THE ASTROPHYSICAL JOURNAL, 441:L85–L88, 1995 March 10

SPECTROSCOPIC STUDIES OF DB WHITE DWARFS: CONFIRMATION AND MODELING OF NEW FORBIDDEN COMPONENTS OF He I

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Received 1994 October 17; accepted 1994 December 19

ABSTRACT

Red optical spectrophotometry of three DB white dwarfs confirms the existence, first reported by Greenstein and Liebert, of new forbidden components of He I transitions near 6068 and 6632 Å in the spectra of these stars. However, our search for the additional components tentatively reported earlier near 5379, 6337, and 6485 Å remained unsuccessful. New model atmosphere calculations are presented which strengthen the identification of the confirmed features as, respectively, the forbidden $2\,^3P$–$3\,^3P$ and $2\,^1P$–$3\,^1P$ transitions in the He I ion, which arise from Stark perturbations of the upper atomic levels. Our calculations show, furthermore, that these features, which should be generally present in the red spectra of hot DB stars, are predicted with a strength comparable to that observed.

Subject headings: atomic processes — line: profiles — stars: atmospheres — white dwarfs

1. INTRODUCTION

White dwarfs with effective temperatures between 13,000 and ~28,000 K are neatly separated into two composition groups: those whose optical spectra are dominated by the Balmer lines, and which have a hydrogen-rich atmospheric composition (the DA stars); and those which have a spectrum dominated by the lines of neutral helium, the DB stars (e.g., Wesemael et al. 1993). Because of their relative rarity (and associated faintness), the properties of DB stars as a whole are much less well understood than those of their relatively plentiful DA counterparts. Specifically, we can identify two important issues which currently remain unsettled for these stars: the first one concerns the puzzling, and by now extremely well-documented absence of helium-line stars between ~28,000 and 45,000 K, the temperature of the coolest DO stars (Wesemael, Green, & Liebert 1985; Thejll, Vennes, & Shipman 1991). Furthermore, while there have been several spectroscopic studies of DB stars (Koester, Schulz, & Wegner 1981; Wickramasinghe & Reid 1983; Koester et al. 1985; Wegner & Nelan 1987), as well as average mass determinations based on good-quality spectrophotometry (Oke, Weidemann, & Koester 1984), there has not been a detailed spectroscopic study of the mass distribution of DB stars, similar in quality and in scope to the recent analysis of Bergeron, Saffer, & Liebert (1992) of the DA stars. Work of this type would, for example, shed some light on the importance of alternative evolutionary scenarios for DB stars.

For these reasons, we embarked a few years ago on a spectroscopic study of DB white dwarfs (Beauchamp 1995) which closely parallels that of Bergeron et al. We thus secured blue (3700–5100 Å) spectra for a sample of 48 DB stars, from which atmospheric parameters have been extracted by simultaneously fitting several lines of the optical spectrum with a detailed grid of synthetic spectra. To carry out this ambitious program, substantial improvements to existing broadening data for several He I lines were required, and have now been implemented.

A first such improvement is the inclusion of the transition from the impact to the quasi-static regime for electron broadening, which occurs, typically, only a few tens of Å in the line wings. This transition was previously included only for the strongest lines at 4471 and 4922 Å.

A second, and more significant, improvement is the inclusion of many more so-called *forbidden components* than were included in previous investigations, while taking into account the transition from quadratic to linear Stark broadening for both the permitted and forbidden components, which may occur near the core for some lines. Only quadratic Stark broadening was included in previous calculations of neutral He I lines, save for the strongest transitions $\lambda\lambda$4471, 4922, 5015, 4388, and 4026. The forbidden transitions are associated with a mixing of upper states in the $2 - n$ optical transitions in He I, a mixing which leads to transitions normally disallowed by the selection rules for electric dipole transitions. In DB spectra, the majority of forbidden components predicted by broadening theories are either strong but blended with the main allowed transition (like the $2\,^3P$–$4\,^3F$ λ4470 transition first observed in main-sequence B stars by Struve 1929a, b), or superposed on other allowed transitions due to the crowding of permitted helium lines, or simply too weak to be observable. There are however a few cases for which a forbidden component is sufficiently well separated from its associated allowed component, far enough from other permitted lines, and strong enough to be detectable. The most famous such forbidden component is the $2\,^3P$–$4\,^3P$ transition at 4517 Å, which was first discovered in DB stars by Liebert et al. (1976), and which is associated with the strong permitted $2\,^3P$–$4\,^3D$ transition at 4471 Å.

