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A CONFIRMATION OF THE OPTICAL SPECTROSCOPY APPROACH: DISCOVERY OF TWO MORE PULSATING DA (ZZ CETI) WHITE DWARFS[1]

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ABSTRACT

We first review and rebut the arguments that have been put forward recently against the use of optical spectroscopy in the determinations of the atmospheric parameters of ZZ Ceti and neighboring stars in the $\log g$–$T_{\rm eff}$ diagram. We reiterate instead the conclusion of Bergeron et al. that optical spectroscopy *alone*, when properly handled and modeled, leads to very accurate and reliable estimates of the surface gravities and effective temperatures of ZZ Ceti pulsators. The optical spectroscopy approach has had a yield of 100% so far in predicting the variability of candidate ZZ Ceti stars, and we present evidence here of its successful application to two more objects. We hence report the detection of multiperiodic luminosity variations in the light curves of two DA white dwarfs, MCT 0145−2211 and HE 0532−5605, selected on the basis of an analysis of their optical spectra. This brings the number of known ZZ Ceti stars to a total of 34. Our study reveals that MCT 0145−2211 has $T_{\rm eff} = 11,550$ K and $\log g = 8.14$, while HE 0532−5605 has $T_{\rm eff} = 11,560$ K and $\log g = 8.49$, which places them both inside the empirical instability strip uncovered by Bergeron et al. We find that the amplitudes, periods, and degree of complexity of the light curves are consistent with the positions of the stars rather near the red edge. Using the same homogeneous approach, we have, so far, analyzed high-quality optical spectra for some 103 nonvariable DA white dwarfs and all of the 34 known ZZ Ceti stars. The picture of the empirical instability strip that emerges is that of a *pure* strip, in which *no* nonvariable stars are found. It has a trapezoidal shape in the $\log g$–$T_{\rm eff}$ plane, with the blue edge showing a stronger dependence on the surface gravity than the red edge does.

Subject headings: stars: interiors — stars: oscillations — white dwarfs

1. INTRODUCTION

The ZZ Ceti stars form a highly homogeneous group of intrinsically variable stars. They are all hydrogen line (DA) white dwarfs, they all show multiperiodic luminosity variations caused by nonradial g-mode instabilities with periods in the range 100–1200 s, and they are all found in a narrow range of effective temperature, $12,500\ {\rm K} \gtrsim T_{\rm eff} \gtrsim 11,100$ K, according to the detailed study of Bergeron et al. (1995b, hereafter B95). As is often the case in astronomy, the first pulsating DA white dwarf, HL Tau 76, was discovered serendipitously, in this instance by Landolt (1968). The class of ZZ Ceti pulsators itself really emerged only after McGraw (1977) carried out a systematic study of the first seven objects of the group.

Fontaine et al. (2001) recently summarized the historical record concerning the discoveries of the 31 ZZ Ceti stars that were known in 2001 March. In the meantime, Mukadam et al. (2002) reported the discovery of luminosity variations in the DA white dwarf G30-20, thus bringing the total of known ZZ Ceti stars to 32. As discussed in Fontaine et al. (2001), the earlier searches for new pulsators were based on qualitative criteria, such as observations of DA white dwarfs in restricted color ranges, for instance, stars with $B-V \sim 0.20$ in the Johnson system or stars with $G-R \sim -0.42$ in the multichannel system used by Greenstein (1976). These general searches had typically low yields. A more quantitative approach was developed by Bergeron & McGraw (1990), who combined optical spectroscopy with models of the emergent flux of DA stars to actually predict (successfully) that GD 165 should be a ZZ Ceti pulsator on the basis of their derived values of its effective temperature $T_{\rm eff}$ and surface gravity $\log g$. This constituted a true quantitative prediction for a specific object and opened a most interesting avenue for further searches for new pulsating DA white dwarfs.

The approach of Bergeron & McGraw (1990) has been firmly consolidated in the follow-up work of B95, who have presented the most complete, systematic, and homogeneous study of the time-averaged atmospheric properties of the ZZ Ceti stars that has been published so far. B95 considered the full sample of 22 ZZ Ceti stars known at the time and demonstrated that optical spectroscopy, when properly handled and modeled, can be used to derive accurate and

[1] Based, in part, on observations gathered at the Canada-France-Hawaii Telescope (CFHT), operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France, and the University of Hawaii, and, in part, on observations performed at the European Southern Observatory, La Silla, Chile.

reliable values of the atmospheric parameters of ZZ Ceti and neighboring stars in the $\log g$–$T_{\rm eff}$ diagram. In particular, B95 demonstrated conclusively that ZZ Ceti stars occupy a definite region in that diagram, the instability strip, where few (if any) constant stars are found. Furthermore, that region in the $\log g$–$T_{\rm eff}$ plane is not a simple band in effective temperature, but a trapezoidal-shaped region with a blue edge showing a strong dependence on the surface gravity.

