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THE PECULIAR COOL WHITE DWARF LHS 1126 REVISITED[1]

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ABSTRACT

We present a detailed analysis of new photometric and spectroscopic data, both in the optical and in the infrared, of the cool white dwarf LHS 1126. We show that the peculiar energy distribution of this object, and especially the large infrared flux deficiency, is the result of the collision-induced absorption by molecular hydrogen due to collisions with helium. The effective temperature and the helium abundance are determined from a fit to the energy distribution while the surface gravity is constrained by the trigonometric parallax measurement. We obtain $T_{\rm eff} = 5400 \pm 200$ K, log $g = 7.85 \pm 0.17$, and log $N({\rm He})/N({\rm H}) = 0.8 \pm 0.2$. The nature of the spectroscopic features observed previously in the infrared and in the optical are rediscussed within the context of both these new observations and our model atmosphere fit.

Subject headings: stars: atmospheres — stars: individual (LHS 1126) — white dwarfs

1. INTRODUCTION

Past infrared observations of cool white dwarfs have primarily been aimed at searching for evidence of the collision-induced (also called pressure-induced) absorption by molecular hydrogen (Mould & Liebert 1978; Liebert, Lebofsky, & Rieke 1981; Wickramasinghe, Allen, & Bessel 1982, hereafter WAB). At the cool end of the white dwarf evolutionary sequence, it is no longer possible to rely on line profile analyses to infer the chemical atmospheric composition of stars since both helium *and* hydrogen become spectroscopically invisible. Below $T_{\rm eff} \sim 5000$ K, however, molecular hydrogen starts to form, and the H_2 collision-induced opacity becomes important and even dominates around $T_{\rm eff} \sim 4000$ K. At the densities characteristic of white dwarf atmospheres, this opacity peaks in the ~1.5–3.0 μm region. Its main photometric signature is a rapid turnover in color-color diagrams (e.g., $[J-H]$ versus $[V-K]$ or $[B-V]$ versus $[V-K]$) of the hydrogen-rich models with respect to the helium-rich models. It is therefore possible, in principle, to distinguish white dwarfs with different atmospheric compositions from their locations in these diagrams.

None of the analyses mentioned above reported any unambiguous evidence for stars showing the H_2 collision-induced opacity, with the glaring exception of the white dwarf LHS 1126 (LTT 375, G266−157, L651−57, WD 0038−226) first analyzed by WAB. This star is classified DC9 in McCook & Sion (1987) but has been reclassified DQ?10 by Greenstein & Liebert (1990). WAB found a strong infrared flux deficiency in LHS 1126, with an exceptionally blue $(J-H)$. The proximity, in a $(J-H)$ versus $(V-K)$ diagram, of LHS 1126 to the coolest hydrogen-rich models calculated by Mould & Liebert (1978) led to the conclusion that the star had a hydrogen-rich atmosphere with a relatively cool temperature of $T_{\rm eff} \sim 4250$ K. This interpretation was later challenged by Liebert & Dahn (1983, hereafter LD), who reported the discovery of strong optical spectroscopic features which they interpreted as pressure-broadened and shifted C_2 features in a *helium-rich* atmosphere. They also showed from their *UBVRI* photometry that LHS 1126 is too blue to be reconciled with a pure hydrogen atmosphere at $T_{\rm eff} \sim 4200$ K. Instead, the suggestion was made that the infrared absorption reported by WAB could be due to C_2 or even CO. Later, Lebofsky & Liebert (1984) obtained narrow-band photometric observations in the 1.25–2.50 μm range which revealed a strong, smooth absorption at 2.0–2.3 μm and also a structured absorption feature near 1.6 μm. The authors remarked that while these features are inconsistent with the H_2 collision-induced opacity, they cannot be connected in a simple way to any known carbon infrared features either. Thus, the source of the infrared flux deficiency and even the chemical composition of LHS 1126 remained a mystery.

LHS 1126 was included in the target list of the ongoing spectroscopic and photometric survey of Bergeron, Ruiz, & Leggett (1994a; see also Ruiz, Bergeron, & Legett 1993) aimed at understanding the chemical composition and evolution of the coolest white dwarfs. In this paper, we demonstrate that the infrared flux deficiency observed in LHS 1126 is the result of the *collision-induced absorption by molecular hydrogen due to collisions with helium*. In § 2 we present the spectroscopic and photometric observations which are analyzed in § 3 with a new generation of model atmospheres. The implications of our result are discussed in § 4.