Coincidentally, new features have recently been reported by Greenstein & Liebert (1990; hereafter GL) in red optical spectra of three bright DB stars (PG 0112+104, GD 358, and GD 378), and these have been tentatively identified as new forbidden components in He I. The features are located near 6068 and 6632 Å, and appear with decreasing certainty in PG 0112+104, GD 358,[3] and GD 378. As well, weaker potential features are reported near 5379, 6337, and 6485 Å. As discussed by GL, the location of the reported features near 5379, 6068,

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[3] The spectrum of GD 358 discussed by GL is not displayed by them. However, an independent spectrum, secured with the same instrument, is displayed by Koester et al. (1985).

and 6632 Å matches well that expected for, respectively, the forbidden $2\,^1S$–$3\,^1S$, $2\,^3P$–$3\,^3P$, and $2\,^1P$–$3\,^1P$ transitions, while that near 6337 Å is tentatively identified as the intersystem ($\Delta S \neq 0$) $2\,^3P$–$3\,^1S$ transition.

To verify the existence of the λ6068 and λ6632 forbidden components, to test whether their presence can be considered a general feature of the red spectrum of DB stars, and to check the reality of the additional potential features reported earlier, we undertook to secure new observations of a small subsample of hot DB white dwarfs in the red region of the spectrum.

2. RED SPECTROPHOTOMETRY OF DB STARS

Red optical spectra of GD 358 (WD 1645+325, EG 239), GD 190 (WD 1542+182, EG 193), and GD 378 (WD 1822+410, EG 242) were secured on UT 1994 June 13 at the Steward Observatory 2.3 m telescope with the Boller and Chivens spectrograph, a 1200 × 800 Loral CCD, and a 600 l mm^{-1} grating in first order, which provided coverage of the ∼5000–7000 Å region at an intermediate resolution of ∼5 Å. Our observations concentrated on the brightest, hottest ($T_{eff} \gtrsim 16{,}000$ K) stars available at that time, as our initial calculations suggested that forbidden components would be strongest at high effective temperatures. Because of technical difficulties, however, we were able to observe only the three objects mentioned above: the first is a well-known variable DB star, while GD 378 is a DBA star, with narrow Balmer lines in its blue optical spectrum.

Our new red spectra, characterized by a S/N ratio of 85–100, are displayed in Figure 1, together with the lower resolution (∼12 Å) Palomar spectrum of PG 0112+104, first displayed by GL. The red spectra of all four stars show strong He I λλ5876, 6678, and 7065 features, while that of GD 378 shows, in addition, a clear Hα. Furthermore, our observations confirm the presence of features near 6068 and 6632 Å in all three objects. The λ6068 feature is coincident with those reported by GL in PG 0112+104 and GD 358, and suspected by them in GD 378; our spectra show that this feature is indeed weakest in GD 378. λ6632, on the other hand, had been seen by GL in their three objects, and is seen even more clearly in our better-resolution data. We have also searched our spectra for signs of features variously reported by GL near 5379 Å ("a possible but weak feature in the three DB's"), 6337 Å ("may be present but need confirmation"), 6485 Å ("a stronger isolated feature"), and of a disturbance near 6535 Å: none are confirmed at our S/N ratio.

