total gas pressure in the line-forming region ($\tau_R \sim 0.1$–$1.0$) is $\log P \gtrsim 9.0$ ($P$ in dyn cm$^{-2}$); we have thus considered values around this boundary. Since the carbon abundance in these objects is obviously unknown, we explore a range of values of $10^{-5} \leq N(\mathrm{C})/N(\mathrm{He}) \leq 10^{-2}$. We further assume $N(\mathrm{H})/N(\mathrm{He}) = 0.1$, characteristic of LHS 1126, and most likely of the other objects as well; we note that the key elemental abundance parameter in the calculations is the $N(\mathrm{H})/N(\mathrm{C})$ ratio since He is inert. The results of some of our calculations are displayed in Figure 4, where the mole fraction ($P_i/P$) of the most abundant $C_n$ or $C_nH_n$ compounds are plotted as a function of temperature. The vertical dotted lines show the temperature range in the line-forming region of LHS 1126 ($T \sim 5200$–$5600$ K).

Since CH is not observed spectroscopically in any of the peculiar stars, the results of Figure 4 can be used to constrain the physical conditions in the line-forming regions of these objects. For example, at low atmospheric pressure ($\log P = 8.5$) or low carbon abundance [$N(\mathrm{C})/N(\mathrm{He}) = 10^{-5}$], CH is a prominent molecular species. At high temperature [$T \gtrsim 6000$ K for $N(\mathrm{C})/N(\mathrm{He}) = 10^{-3}$; $T \gtrsim 7000$ K for $N(\mathrm{C})/N(\mathrm{He}) = 10^{-2}$], carbon is mostly atomic and neutral, and CH also dominates. We conclude from the absence of the CH $\lambda$4300 feature that the temperature in the line-forming region of these stars is low ($T \lesssim 7000$ K), the atmospheric pressure is large ($\log P \gtrsim 9.0$), and most importantly, the carbon abundance is of the order of $10^{-3}$ or greater.

Our results also indicate that $C_2H$ is the molecule preferentially formed under these physical conditions. It is therefore tempting to associate the observed spectroscopic features with the $C_2H$ molecule. The features could be the equivalent of the electronic transitions in the $C_2$ molecule that lead to the formation of the Swan bands. The presence of hydrogen might modify the potential of the $C_2$ molecule in such a way as to shift the transitions to the blue. Perić, Peyerimhoff, & Buenker (1991) have calculated the vibronic spectrum of $C_2H$ by ab initio methods, but their calculations extend only up to 7000 cm$^{-1}$ ($\lambda \gtrsim 1.4$ $\mu$m). Unfortunately, we are unaware of any detailed theoretical calculations of $C_2H$ (or $C_2H_2$) electronic transitions in the optical, and a definitive identification of the spectroscopic features must await the results of such calculations. We note finally that under the physical conditions explored here, the abundance of $C_2$ is always at least a factor of 10 lower than the abundance of $C_2H$, a result which offers a natural explanation for the absence of the $C_2$ Swan bands in the spectra of these peculiar objects.

Carbon abundances as large as $\sim 10^{-3}$ have also been invoked to reproduce the spectrum of G99−37 (Grenfell 1974), with an estimated temperature of $T_{\mathrm{eff}} = 6300$ K. We have performed a comparable chemical equilibrium analysis for this object to verify the internal consistency of our interpretation. Here we have assumed $\log P = 9.0$, $10^{-4} \leq N(\mathrm{H})/N(\mathrm{He}) \leq 10^{-2}$, and $N(\mathrm{C})/N(\mathrm{He}) = 10^{-5}$ and $10^{-3}$. Although not displayed here, our results indicate that for $T \sim 6300$ K and $N(\mathrm{C})/N(\mathrm{He}) = 10^{-5}$, $C_2$ and CH are the dominant molecular species; the abundances are about a factor of 100 larger than $C_2H$, except for the largest hydrogen concentrations ($10^{-2}$) where the abundance of $C_2H$ becomes comparable to that of $C_2$. We note, however, that for such large hydrogen abundances, H$\alpha$ should be spectroscopically detectable (Wegner & Yackovich 1984), in contradiction with the observations. For $N(\mathrm{C})/N(\mathrm{He}) = 10^{-3}$, $N(\mathrm{H})/N(\mathrm{He}) \leq 10^{-3}$, and $T \sim 6300$ K, the abundances of CH and $C_2H$ are the same to within a factor of 3. This last result suggests that the carbon abundance in G99−37 may be somewhat lower than that determined by Grenfell (1974). A lower carbon abundance in G99−37 would account for the fact that the observed strengths of the $C_2$ Swan bands are comparable to those of normal DQ stars at the same temperature, in which carbon abundances of only $\sim 10^{-6}$ have been inferred (Wegner & Yackovich 1984).