Computations modeled closely after the work of B95 have led to the discoveries of four additional ZZ Ceti stars after the initial success of Bergeron & McGraw (1990) for GD 165. These are HS 0507+04334B (Jordan et al. 1998), PG 1541+650 (Vauclair et al. 2000), GD 244 (Fontaine et al. 2001), and KUV 02464+3239 (Fontaine et al. 2001). With these five discoveries, the optical spectroscopy approach had a yield of 100% up to that point in time. Despite this success, and despite the consistent picture that emerged from the study of B95, the optical spectroscopy method has been criticized, notably in the series of papers by Koester & Vauclair (1997), Koester & Allard (2000), and Koester & Holberg (2001). According to these authors, the effective temperatures of ZZ Ceti stars (based on spectroscopic determinations) are uncertain by up to 2000 K, significantly larger than the width of the strip itself, and the true location of the strip cannot be pinned down with any certainty. If those claims were true, the perfect record of the optical spectroscopy approach at predicting the variability of candidate stars would have to be a most amazing coincidence.[2]

In this paper, we first respond to the criticisms that have been leveled at the method put forward by B95. We also report on an extension of the study of B95 to additional stars, including 12 ZZ Ceti stars that were not known in 1995—the variability of two of those is reported for the first time here—and several nonvariable stars. Over the years, we have gathered high-quality optical spectra for several DA stars known to be nonvariable from various published surveys. We have analyzed those spectra, as well as the spectra of the 12 new ZZ Ceti stars, using the exact same tools as in B95, thus guaranteeing the homogeneity of our derived atmospheric parameters. Given that the instability strip is quite narrow, this homogeneity in our approach is of utmost importance. We thus obtain what we claim to be the most reliable and coherent description of the empirical ZZ Ceti instability strip. We next report on the discoveries of two new ZZ Ceti stars identified, once again, through the optical spectroscopy approach, which has now led to the uncovering of seven of these pulsators with 100% predictive power. We take this as a very strong additional proof of the validity of the approach. The two candidates stars were picked from the sample of Koester et al. (2001), who have provided estimates of $T_{\rm eff}$ and $\log g$ for a number of DA stars in the SPY project on the basis of optical spectroscopy only and using model atmospheres copied after B95.

[2] Note, in this connection, that the value $T_{\rm eff} = 14,620$ K reported by Bragaglia, Renzini, & Bergeron (1995) for GD 165 is incorrect in that it corresponds to the " hot-side solution " for spectroscopic analyses in that temperature range. The correct choice would have been the cold solution obtained by B95, where full details about this ambiguity between hot and cold solutions for ZZ Ceti stars can be found.

2. THE OPTICAL SPECTROSCOPY APPROACH AND THE EMPIRICAL ZZ CETI INSTABILITY STRIP

In an ensemble approach, B95 have combined optical spectroscopy with ultraviolet observations to produce the most comprehensive analysis of the atmospheric properties of ZZ Ceti stars. They used data for *all* the 22 pulsators known at the time. They showed that model atmospheres calculated with the so-called ML2/$\alpha = 0.6$ version of the mixing-length theory provides the best internal consistency between optical and UV effective temperatures, trigonometric parallaxes, V magnitudes, and gravitational redshifts. With this internal consistency achieved, it is then possible to rely on high signal-to-noise ratio (S/N $\gtrsim 80$) optical spectroscopy *alone* to determine with great accuracy the atmospheric parameters ($T_{\rm eff}$ and $\log g$) of any ZZ Ceti star. This is the key point: once the appropriate convective efficiency to be used in the computations of model atmospheres has been calibrated for the *whole* class of ZZ Ceti stars (through the requirement of optimal consistency between the various available data sets in B95), there is no need anymore to gather UV photometry/spectroscopy, parallax measurements, gravitational redshift measurements, or optical photometry along with optical spectroscopy for each new object and play with the convective efficiency. By doing that, one destroys the internal consistency obtained by B95 for the ZZ Ceti stars as a class. It is precisely this point that seems to have been overlooked by the critics of the method. In the following, we thus review and rebut the main arguments presented in various proceedings papers.

Koester & Vauclair (1997) have argued that the spectroscopic technique is basically flawed because the ZZ Ceti stars are found close to the maximum in the strength of the Balmer lines, where a significant change in atmospheric parameters results only in very small changes in the visible spectra. In particular, according to these authors, there would be practically no sensitivity to variations in effective temperature. To quantify this claim, we investigate in Figure 1 the sensitivity of the equivalent widths (W) of Hβ, Hγ, and Hδ to variations of $T_{\rm eff}$ (i.e., $dW/dT_{\rm eff}$) as a function of the effective temperature at a fixed typical value of

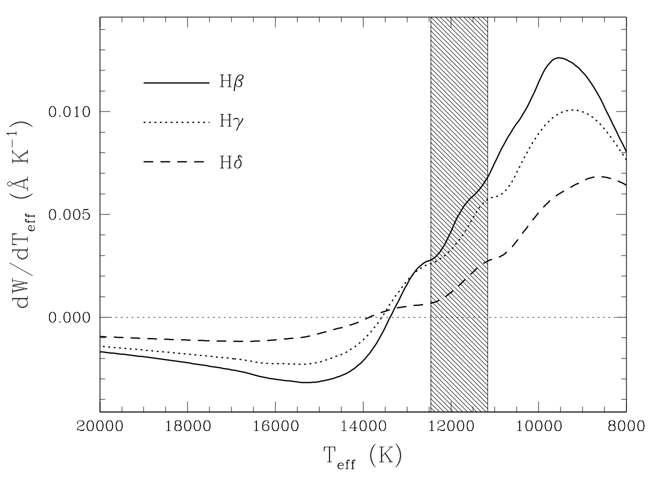

FIG. 1.—Derivative of the equivalent width of Hβ, Hγ, and Hδ with respect to $T_{\rm eff}$ as a function of the effective temperature for models of DA white dwarfs. The surface gravity is held fixed here at a value of $\log g = 8.0$. The shaded region corresponds to the location of the ZZ Ceti instability strip.