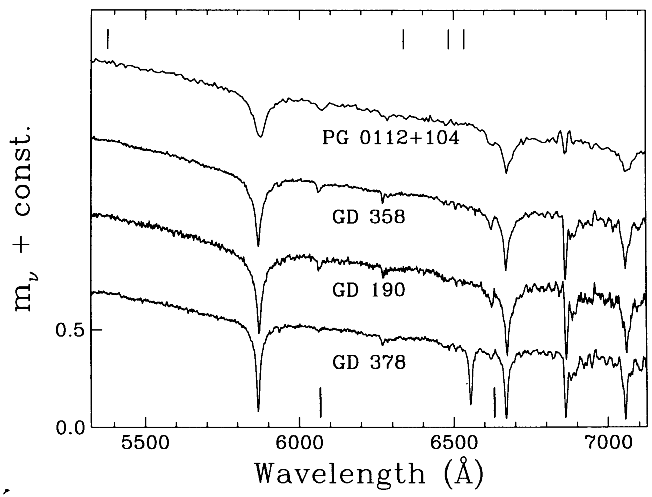

FIG. 1.—Red optical spectra (at ∼5 Å resolution) of the three stars observed in the course of this work (GD 358, GD 190, and GD 378), together with that of PG 0112+104, taken from GL. The latter has a spectral resolution of 12 Å. The spectra are ordered, from top to bottom, in approximate order of decreasing effective temperature. The forbidden components near 6068 and 6632 Å, initially identified by GL, are marked with thick vertical tick marks at the bottom of the frame. The Hα feature in the DBA star GD 378 is clearly seen as well. The locations of additional features near 5379, 6337, 6485, and 6535 Å tentatively reported by GL are marked by thin vertical tick marks at the top of the frame; these are not confirmed by the present observations. The features near 6250 and 6850 Å are due to night-sky lines and to an incomplete correction for atmospheric O_2, respectively.

Because all four objects are rather normal DB stars, albeit all at the hot end of the sequence, it seems extremely likely that these forbidden components are commonplace among DB stars. Improved signal-to-noise ratio and spectral resolution in a somewhat overlooked region of the spectrum have both been instrumental in revealing these new features to us.[4]

3. MODEL ATMOSPHERE ANALYSIS

3.1. *Model Atmosphere Calculations*

It turns out that the inclusion of forbidden components in many more He I transitions, both in the blue and in the red, is a major new ingredient in the new model atmosphere calculations currently being carried out by Beauchamp (1994). This timely investigation thus provides a convenient theoretical framework for the understanding of the features revealed by our observations. These new models are in LTE, are line-blanketed, and include convective energy transport (as described by Bergeron, Wesemael, & Fontaine 1991). The assumed chemical composition ranges from a pure helium atmosphere, to one with a variable H/He ratio. The calculations of the synthetic He I line spectrum take into account both van der Waals and resonance broadening at low effective temperatures, as well as the quadratic (and linear) Stark effect, which dominates in the hotter stars. Note here that we now include the transition from impact to quasi-static broadening by the electrons, while the ions are always treated within the quasi-static approximation. Further details are given by Beauchamp (1995).

3.2. *A Simple Picture, and Modeling of the Forbidden Components*

Forbidden components in He I appear because of the perturbation of the electronic wavefunctions and energy levels caused by the presence of an electric field due to ions and electrons. In the absence of that perturbing field, the Schrödinger equation for the wavefunction of the atomic system consisting of an electron in the ground state and an excited electron in a level characterized by n_0, l_0, and m_0 is written

$$H_0\,|\alpha_{n_0 l_0 m_0 S_0}\rangle = E_0\,|\alpha_{n_0 l_0 m_0 S_0}\rangle\,, \quad (1)$$

where H_0, S_0, and $|\alpha_{n_0 l_0 m_0 S_0}\rangle$ are the Hamiltonian, total spin, and normalized wavefunction of the unperturbed atom, respectively, and E_0 is its energy, which depends on n_0, l_0, and S_0, but is independent of m_0. For this illustration, we neglect the spin-

[4] Note that, in retrospect, the λ6632 feature may have been detected, but remained unrecognized, in the red spectrum of GD 190 presented by Liebert (1977). Furthermore, the unidentified, weak feature at 6635 ± 3 Å discovered by Wickramasinghe & Whelan (1977) in the spectrum of LDS 785A can also be unambiguously identified with the same λ6632 forbidden transition.

orbit interaction term in H_0; intersystem transitions ($\Delta S \neq 0$) can thus not be predicted within this simplified picture.