2. OBSERVATIONS

The *B*, *V*, *R*, and *I* photometry was obtained on 1991 August 11 using a TEK CCD array attached to the CTIO 1.5 m tele-

[1] This work is partially based on data obtained at La Silla (ESO).

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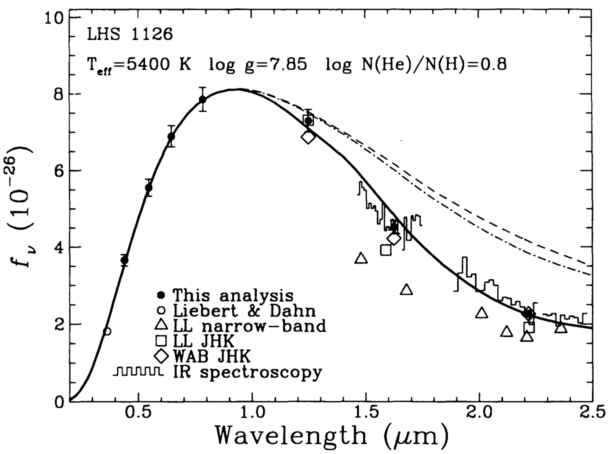

FIG. 1.—Our best fit to the energy distribution of LHS 1126. In the fitting procedure, only the photometry from this analysis has been used. Also shown are the *U* photometry from Liebert & Dahn (1983), the infrared *JHK* photometry of Wickramasinghe et al. (1982; WAB), and the broad- and narrow-band infrared photometry of Lebofsky & Liebert (1984; LL). The histogram is our infrared spectroscopy. The thick line represents the best-fitting model whose parameters are indicated on top. The dash-dotted line represents the fluxes calculated from the same atmospheric structure, but with the H_2-He collision-induced opacity turned off; the dashed line is with all collision-induced opacities turned off (see text). Except for our photometry, the uncertainties correspond approximately to the size of the symbols.

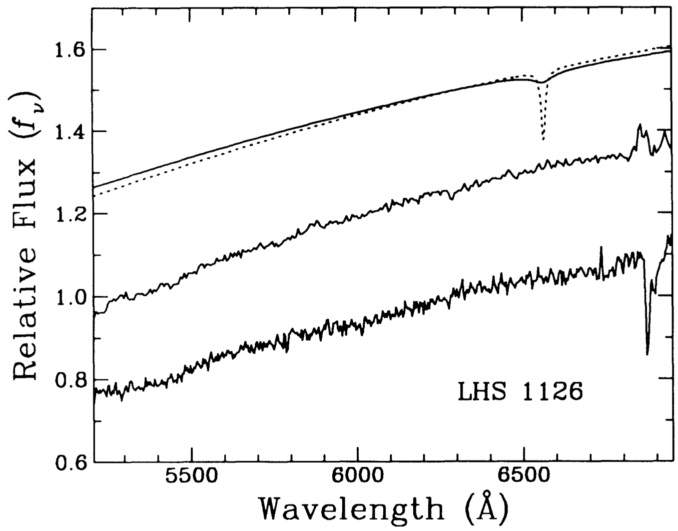

FIG. 2.—Our optical spectrum (*bottom*) of LHS 1126 compared with that of Greenstein & Liebert (1990; *middle*). The S/N in both spectra is comparable, but the resolution of the bottom spectrum is better (8 Å) than that of the middle spectrum (15 Å). The features around 6900 Å are terrestrial atmospheric absorption lines. The theoretical spectra shown at the top are calculated with the atmospheric parameters given in Fig. 1 (*solid line*) and with a pure hydrogen atmosphere at the same T_{eff} and log *g* (*dotted line*), and have been convolved with an 8 Å instrumental (Gaussian) profile.

scope; the infrared *J*, *H*, and *K* photometry was obtained on 1991 August 27 with the CTIO 4 m telescope equipped with the IR imager. Additional information about the observing procedure and data reduction can be found in Bergeron, Ruiz, & Leggett (1992). The optical and infrared photometry is presented in Table 1 and Figure 1, where the data are given in the Johnson *B* and *V* system, the Cousins *R* and *I* system, and the CIT *J*, *H*, and *K* system. The uncertainty is ~4% at all filters. We also compare in Table 1 this photometry with that of LD and WAB, where the latter data has been converted from the AAO system to the CIT system following the transformation equations of Leggett (1992). The optical photometry is in excellent agreement except at *I* where the flux from LD is ~10% larger. Comparison with the infrared photometry is discussed below (see § 4).