$\log g = 8.0$. Note, in this context, that Balmer lines are always sensitive to $\log g$ in the range of $T_{\rm eff}$ considered here. The results indicate that the $T_{\rm eff}$ sensitivity vanishes around $T_{\rm eff} \sim 13,500$ K ($dW/dT_{\rm eff} \sim 0$), but in the region where ZZ Ceti stars are found ($12,500 \text{ K} \gtrsim T_{\rm eff} \gtrsim 11,100$ K), all Balmer lines are extremely sensitive to variations of $T_{\rm eff}$, even more sensitive than for hotter DA stars, to which the spectroscopic technique has been applied extensively.

Because Balmer lines in the ZZ Ceti range are, in fact, very sensitive to both $T_{\rm eff}$ and $\log g$, internal errors obtained from least-squares fits to high-S/N optical spectra are meaningless, as discussed in B95. The typical good fits that are achieved only reflect the ability of the model spectra to match the data, and the error budget is actually dominated by uncertainties of the flux calibration. On this account, Koester & Allard (2000) and Koester & Holberg (2001) have argued that very small errors in the reduction of observed spectra could result in large differences in the derived atmospheric parameters. Of course, this conclusion is largely dependent on the observing conditions, as well as on the observer's skills and attention to details. To assess more quantitatively this claim in the case of the B95 analysis, we compare in Figure 2 the atmospheric parameters of a subset of stars in B95 with those derived from spectra obtained independently by Chris Moran (2000, private communication), using a completely different setup and reduction procedure. As can be seen, the values of $T_{\rm eff}$ and $\log g$ are in excellent agreement, and the standard deviations between both sets of measurements allow us to estimate the real external errors, $\sigma(T_{\rm eff}) \sim 200$ K and $\sigma(\log g) \sim 0.05$. We note that in the absence of external data of comparable quality, B95 had adopted somewhat more conservative estimates of the external errors, namely, $\sigma(T_{\rm eff}) \sim 350$ K and $\sigma(\log g) \sim 0.05$. The latter were derived by Bergeron, Saffer, & Liebert (1992) for their sample of warmer DA stars, and since, as we have seen above, the sensitivity of the spectral lines to the effective temperature is in fact smaller in warmer stars than in ZZ Ceti stars, the value of $\sigma(T_{\rm eff}) \sim 350$ K is an overestimate for the pulsators.

It has also been argued that accurate determinations of the atmospheric parameters of ZZ Ceti pulsators *necessarily* require the use of additional constraints, such as parallaxes, V magnitudes, or UV spectrophotometry. However, as pointed out above, B95 have already demonstrated that the spectroscopic solutions were entirely *consistent* with these additional constraints, so the arguments are not repeated here. We simply point out in this context that our predicted value of $M_V = 12.020 \pm 0.082$ for G226-29 agrees within 0.2 σ with the value measured by *Hipparcos*, $M_V = 12.038 \pm 0.056$; similarly, our predicted value of $M_V = 11.770 \pm 0.080$ for GD 165 agrees within 0.3 σ with the value of $M_V = 11.825 \pm 0.172$ obtained from the Yale Parallax Catalogue.

If determinations of atmospheric parameters based on the optical spectroscopy approach were unreliable, as claimed by some, it would be virtually impossible to make real progress in the field of ZZ Ceti asteroseismology. Fortunately, this is not the case, as demonstrated in Figure 3, where we show our effective temperature and surface gravity determinations for all 34 known ZZ Ceti stars (*open circles*). Those include the positions of the 22 objects already considered in B95 and of 12 additional ZZ Ceti stars discovered since 1995, with atmospheric parameters inferred from optical spectroscopy and modeled in the same homogeneous manner. For completeness, we provide in Table 1 the values of the atmospheric parameters for those 12 additional pulsators (to be combined with the data provided in Table 4 of B95). Note that the stellar masses have been derived from the models of Wood (1995) for carbon core compositions, helium layers of $M_{\rm He} = 10^{-2} M_*$, and hydrogen layers of $M_{\rm H} = 10^{-4} M_*$.

Also shown in Figure 3 are our determinations for 20 DA stars with measured constant light curves (*filled circles*). Interestingly, those are part of a much larger sample of 103 DA stars known to be constant through various published surveys and for which we have gathered high-S/N optical spectra. Using again our same homogeneous modeling, we find that the majority of the stars in that sample have $T_{\rm eff}$