Let us now, for simplicity, immerse the atom in a constant, uniform electric field F in the z direction, which is associated with the presence of quasi-static ions. In this situation, n_0 and l_0 are no longer "good" quantum numbers, while total spin and magnetic quantum number remain conserved quantities. Under these conditions, we now write the perturbed wavefunction as $|\alpha(F)\rangle$, and its Schrödinger equation now reads

$$(H_0 + eFz)|\alpha(F)\rangle = E_F|\alpha(F)\rangle \,, \tag{2}$$

where e is the electronic charge, and eFz is the interaction energy of the excited electron in a uniform electric field.

Since the set of all discrete and continuum wavefunctions of the unperturbed helium atom forms a complete set, any perturbed wavefunction $|\alpha(F)\rangle$ can be expanded in the following way

$$|\alpha(F)\rangle = \sum_{n'}\sum_{l'} C_{n'l'}^{m_0 S_0}(n_0, l_0, F)|\alpha_{n'l'm_0S_0}\rangle + \sum_{l'}\int_0^{\infty} dE\, C_{El'}^{m_0 S_0}(n_0, l_0, F)|\alpha_{El'm_0S_0}\rangle \,. \tag{3a}$$

In principle, this sum must be carried out over *all* the possible states of the neutral helium atom with the same S and m values as the unperturbed solution (i.e., S_0 and m_0). However, since the levels characterized by $n' = n_0$ generally provide the dominant contributions to the perturbation (Griem 1968; Barnard, Cooper, & Shamey 1969; Barnard & Cooper 1970), the integral in equation (3a) is usually neglected, and the summation restricted to those levels with $n' = n_0$. Thus

$$|\alpha(F)\rangle \simeq \sum_{l'=|m_0|}^{n_0-1} C_{n_0 l'}^{m_0 S_0}(n_0, l_0, F)|\alpha_{n_0 l' m_0 S_0}\rangle \,. \tag{3b}$$

An interesting consequence of equation (3b) can be derived by calculating the expectation value of the angular momentum of the perturbed level initially characterized by l_0, namely

$$\langle\alpha(F)|\boldsymbol{L}|\alpha(F)\rangle = \sum_{l'=|m_0|}^{n_0-1} l'|C_{n_0 l'}^{m_0 S_0}(n_0, l_0, F)|^2 \,. \tag{4}$$

Equation (4) shows that this level has, once perturbed, a finite probability $|C_{n_0 l'}^{m_0 S_0}(n_0, l_0, F)|^2$ of being characterized by the angular momentum l' ($|m_0| \leq l' \leq n_0 - 1$). As an illustration, let us consider the case of the transition $2\,^3P$–$3\,^3D$ λ5876. When perturbed by an electric field, the nearby $3\,^3S$ and $3\,^3P$ upper levels both will have a finite probability of being characterized by $l = 2$, while the lower $2\,^3P$ state is assumed to be unperturbed. Thus, the perturbed transition[5] identified as $2\,^3P$–$3\,^3D$ actually consists of *three* transitions, namely $2\,^3P$–$3\,^3S$ λ7065, $2\,^3P$–$3\,^3P$ λ6068, and $2\,^3P$–$3\,^3D$ λ5876. Of course, the former ($2\,^3P$–$3\,^3S$ λ7065) is a permitted transition in its own right, while $2\,^3P$–$3\,^3P$ violates the $\Delta l = 1$ electric dipole selection rule, and is a forbidden transition. Thus, an accurate prediction of the line profile of the λ5876 transition requires consideration of both the main $2\,^3P$–$3\,^3D$ transition, as well as allowance for the other two. While all three transitions are considered in the calculations of the $C_{n_0 l'}^{m_0 S_0}(n_0 = 3, l_0 = 2, F)$ coefficients, only λ5876 and λ6068 have a significant intensity, and are included in the synthetic spectrum calculations.