The optical spectrum of LHS 1126 was obtained on 1992 August 3 at La Silla (ESO) using the 3.6 m telescope equipped with the EFOSC, the O150 grism, and a 512 × 512 TEK CCD detector. The spectral coverage is 5200–7000 Å at ~8 Å resolution, with a signal-to-noise ratio of S/N ~100. In Figure 2, we compare our optical spectrum with that discussed by Greenstein & Liebert (1990); the latter has a comparable S/N, but a much lower resolution of ~15 Å. The comparison between both data sets reveals no detectable feature in the overlapping spectral range. The reported C_2 features (see § 4) are blueward of this spectral coverage.

In addition, one of us (SKL) obtained infrared spectroscopy in 1987 September at the NASA InfraRed Telescope Facility (IRTF) on Mauna Kea. The CGAS spectrometer was used with a 75 lines mm^{-1} grating which gave a resolving power of ~120 (or resolution around 0.01 μm). The data is displayed in Figure 1 and the uncertainty in the continuum flux level is ~10%. The observed infrared spectrum is consistent with a smooth energy distribution; i.e., the apparent infrared spectroscopic features are not significant.

3. ATMOSPHERIC PARAMETER DETERMINATION

Our analysis relies on new model atmospheres for cool white dwarfs developed by Bergeron, Saumon, & Wesemael (1994b). The main improvement over previous generations of model atmospheres is the more accurate treatment of the H_2-H_2, H_2-H, and H_2-He collision-induced absorptions, following the prescription of Lenzuni, Chernoff, & Salpeter (1991) which is based partially on the work of Borysow & Frommhold (see Lenzuni et al. and references therein). A detailed comparison of their cross-section calculations with previous formalisms can be found in Lenzuni et al. All chemical species included in their calculation are taken into account here. In particular, it is now straightforward to calculate realistic white dwarf models with *mixed helium and hydrogen compositions*, a task never accomplished before at very low temperatures ($T_{eff} \lesssim 6000$ K). The

TABLE 1

PHOTOMETRY OF LHS 1126

Observation	*V*	*B−V*	*V−R*	*R−I*	*J*	*J−H*	*H−K*
This study	14.51	+0.68	+0.42	+0.36	13.32	−0.12	−0.22
WAB	...	...	...	...	13.38	−0.13	−0.15
Liebert & Dahn	14.50	+0.68	+0.42	+0.46	...	...	...

results of Bergeron et al. (1994b) indicate that in cool, helium-rich models, *the* H_2-He *collision-induced opacity becomes the dominant source of opacity in the infrared.* In color-color diagrams, the turnover observed in hydrogen-rich models becomes even more pronounced in helium-rich models.

Details of our fitting procedure are given in Bergeron et al. (1992). Briefly, the optical *BVRI* and infrared *JHK* photometry are transformed in flux units and fitted to model fluxes with a least-squares method. The effective temperature, surface gravity, and helium abundance of the model, as well as the solid angle (R^2/D^2, the square of the ratio of the radius of the star to its distance from Earth) are considered free parameters.

Early attempts to reproduce the energy distribution of LHS 1126 using either our grid of pure hydrogen models or pure helium models failed. Instead, the observed colors of LHS 1126 in our $(J-H)$ versus $(V-K)$ and $(B-V)$ versus $(V-K)$ diagrams suggest that the star can be interpreted as a helium-rich object with $1 \lesssim N(\mathrm{He})/N(\mathrm{H}) \lesssim 10$, at an effective temperature of $T_{\mathrm{eff}} \sim 5500$ K. This interpretation is confirmed by a detailed modeling of the energy distribution with *helium-rich* models, and excellent fits to the energy distribution can be achieved. Since it is possible to reach an acceptable fit by simply adjusting the effective temperature for any reasonable value of log g, we use the trigonometric parallax measurement to constrain the surface gravity. From the new Yale General Catalogue of Trigonometric Stellar Parallaxes (van Altena, Lee, & Hoffleit 1993), we obtain a value of $\pi = 0\farcs1008 \pm 0\farcs0114$ and an absolute visual magnitude of $M_V = 14.53 \pm 0.25$.