## 5. DISCUSSION

In light of our results, the interpretation of the features observed in LP 790−29 can be examined anew. It is no longer clear from an examination of Figure 3 whether LP 790−29 belongs to the DQ spectral class, or to the group newly identified in this paper. However, the most recent temperature estimate of LP 790−29, $T_{\mathrm{eff}} \sim 7500$ K (Bues 1993), is too hot to interpret the observed features in terms of $C_2H$ (or another $C_nH_n$ compound). Therefore, we believe that the assignment of the features observed in LP 790−29 to magnetically shifted $C_2$ Swan bands is still valid.

It is interesting to speculate on the evolutionary status of our peculiar objects in which H, He, and C are coexistent. In DQ stars, the presence of carbon has been successfully interpreted in terms of a dredge-up model in which carbon diffusing upward from the core is carried to the surface by the helium convection zone (see e.g., Pelletier et al. 1986). Even though Pelletier et al. considered only helium-rich atmospheric compositions, they mention that carbon pollution must also occur in hydrogen-rich white dwarfs, but that the expected abundances are not likely to be measurable. Indeed, if the overlying hydrogen atmosphere is thick enough, carbon needs to travel through a mostly radiative hydrogen layer in which the carbon diffusion tail extends only over a very short range (see Pelletier et al. for details). However, if the hydrogen layer is sufficiently thin ($M_{\mathrm{H}} \lesssim 10^{-8}$ $M_\odot$), convective mixing of the superficial hydrogen layer with the deeper helium convection zone may