[5] In the presence of a perturbation, the designation $n^{2S+1}L$ is not rigidly valid, since the states consist of admixtures of various l'-levels and n'-levels (see eq. [3a]). However, because the designated level is the leading term in the expansion, and for convenience, it is customary to continue to label the perturbed states with the term designation.

Similarly, the profile of the perturbed transition identified as $2\,^1P$–$3\,^1D$ λ6678, consists of three components: that associated with the main $2\,^1P$–$3\,^1D$ transition, that of the forbidden $\Delta l = 0$ transition $2\,^1P$–$3\,^1P$ λ6632, which is now included in our spectrum calculations and which has been extensively studied in the laboratory (Ya'akobi et al. 1972; Greig, Jones, & Lee 1974), as well as a very weak one associated with the $2\,^1P$–$3\,^1S$ λ7281 transition, omitted in our spectra.

Figure 2 shows sample predictions of our new synthetic spectrum calculations appropriate to the red spectral region of DB stars. We have not attempted fits to the complete spectrum here, but rather show spectra characterized by values of $T_{\rm eff}$, log g, and log N(H)/N(He) which appear appropriate to the three stars considered: GD 358 and GD 190 are both hot DB stars with no sign of hydrogen, while GD 378 is both cooler and more hydrogen-rich. Detailed fits to both the blue and red spectral region will be presented elsewhere. The match presented here, however, is sufficient to allow us to confirm unambiguously the identification of the features near 6068 and 6632 Å with new forbidden components of He I transitions. Our calculations reproduce satisfactorily the intensity of these components, and do so in all three objects. Furthermore, we note that no observable feature is predicted by our models near 5379 Å, even though the forbidden component $2\,^1S$–$3\,^1S$ (λ5379) is included in our calculation of the 2^1S–$3\,^1P$ (λ5015) profile. This is in agreement with our observations, which show no feature at that location.

4. CONCLUDING REMARKS

The confirmation of the existence of new features in the He I spectrum of DB stars provides a valuable opportunity of sharpening our understanding of the atomic physics of these