We find a consistent solution at $T_{\mathrm{eff}} = 5400 \pm 200$ K, $\log g = 7.85 \pm 0.17$, and $\log N(\mathrm{He})/N(\mathrm{H}) = 0.8 \pm 0.2$ [or $N(\mathrm{He})/N(\mathrm{H}) = 6.3^{+3.7}_{-2.3}$], where the uncertainties have been propagated from the formal error of the fit and that of the trigonometric parallax. The corresponding bolometric correction, BC $= -0.14$ (or $M_{\mathrm{bol}} = 14.39$), has been calculated following Wesemael et al. (1980). The atmospheric parameters translate into a mass of $M = 0.48 \pm 0.09\ M_{\odot}$ (or a radius of $R = 0.0137 \pm 0.0013\ R_{\odot}$) using the evolutionary models of Wood (1990) for carbon core compositions. Our fit is displayed in Figure 1. The predicted fluxes represent an excellent match to our *BVRI* and *JHK* photometry, as well as to the infrared spectroscopy. The solution is also consistent with the *U* flux measured by LD.

The quality of the fit, especially in the infrared, relies entirely on the H_2-He collision-induced opacity. To illustrate this better, we have used the same atmospheric structure as before, but recalculated the emergent energy distributions by turning off all collision-induced opacities, and also by including only the contributions from the H_2-H_2 and H_2-H interactions. We note that since the opacity is altered only in the calculation of the energy distributions (and not in the calculation of the atmospheric structure itself), the integrated flux is *not* equal to $\sigma T_{\mathrm{eff}}^4$. Our results are displayed in Figure 1 where the energy distributions have been normalized using the same value of the solid angle as inferred from our optimal fit. At the low hydrogen abundance determined above, the contribution of the H_2-H_2 and H_2-H interactions to the total collision-induced opacity is negligible, and the infrared opacity is shown to be dominated by the contribution from the H_2-He interaction. Our ability to model *for the first time and without any ad hoc assumption*, the energy distribution of LHS 1126 strengthens our confidence in the relevance of the new models of Bergeron et al. (1994b), as well as in the cross section calculations used by Lenzuni et al. (1991).

Finally, we need to ensure that the proposed solution is consistent with the lack of observed Hα profile. Following the approach outlined in Bergeron, Wesemael, & Fontaine (1991), modified to take into account nonresonant collisional broadening as discussed by Hammond et al. (1991), we have calculated line profiles for both a pure hydrogen composition, and for the helium abundance of LHS 1126 determined above. The results of our calculation are displayed in Figure 2. Although Hα would have been easily detected in a pure hydrogen atmosphere, the predicted profile in a helium-rich atmosphere is broad and shallow due to van der Waals broadening by helium, and would clearly be difficult to detect. Additional calculations show that the predicted Hα profile becomes completely undetectable at 5300 K, well within the uncertainty of our temperature determination. We therefore conclude that our solution is also consistent with the observations at Hα.

4. THE SHIFTED CARBON FEATURES OF LHS 1126

We have successfully demonstrated that the energy distribution of LHS 1126 can be reproduced with a mixed hydrogen and helium atmosphere, with the strong infrared absorption explained in terms of the H_2-He collision-induced absorption. There is no direct evidence for the presence of hydrogen (or helium) otherwise. However, other spectral features have been reported in previous observational studies of LHS 1126, and these are now discussed in turn.

LD discovered a broad absorption feature near 5000 Å which they interpreted as pressure-broadened and shifted C_2 Swan bands. Higher signal-to-noise spectroscopy by Greenstein & Liebert (1990) revealed the presence of at least two bands near 4590 and 4990 Å, and perhaps even more at shorter wavelengths. A portion of their spectrum, adapted from the Atlas of Optical Spectra of White Dwarf Stars (Wesemael et al. 1993), is reproduced here in Figure 3. When compared with other DQ stars (see, e.g., Fig. 13 of Wesemael et al. 1993), LHS 1126 appears as a very cool extension of the DQ sequence, but with the C_2 features blueshifted by ~150 Å. LD suggested that these large shifts were the result of the high atmospheric pressure encountered in a cool helium-rich atmosphere (see also Greenstein & Liebert 1990). However, the presence of even small traces of carbon (or hydrogen) in a pure helium atmo-