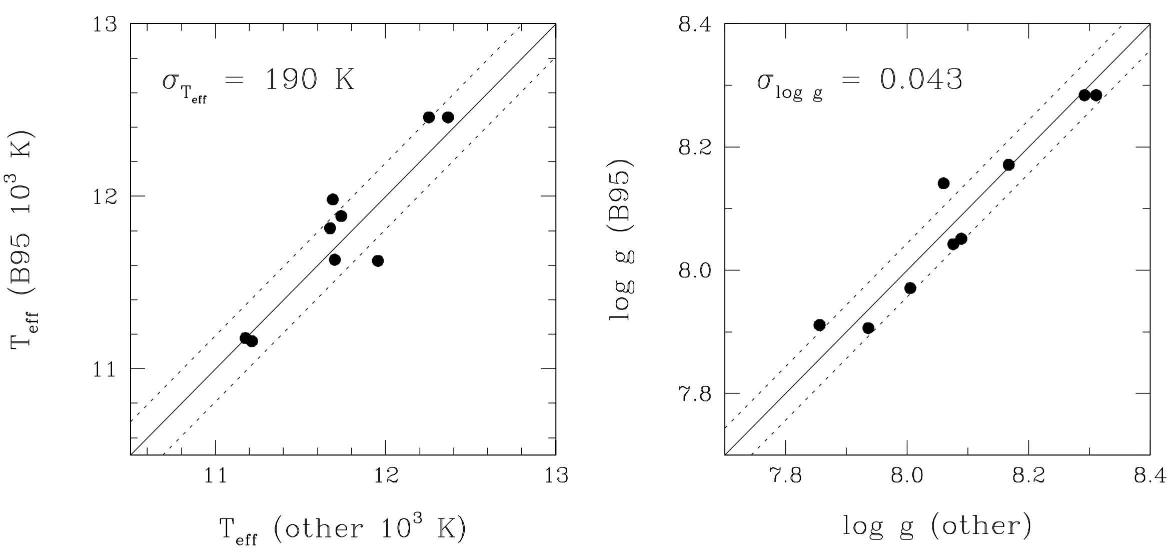

Fig. 2.—Comparison of $T_{\rm eff}$ and $\log g$ determinations from B95 with other estimates from independent spectra. The solid line represents the 1 : 1 relationship, while the dotted lines represent the ± 1 σ values reported in the figure.

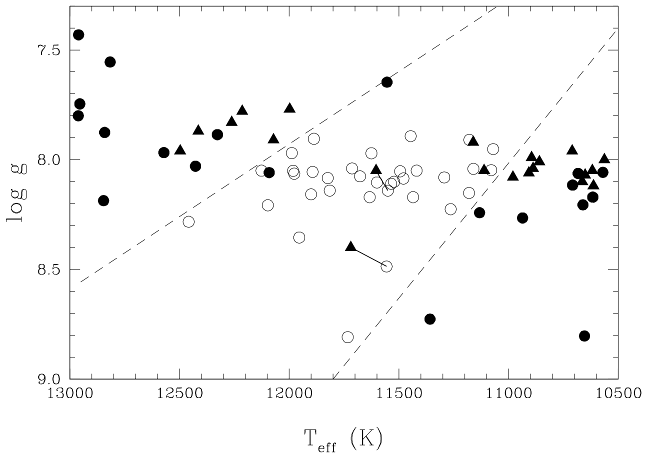

FIG. 3.—Surface gravity–effective temperature distribution for various samples of DA white dwarfs. The open circles represent the ZZ Ceti stars (22 from B95 and 12 from Table 1) with reliable and homogeneous estimates of the atmospheric parameters. Filled circles are for DA stars that are known to be nonvariable and whose atmospheric parameters have been determined by us on the basis of the same homogeneous approach as used for the ZZ Ceti stars. Triangles correspond to the SPY determinations from Koester et al. (2001), with all known ZZ Ceti stars excluded. No information was available as to the variability of the stars represented by the triangles. A line joins the triangle (SPY) and the open circle (this study) giving the estimated locations of MCT 0145−2211 in the two independent studies. A similar structure, located lower in the diagram, gives the positions of HE 0532−5605. The dashed lines represent the empirical blue and red edges of the instability strip.

either higher than 13,000 K or lower than 10,500 K, i.e., outside the range of interest for the ZZ Ceti instability strip. This presumably reflects the poor accuracy of the colors on which most surveys for variability were based, which explains, after the fact, the poor yields of such surveys. There are two constant stars formally inside the empirical instability strip. One is LP 550-52, located at $T_{\rm eff} = 11,550$ K and $\log g = 7.65$, an unresolved degenerate binary with a period of 1.157 days whose atmospheric parameters are thus uncertain (Maxted & Marsh 1999). The other is GD 133, located at $T_{\rm eff} = 12,090$ K and $\log g = 8.06$. Given the uncertainties, the position of that object inside the strip, but very close to the blue edge, remains consistent with the idea of a pure strip.

Our results clearly indicate that, within the uncertainties, *there are no nonvariable stars inside the ZZ Ceti instability strip*, a conclusion that supports our understanding that ZZ Ceti stars represent a phase through which all DA stars must evolve. And indeed, for a given mass, nonadiabatic pulsation theory predicts that $T_{\rm eff}$ is the single parameter that is responsible for the onset of instabilities. Note that this question of the purity of the ZZ Ceti instability strip has been debated in the literature since the early suggestion by Fontaine et al. (1982) that the strip ought indeed to be pure. Over the years, this thesis has been developed and defended by our group at Université de Montréal (see, e.g., Fontaine & Wesemael 1984; Wesemael & Fontaine 1985; Fontaine et al. 1985; Wesemael, Lamontagne, & Fontaine 1986; Lamontagne et al. 1989; Wesemael et al. 1991; B95). Our present results represent the culmination of these efforts, and we hope that they will put to rest once and for all the reports that have appeared from time to time that the instability strip contains both variable and nonvariable stars (e.g., Dolez, Vauclair, & Koester 1991; Kepler & Nelan 1993; Kepler et al. 1995; Silvotti et al. 1997; Giovannini et al. 1998). Every time such claims were made, we were able, upon close examination, to bump the "offending" constant stars outside of the instability strip. The homogeneity (or lack thereof) of the data sets and of the methods of analysis used was always the culprit for these false alerts. We claim that Figure 3 currently represents the most complete and most reliable description of the empirical ZZ Ceti instability strip. Nonadiabatic pulsation theory will have to explain the location and extent of that strip.