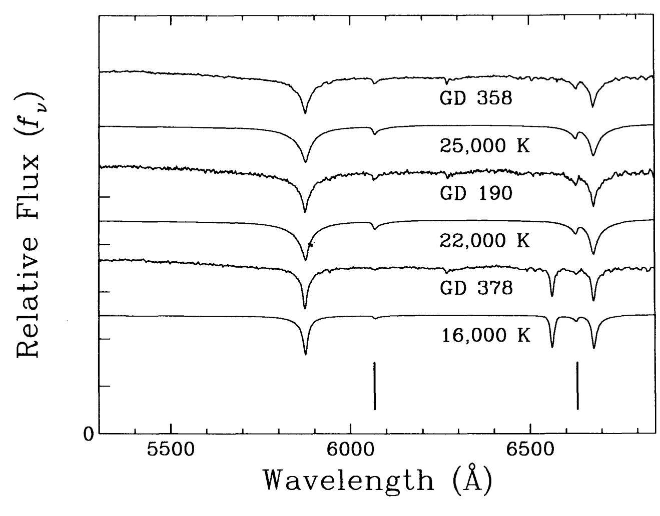

FIG. 2.—Comparison of the Steward Observatory spectra of three DB stars with the predictions of our synthetic spectra. The plots are, from top to bottom, GD 358; a model spectrum for $T_{\rm eff} = 25{,}000$ K, log $g = 8.0$; GD 190; a model spectrum for $T_{\rm eff} = 22{,}000$ K, log $g = 8.0$; GD 378; and a model spectrum for $T_{\rm eff} = 16{,}000$ K, log $g = 8.0$, log N(H)/N(He) $= -4.4$. The forbidden components near 6068 and 6632 Å are marked with thick vertical tick marks at the bottom of the frame. For reference, the normal field strength near Rosseland optical depth of 0.2 (where the weak forbidden lines are formed) is of the order of 300 statvolt cm^{-1} in the 22,000 K and 25,000 K DB models, and of 200 statvolt cm^{-1} in the 16,000 K DBA model. Note that the feature near 6250 Å in the observed spectra is due to night-sky lines. The plots are rectified in the range 5300–6900 Å, and are shifted vertically for clarity, with the respective zero points indicated along the vertical axis.

forbidden components. While our preliminary modeling of these features has been quite successful, much remains to be investigated. These new features differ in an important way from the satellite $2\,^3P$–$4\,^3P$ $\lambda 4517$ transition: they connect to the $n = 3$, rather than $n = 4$, level in He I. While levels with $n \geq 4$ may be treated in the Coulomb approximation, this approximation (which is made here) appears less justifiable in the case of a lower lying level. Among forbidden transitions connecting to $n = 3$, the two modeled here offer the best hope of testing the validity of the Coulomb approximation, as they are not crowded by other allowed transitions. Furthermore, the effect of the perturbation on the lower level of the transitions, neglected here, also needs to be further investigated. Finally, a detailed modeling of the red forbidden components could require consideration of the contribution of levels with values of n other than that of the unperturbed upper level (see eq. [3]). Further consideration of these approximations may well provide a useful testing ground of our description of the physics of the neutral helium atom.

We are grateful to G. Fontaine for informative discussions and for his continued interest in this project, and to R. Lamontagne for reducing the CCD data. We also acknowledge the useful comments of an anonymous referee. This work was supported in part by the NSERC Canada, by the Fund FCAR (Québec), and by the NSF grant AST 91-45162.

REFERENCES

Barnard, A. J., & Cooper, J. 1970, J. Quant. Spectros. Rad. Transf., 10, 695
Barnard, A. J., Cooper, J., & Shamey, L. J. 1969, A&A, 1, 28
Beauchamp, A. 1995, Ph.D. thesis, Univ. Montréal
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bergeron, P., Wesemael, F., & Fontaine, G. 1991, ApJ, 367, 253
Greenstein, J. L., & Liebert, J. 1990, ApJ, 360, 662 (GL)
Greig, J. R., Jones, L. A., & Lee, R. W. 1974, Phys. Rev. A, 9, 44
Griem, H. R. 1968, ApJ, 154, 1111
Koester, D., Schulz, H., & Wegner, G. 1981, A&A, 102, 331
Koester, D., Vauclair, G., Dolez, N., Oke, J. B., Greenstein, J. L., & Weidemann, V. 1985, A&A, 149, 423
Liebert, J. 1977, ApJ, 214, 446
Liebert, J., Beaver, E. A., Robertson, J. W., & Strittmatter, P. A. 1976, ApJ, 204, L119
Oke, J. B., Weidemann, V., & Koester, D. 1984, ApJ, 281, 276
Struve, O. 1929a, ApJ, 69, 173
———. 1929b, ApJ, 70, 85
Thejll, P., Vennes, S., & Shipman, H. L. 1991, ApJ, 370, 355
Wegner, G., & Nelan, E. P. 1987, ApJ, 319, 916
Wesemael, F., Green, R. F., & Liebert, J. 1985, ApJS, 58, 379
Wesemael, F., Greenstein, J. L., Liebert, J., Lamontagne, R., Fontaine, G., Bergeron, P., & Glaspey, J. W. 1993, PASP, 105, 761
Wickramasinghe, D. T., & Reid, N. 1983, MNRAS, 203, 887
Wickramasinghe, D. T., & Whelan, J. A. J. 1977, MNRAS, 178, 11P
Ya'akobi, B., George, E. V., Bekefi, G., & Hawryluk, R. J. 1972, J. Phys. B, 5, 1017