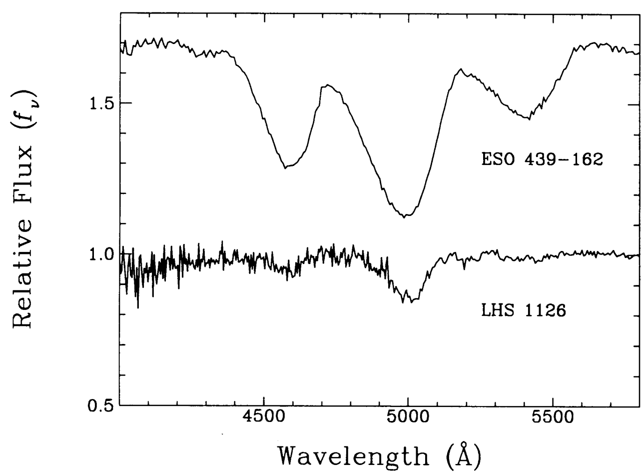

FIG. 3.—Comparison of the blue spectrum of LHS 1126 obtained by Greenstein & Liebert (1990) with that of ESO 439−162. The continuum has been normalized to unity by the use of a low-order spline and the spectrum of ESO 439−162 has been shifted upward by an amount of 0.7 for clarity.

sphere provides enough free electrons to increase the He^- opacity, which in turn reduces the atmospheric pressure significantly. For example, in the coolest DQ stars analyzed by Wegner & Yackovich (1984; $T_{eff} \sim 6600$ K, see also Yackovich 1982), the atmospheric pressure in the continuum forming region is ~ 70 times smaller than in a pure helium model at the same temperature. A similar effect is observed in our model of LHS 1126, where the presence of hydrogen reduces the photospheric pressure by a factor of $\sim 10^3$ compared to that in a pure helium model at similar T_{eff} and log g. More important, even though LHS 1126 is a much cooler object, its photospheric pressure is ~ 3 times *smaller* than in those coolest DQ stars analyzed by Wegner & Yackovich *where such large shifts of the* C_2 *features are not observed.* It is therefore improbable that the observed shifts in LHS 1126 are induced by pressure effects.

In Figure 3, we compare the spectrum of the DQH?8 star ESO 439−162 ($T_{eff} \sim 6300$ K) obtained by Ruiz & Maza (1988) with that of LHS 1126 (see also Fig. 13 of Wesemael et al. 1993 for a further comparison of both spectra with that of a normal DQ star). Although the carbon features in ESO 439−162 are much stronger than in LHS 1126, the location, symmetry, and overall shape of the profiles are remarkably similar. The weaker carbon features in LHS 1126 could be the result of a lower carbon abundance, or a higher continuum opacity (due to the presence of hydrogen) with respect to ESO 439−162. Hintzen et al. (1989) show the spectrum of another object, LP 77-57, whose carbon features are almost identical to those of ESO 439−162, while Greenstein & Liebert (1990) report similar shifted features in the DQ8+ star G225−68 (WD 1633+572). Therefore, DQ stars with strongly shifted carbon features are not unusual.

Such large shifts have been observed in at least one other object, LP 790-29 (DQP9), in which strong, blueshifted carbon features have been reported by Liebert et al. (1978). In that analysis, LP 790-29 is shown to be strongly magnetic, with a field strength above 100 MG. The observed shifts of ~ 240 Å are interpreted in terms of quadratic Zeeman effects. Detailed modeling by Bues (1991) indicates that the observed features are consistent with a polar field strength of approximately 250 MG. By analogy, magnetism has been invoked to account for the large shifts observed in the three other stars mentioned above, although its presence has not been confirmed by polarimetric measurements.

In LHS 1126, Liebert & Stockman (1980; see also Angel, Borra, & Landstreet 1981) measured very low circular polarization ($V = -0.008 \pm 0.04\%$) but, since the measurement was obtained over a very large bandpass (3200−8600 Å), it was not possible to rule out completely the presence of a strong magnetic field since cancellation effects (positive and negative circular polarization) may still lead to a null *integrated* value. More recently, however, Schmidt (1993) obtained high signal-to-noise spectropolarimetry of LHS 1126 using the instrument and observing techniques described in Liebert et al. (1993a). The observed circular polarization over the 4700–6800 Å range is always below 0.5%, with no apparent structure near the strong C_2 absorption features. The total polarization integrated over that spectral range is $+0.04 \pm 0.04\%$. Although the particular orientation of the magnetic field with respect to the observer might still lead to very low polarization measurements even in the presence of a large magnetic field (see, e.g., Liebert et al. 1993b), *it seems very unlikely that magnetism is the cause of the observed shifts in LHS 1126.* Unfortunately, this important null result leaves, within the new interpretation offered in § 3, no obvious source for the shifts observed in LHS 1126. Furthermore, the similarity of LHS 1126 to ESO 439−162, LP 77-57, and G225−68 now casts some doubt upon the interpretation of the shifts observed in these objects as being of a magnetic nature.