Finally, to illustrate further the power of optical spectroscopy for determining the atmospheric parameters of ZZ Ceti stars, we included in Figure 3 the values of $T_{\rm eff}$ and $\log g$ for the DA white dwarfs in the SPY program (Koester et al. 2001) that happen to fall in the range of effective temperature shown in the figure (*triangles*). We note that the determinations of the atmospheric parameters of the stars in the SPY sample are based solely on high-quality optical spectra obtained by others, using a setup and reduction procedure completely different from ours. However, the model atmospheres of Koester et al. (2001) used the same "calibration" of convection proposed by B95 and are thus quite similar to our own models. With the exception of seven ZZ Ceti stars (not shown in Fig. 3), we had no a priori

TABLE 1

ATMOSPHERIC PARAMETERS OF ZZ CETI STARS NOT IN B95

WD	Name	$T_{\rm eff}$ (K)	$\log g$	M ($M_\odot$)	M_V
0145−221[a]	MCT 0145−2211	11,550	8.14	0.69	11.97
0246+326	KUV 02464+3239	11,290	8.08	0.65	11.93
0507+045	HS 0507+0435B	11,630	8.17	0.71	11.99
0532−560[a]	HE 0532−5605	11,560	8.49	0.92	12.52
0836+404	KUV 08368+4026	11,490	8.05	0.64	11.85
1137+423	KUV 11370+4222	11,890	8.06	0.64	11.77
1401−147	EC 14012−1446	11,900	8.16	0.70	11.92
1541+650	PG 1541+651	11,600	8.10	0.67	11.90
1714−547	BPM 24754	11,080	8.05	0.63	11.94
2254+126	GD 244	11,680	8.08	0.65	11.84
2347+128	G30-20	11,070	7.95	0.58	11.80
2348−244	EC 23487−2424	11,520	8.10	0.67	11.91

[a] This paper.

knowledge that the SPY stars illustrated in the figure are constant or variable. Two filled triangles in the middle of the instability strip obviously stand out (MCT 0145−2211 at the top and HE 0532−5605 at the bottom). They immediately attracted our attention since, to our knowledge, they had never been looked at for variability. We took the first opportunities available to observe them and, as reported in the next section, they both turned out to be genuine ZZ Ceti pulsators. We take these findings as a strong confirmation of the optical spectroscopy approach.

3. DISCOVERY OF TWO NEW ZZ CETI STARS

3.1. *Spectroscopic Observations*

The values of the atmospheric parameters derived by Koester et al. (2001) for MCT 0145−2211 and HE 0532−5605 are $T_{\rm eff} = 11{,}604$ K, $\log g = 8.05$ (an average of two measurements) and $T_{\rm eff} = 11{,}719$ K, $\log g = 8.40$, respectively. As seen in Figure 3, these values put the two stars well inside the instability strip uncovered by B95. In order to obtain an independent check and retain our homogeneous approach to such data, we gathered a high-S/N optical spectrum for each of the two stars. This was done by one of us (M. B.) with the EMMI instrument attached to the 3.6 m New Technology Telescope (NTT) at the ESO La Silla Station. The spectra cover the wavelength range 3750–5100 Å at ∼5.5 Å resolution and were reduced in a standard way through the IRAF package. Integration times of 2400 and 1800 s for MCT 0145−2211 and HE 0532−5605, respectively, were used, longer than any expected periods of brightness variations, thus ensuring that the data are meaningful, time-averaged spectra.

Figure 4 shows our best (in a least-squares sense) fits to the available hydrogen Balmer lines (Hβ through H9) in the optical spectra of MCT 0145−2211 and HE 0532−5605. The fitting procedure is the same as that used by B95, and we refer the reader to that paper for details. The input physics used in our model atmospheres and synthetic spectra is that described in Bergeron, Saumon, & Wesemael (1995a), but also incorporates the improvements discussed in B95. Following these latter authors, we have adopted the ML2/$\alpha = 0.6$ parameterization of the mixing-length theory to describe convection.

The derived atmospheric parameters for MCT 0145−2211 are $T_{\rm eff} = 11{,}550$ K and $\log g = 8.14$, while those for HE 0532−5605 are $T_{\rm eff} = 11{,}560$ K and $\log g = 8.49$. These values are reported in Table 1. As alluded to in § 2, the formal 1 σ errors associated with our fitting procedure are unrealistically small, and we instead adopt the values of $\sigma(T_{\rm eff}) \sim 200$ K and $\sigma(\log g) \sim 0.05$, obtained from a comparison of the B95 and Moran data, as more realistic estimates of the uncertainties. We note that our determinations of the atmospheric parameters of the two target stars are consistent with those of Koester et al. (2001), assuming that these authors have similar uncertainties on their values.