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



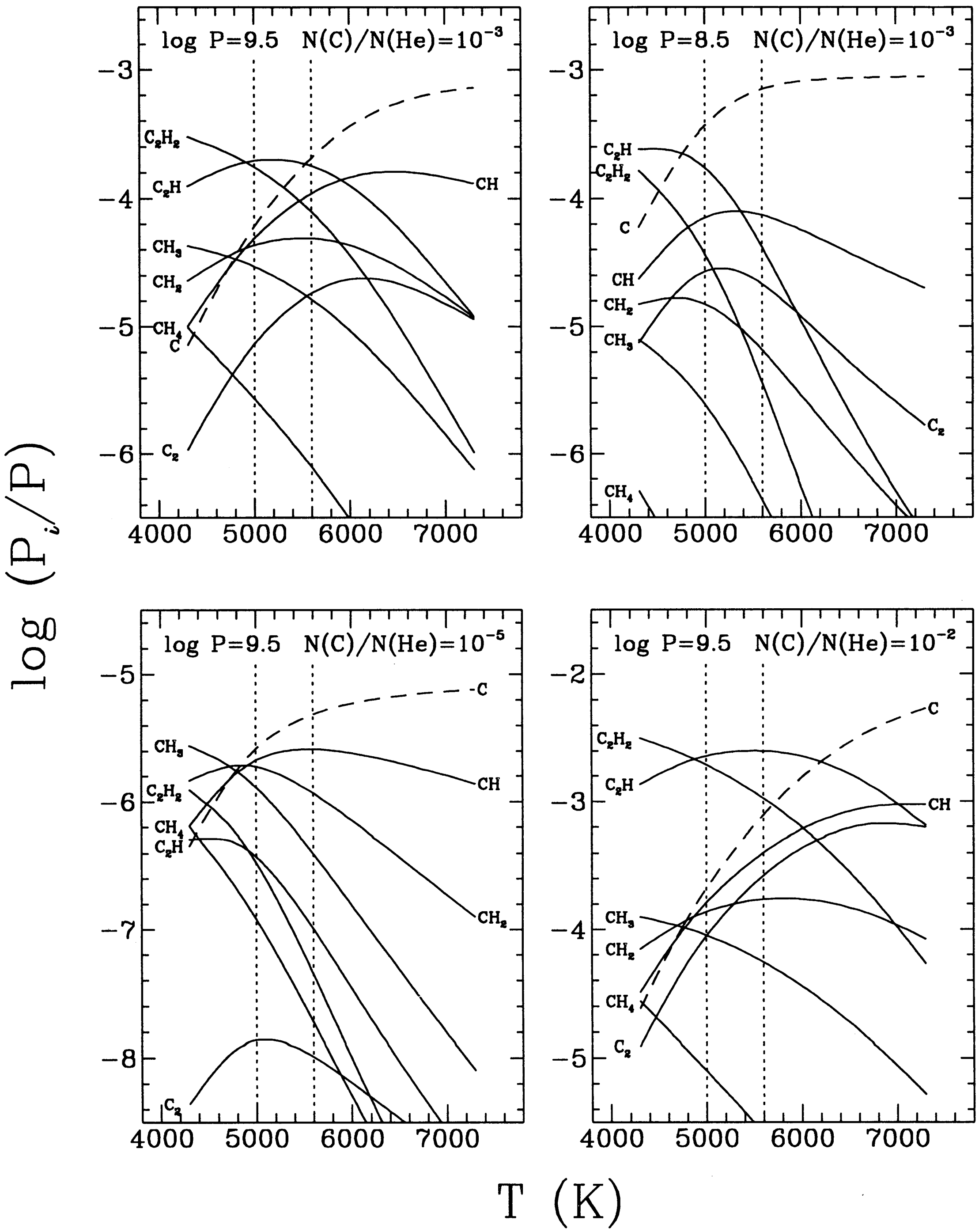


FIG. 4.—Mole fraction ($P_i/P$) of the most abundant $C_n$ or $C_nH_n$ compounds as a function of temperature for various total pressures ($P$ in dyn cm$^{-2}$) and carbon abundances; $N(H)/N(He) = 0.1$ is assumed throughout. The neutral carbon abundance is shown by a dashed line while dotted lines indicate the temperature range of the line-forming region in LHS 1126.

occur (Koester 1976; Vauclair & Reisse 1977; D'Antona & Mazzitelli 1979). The simultaneous presence, in our peculiar stars, of hydrogen and helium in comparable amounts strongly suggests that convective mixing is indeed occurring in these objects. Convective mixing at such low temperatures (LHS 1126 has $T_{\rm eff} = 5400$ K) implies that the mass of the hydrogen layer is of the order of $M_{\rm H} \sim 10^{-8}\ M_\odot$ (stars with thinner hydrogen envelopes mix at higher temperatures; see references above). Such a process would not only turn a hydrogen-rich atmosphere into a helium-rich atmosphere, but carbon thoroughly mixed in the underlying helium convection zone would also be brought up to the surface. Therefore, if the He/H abundances of the peculiar objects are indeed the result of convective mixing, such a scenario would provide a natural explanation for the simultaneous presence of carbon as well.

In some cases, the presence of hydrogen in a helium-rich atmosphere may be the result of accretion from the interstellar medium. Such a model has been invoked to account for the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...443..274S



hydrogen in DBA stars (MacDonald & Vennes 1991) and also the peculiar DQ white dwarf G35−26 (Thejll et al. 1990). In these objects, however, hydrogen remains a trace element in a helium background [$N$(C)/$N$(He) $\sim 10^{-4}$]. It seems implausible that large amounts of hydrogen, such as those encountered in LHS 1126, can be produced by accretion, otherwise it would be difficult to explain the presence of DQ, DZ, and DC stars, most of which show no trace of hydrogen at all.