Lebofsky & Liebert (1984) have also reported additional spectral features in the infrared. Their narrow- and wide-band photometric data are displayed in Figure 1 together with the infrared data of WAB. Although the Lebofsky & Liebert photometry at J is in excellent agreement with ours, it is systematically lower at H and K. This difference cannot be attributed to the choice of flux calibration, since the calibration uncertainty is only of the order of $\lesssim 3\%$. Furthermore, their narrow-band photometry, both relative and absolute, cannot be reconciled with any of the data displayed in Figure 1. In particular, the strong dip around 2.2 μm is *not confirmed* by our infrared spectroscopy. Also, Lebofsky & Liebert have suggested that the large discrepancy between their monochromatic flux at H and their narrow-band fluxes around 1.6 μm could be due to regions of higher fluxes within the H filter bandpass that are not covered in the narrow-band filters. Again, this interpretation is not confirmed by our infrared spectroscopic observations. We therefore believe that their narrow-band observations are suspect, and that no additional sources of opacity need to be invoked to explain the observed infrared energy distribution of LHS 1126.

It is now widely accepted that the presence of carbon in cool, helium-rich white dwarf atmospheres is due to dredge-up from the tail of the carbon equilibrium distribution (Pelletier et al. 1986 and references therein). The simultaneous presence of carbon *and* hydrogen in a helium-rich atmosphere is very rare, however. In Wesemael et al. (1993), the spectra of three such objects are displayed: G227−5 and G35−26 (DQA spectral class) with effective temperatures considerably higher ($T_{eff} \gtrsim$ 11,000 K) than that of LHS 1126, and the weakly magnetic DQP8 star G99−37, with a temperature of ~ 6300 K (Grenfell 1974). For the carbon dredge-up process to work, the atmosphere needs to be extremely helium-rich otherwise the bottom of the convection zone may not extend deep enough to reach the carbon regions (Pelletier et al. 1986). Dredge-up calculations in cool envelope models with mixed helium/hydrogen compositions are not available, and it is currently not possible to determine the expected amount of carbon pollution in the atmosphere of LHS 1126.

The presence of hydrogen in G99−37 has been inferred from the CH λ4340 feature in its optical spectrum. The absence of such a feature in LHS 1126 could be simply an abundance effect since the carbon abundance in LHS 1126 is presumably lower than in G99−37. Detailed models with mixed compositions of carbon, hydrogen, and helium would be required to analyze further the carbon features, and to predict the strength of the CH λ4340 feature in LHS 1126.

The simultaneous presence of hydrogen and helium in a cool white dwarf atmosphere is also unusual. Preliminary results of a spectroscopic and photometric survey reported by Ruiz et al. (1993) indicate that the dichotomy observed in hotter nonmagnetic white dwarf atmospheres, namely that the photosphere is composed either of nearly pure hydrogen or of nearly pure helium, persists at low effective temperatures. In particular, no cool ($T_{eff} \lesssim 6500$ K) white dwarf stars with a helium-to-hydrogen ratio near unity have been found, with the exception of LHS 1126 presented here. More detailed results on this analysis will be reported in due time. The presence of a mixed hydrogen and helium composition in LHS 1126 could be the result of convective mixing of the superficial hydrogen layer with the deeper and more massive helium convection zone, or the accretion of hydrogen from the interstellar medium onto a normal cooling helium-rich DQ star, or both. In contrast to heavier elements, hydrogen will not diffuse at the bottom of the helium convection zone and its atmospheric abundance can only increase with time.

We are grateful to G. Schmidt for informing us of his important spectropolarimetic result on LHS 1126, to M. Bird for helping to obtain and for reducing the infrared spectroscopic data, to G. Fontaine and N. Achilleos for enlightening discussions, and to P. Lenzuni for providing us with unpublished material. This work was supported in part by the NSERC Canada, by the Fund FCAR (Québec), and by the FONDECYT grant 92-880, and by the NSF grant AST 89-10780.

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Note added in proof.—Schmidt (1993) recently obtained high signal-to-noise spectropolarimetry of G225-68 using the same setup as described above. The observed circular polarization over the 4700–6800 Å range is always below 1%, with no apparent structure near the strong C_2 absorption features. Therefore, it would appear that magnetism is not the cause of the observed shifts in G225-68 either.