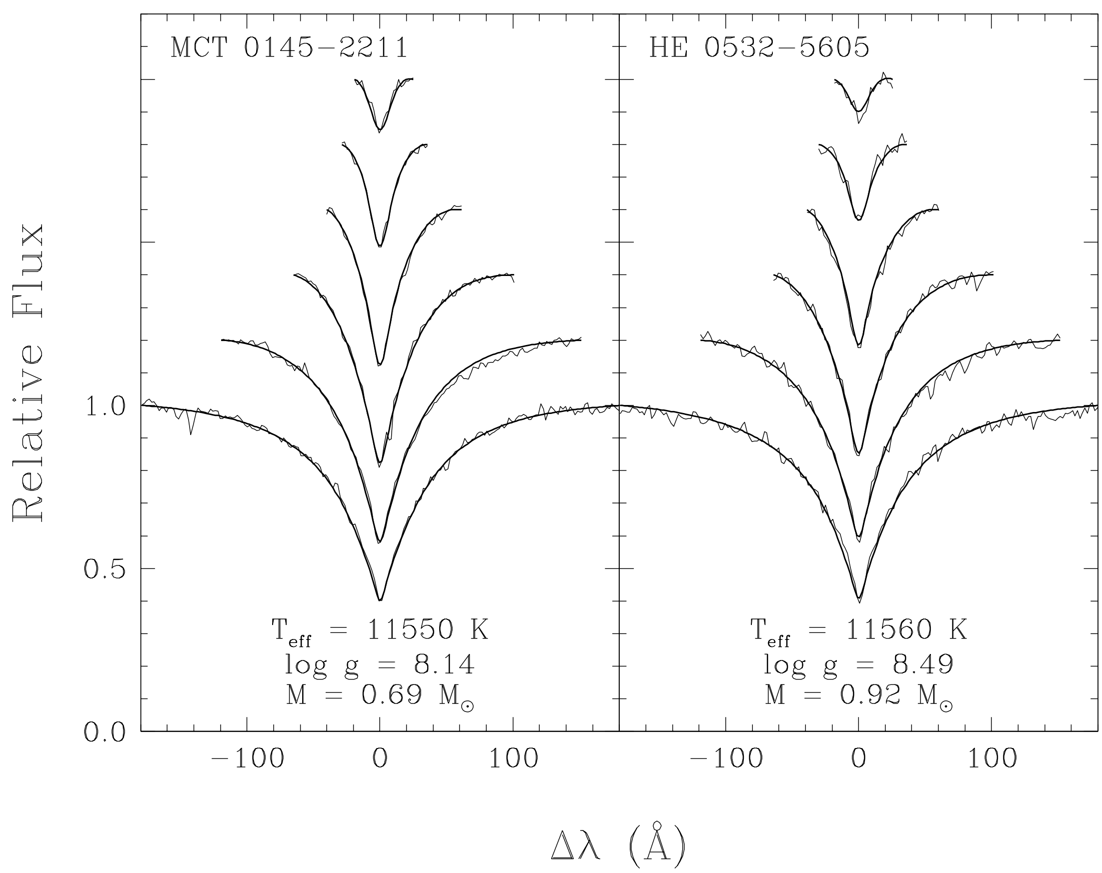

FIG. 4.—Model fits to the individual Balmer line profiles of MCT 0145−2211 and HE 0532−5605. The lines range from Hβ (*bottom*) to H9 (*top*), each offset vertically by a factor of 0.2. Values of $T_{\rm eff}$ and $\log g$ have been determined from ML2/$\alpha = 0.6$ models, while the stellar masses have been derived from the models of Wood (1995) for carbon core compositions, helium layers of $M_{\rm He} = 10^{-2} M_*$, and hydrogen layers of $M_{\rm H} = 10^{-4} M_*$.

There could be, however, a small systematic effect, in the sense that we get higher values of $\log g$ and smaller values of $T_{\rm eff}$. The triangle and the open circle indicating the two independent determinations of the atmospheric parameters for MCT 0145−2211 are joined by a straight line segment in Figure 3. The same is true for HE 0532−5605. Given the observed periods (see below), we point out that our values, which put the stars closer to the red edge, are in better agreement with the period–effective temperature relation observed in ZZ Ceti pulsators (see, e.g., Winget & Fontaine 1982).

3.2. *Integrated Light Photometry of MCT 0145−2211*

We took the opportunity to observe MCT 0145−2211 during the course of a four-night observing run at the 3.6 m CFHT (Mauna Kea) in 2002 July. This run was dedicated to follow-up observations of the pulsating/ellipsoidal variable sdB star KPD 1930+2752, a project carried out by two of us (G. F. and S. C.). Our aim was simply (and hopefully!) to establish the variability of our extra target without perturbing in any significant way the main science goals of the mission. Thus, we looked at MCT 0145−2211 near the end of the first two nights, when KPD 1930+2752 was well past the $3^{\rm h}$ angle. The observing conditions were superb throughout these two nights.