We are pleased to acknowledge helpful discussions with J. Black regarding molecular spectra and $C_2$ in particular, and with A. Borysow concerning the importance of collision-induced processes. We are also grateful to F. Wesemael for enlightening discussions regarding the nature of the problem in general. P. Smith, B. Jannuzi, and R. Elston assisted at the telescope. The manuscript was completed while G. S. enjoyed a sabbatical leave at Lowell Observatory. Support was provided by the National Science Foundation through grant AST 91-14087, by the NSERC Canada, by the Fund FCAR (Québec), and by the NASA Planetary Atmosphere Program (grant NAGW-2861).

REFERENCES

A'Hearn, M. F. 1982, in Comets, ed. L. L. Wilkening (Tucson: Univ. Arizona Press), 433
Angel, J. R. P., Borra, E. F., & Landstreet, J. D. 1981, ApJS, 45, 457
Angel, J. R. P., & Landstreet, J. D. 1974, ApJ, 191, 457
Bergeron, P., Ruiz, M.-T., & Leggett, S. K. 1994a, in preparation
Bergeron, P., Ruiz, M.-T., Leggett, S. K., Saumon, D., & Wesemael, F. 1994b, ApJ, 423, 456 (B94)
Bues, I. 1993, in White Dwarfs: Advances in Observation and Theory, ed. M. A. Barstow (Dordrecht: Kluwer), 213
Bues, I., & Pragal, M. 1989, White Dwarfs, Proc. IAU Coll. 114, ed. G. Wegner (Berlin: Springer-Verlag), 329
D'Antona, F., & Mazzitelli, I. 1979, A&A, 74, 161
Fegley, B., Jr., & Lodders, K. 1994, Icarus, 110, 117
Gredel, R., van Dishoeck, E. F., & Black, J. H. 1989, ApJ, 338, 1047
Greenstein, J. L., & Liebert, J. W. 1990, ApJ, 360, 662
Grenfell, T. C. 1974, A&A, 31, 303
Herzberg, G. 1950, Molecular Spectra and Molecular Structure I. Spectra of Diatomic Molecules (2d ed.; Princeton: Van Nostrand), 124
Hintzen, P., Oswalt, T. D., Liebert, J., & Sion, E. M. 1989, ApJ, 346, 454
Koester, D. 1976, A&A, 52, 415
Liebert, J., Angel, J. R. P., Stockman, H. S., & Beaver, E. A. 1978, ApJ, 225, 181
Liebert, J., & Dahn, C. C. 1983, ApJ, 269, 258
Liebert, J., & Stockman, H. S. 1980, PASP, 92, 657
Lodders, K., & Fegley, B., Jr. 1993, Earth Planet Sci. Lett., 117, 125
MacDonald, J., & Vennes, S. 1991, ApJ, 371, 719
Massey, P., Stobel, K., Barnes, J. V., & Anderson, E. 1988, ApJ, 328, 315
Pelletier, C., Fontaine, G., Wesemael, F., Michaud, G., & Wegner, G. 1986, ApJ, 307, 242
Perić, M., Peyerimhoff, S. D., & Buenker, R. J. 1991, Z. Phys. D, 24, 177
Phillips, J. G. 1948, ApJ, 108, 434
Ruiz, M.-T., Bergeron, P., & Leggett, S. K. 1993, in White Dwarfs: Advances in Observation and Theory, ed. M. A. Barstow (Dordrecht: Kluwer), 245
Ruiz, M. T., & Maza, J. 1988, ApJ, 335, L15
Schmidt, G. D., Stockman, H. S., & Smith, P. S. 1992, ApJ, 398, L57
Thejll, P., Shipman, H. L., MacDonald, J., & MacFarland, W. M. 1990, ApJ, 361, 197
Vauclair, G., & Reisse, C. 1977, A&A, 61, 415
Wegner, G., & Yackovich, F. H. 1984, ApJ, 284, 257
Wesemael, F., Greenstein, J. L., Liebert, J., Lamontagne, R., Fontaine, G., Bergeron, P., & Glaspey, J. W. 1993, PASP, 105, 761
Wickramasinghe, D. T., & Bessell, M. S. 1979, MNRAS, 188, 841

© American Astronomical Society • Provided by the NASA Astrophysics Data System