MCT 0145−2211 (WD 0145−221, PHL 1159, GD 1400; $V = 15.3$) was observed in integrated (white-light) "fast" photometric mode for 3740 s on the night of 2002 July 14 and for 5780 s on the following night. The photometric observations were gathered with LAPOUNE, the portable Montréal three-channel photometer. We refer the interested reader to Billères et al. (1997) for details on our standard observational procedure. Figure 5 shows the full sky-subtracted, extinction-corrected light curve of MCT 0145−2211 obtained on the second night. The first light curve is comparable in quality but is shorter. The light curve shown in the figure is expressed in terms of the residual amplitude relative to the mean intensity of the star, and each plotted point corresponds to a sampling time of 10 s. Very clearly, MCT 0145−2211 is a multiperiodic luminosity variable, another ZZ Ceti star. We point out that, interestingly, the amplitudes, periods, and degree of complexity of its light curve are consistent with the position of MCT 0145−2211 in the $\log g$–$T_{\rm eff}$ plane, as inferred above from optical spectroscopy. Indeed, that star shares many characteristics with neighboring stars in that diagram, such as HS 0507+0435, BPM 31594, PG 2303+249, and G191-16.

We have computed a standard Fourier spectrum of the light curve of MCT 0145−2211, using the two consecutive nightly segments together. The results are shown in Figure 6. It illustrates the Fourier (amplitude) spectrum of the light curve in the 0–10 mHz bandpass. The spectrum in the region from 10 mHz out to the Nyquist frequency (50 mHz) is entirely consistent with noise and is not shown. While more detailed observations will obviously be needed to resolve fully the frequency spectrum, Figure 6 reveals a relatively complex structure characteristic of large-amplitude ZZ Ceti pulsators. We provisionally identify three significant frequency components corresponding to periods of 823.2, 727.9, and 462.2 s, the latter mode having the dominant amplitude. There are most probably other significant peaks, as well as nonlinear structure, in the light curve of MCT 0145−2211, but longer observations will be required to identify them.

3.3. *Integrated Light Photometry of HE 0532−5605*

A program of follow-up observations of pulsating sdB stars on a midsize telescope in the southern hemisphere has been initiated by one of us (M. B.). This uses SUSI2, the high-resolution optical CCD at the NTT, in the fast photometry (windowing) mode with no filter in front. For an initial report on that program, see Billères & Fontaine (2003). We took the opportunity, during one of the nights assigned to this program, to gather a short light curve of HE 0532−5605, in the hope of establishing its variability. We were thus able to observe HE 0532−5605 (WD 0532−560; $V \sim 15$) in the fast photometric mode for 7040 s. The reduced light curve, expressed in terms of the residual amplitude relative to the mean intensity of the star, is shown in Figure 7. Each plotted point corresponds to a sampling time of 40 s. Note that, allowing for readout delays, the effective exposure time of each image was 25 s. While the observing conditions were less than ideal, the light curve illustrated in Figure 7 is compelling: HE 0532−5605 is clearly another ZZ

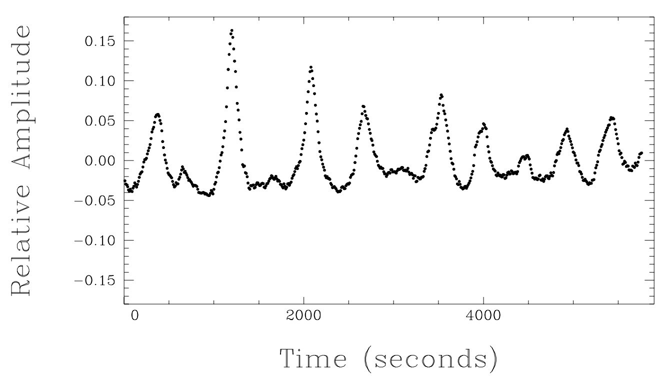

FIG. 5.—"White-light" light curve of MCT 0145−2211, observed on 2002 July 15 with LAPOUNE attached to the CFHT (run cfh-100). The light curve is expressed in terms of residual amplitude relative to the mean brightness of the star. Each point represents a sampling time of 10 s.

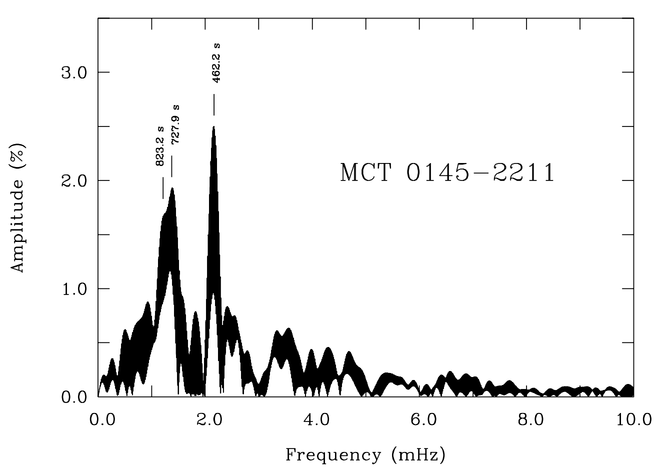

FIG. 6.—Fourier (amplitude) spectrum of the light curve of MCT 0145−2211 (runs cfh-098 and cfh-100 together) in the 0–10 mHz bandpass. The amplitude axis is expressed in terms of the percentage variations about the mean brightness of the star. Three periodicities are clearly seen, but other peaks are also probably significant.

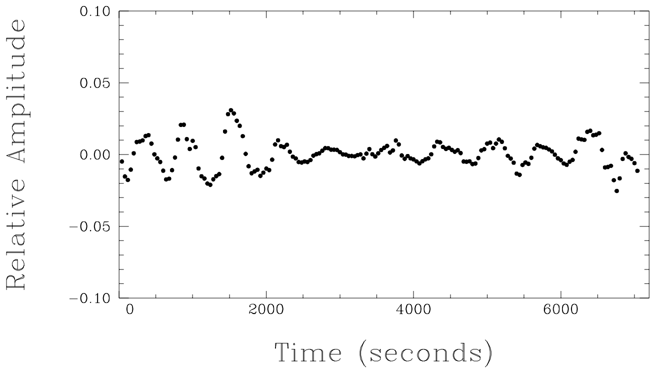

FIG. 7.—"White-light" light curve of HE 0532−5605 gathered with the optical CCD camera SUSI2 attached to the NTT. The light curve is expressed in terms of residual amplitude relative to the mean brightness of the star. Each plotted point represents a sampling time of 40 s.

Ceti pulsator. It is worthwhile to point out that the light curve of HE 0532−5605 is intermediate in structure (amplitudes, periods) and complexity between those of BPM 30551 ($T_{\rm eff} = 11,260$ K, $\log g = 8.23$) and BPM 37093 ($T_{\rm eff} = 11,780$ K, $\log g = 8.86$), its two nearest neighbors in the $\log g$–$T_{\rm eff}$ plane. This adds credibility to the overall internal consistency of our picture of the ZZ Ceti instability strip.

Figure 8 illustrates the Fourier (amplitude) spectrum of our light curve of HE 0532−5605 in the 0–10 mHz bandwidth, where all photometric activity is concentrated. Again, it will be necessary to gather much longer light curves to decipher the underlying structure. Nevertheless, we tentatively identify the two dominant frequency components corresponding to periods of 688.8 and 586.4 s. It seems clear that other significant peaks are present in the light curve, as well as nonlinear structure, which is in line with the position of HE 0532−5605 rather close to the red edge of the strip. As in the case of MCT 0145−2211, longer observations will be needed to make further progress. The goal of the exercise here was to establish the variability of our two target stars, and on this account, we have clearly succeeded.

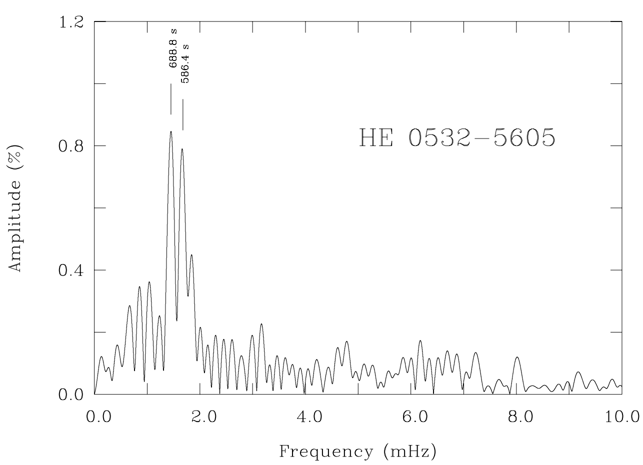

FIG. 8.—Fourier (amplitude) spectrum of the light curve of HE 0532−5605 in the 0–10 mHz bandpass. The amplitude axis is expressed in terms of the percentage variations about the mean brightness of the star. The (low-resolution) spectrum is dominated by two large peaks corresponding to periods of 688.8 and 586.4 s, as labeled.

4. CONCLUSION

Contrary to certain claims, we reiterate the conclusion of B95 that optical spectroscopy alone can provide accurate and reliable determinations of the atmospheric parameters of ZZ Ceti and neighboring stars in the $\log g$–$T_{\rm eff}$ diagram. This is possible provided that (1) high-quality spectra are gathered, (2) model atmospheres comparable to those of B95 (and based on the calibration of the mixing-length theory proposed there) are used, and (3) attention to details is provided. We have reviewed and rebutted the main arguments put forward by some authors against the use of optical spectroscopy for ZZ Ceti pulsators. We hope very much that our efforts will put to rest the rumors that the spectroscopic approach of B95 is problematic and that the current estimates of the atmospheric parameters of ZZ Ceti stars are uncertain. Above all, we hope that confusion regarding this issue among the ranks of asteroseismologists will cease.

The three conditions above for the successful use of optical spectroscopy were met in the study of Koester et al. (2001) concerning their SPY project. In particular, according to their own results, two of the DA stars in their sample fall right in the middle of the instability strip uncovered by B95. Since those two stars, MCT 0145−2211 and HE 0532−5605, had not been observed before for possible rapid luminosity variations, they became obvious ZZ Ceti candidates. In order to maintain the homogeneity of our approach, we obtained and analyzed our own high-S/N optical spectra for these two stars. Our independent results confirmed the locations of the two objects inside the instability strip. It was then a matter of seizing the first opportunities to carry out high time resolution photometric observations on them. We found, with no surprise to us, that both MCT 0145−2211 and HE 0532−5605 are genuine ZZ Ceti pulsators, with general characteristics in excellent agreement with their individual locations in the $\log g$–$T_{\rm eff}$ plane. Our findings have brought the number of known ZZ Ceti stars to 34. We also point out that the optical spectroscopy approach for uncovering new pulsators, first put forward by Bergeron & McGraw (1990), has now yielded seven ZZ Ceti stars, a perfect record so far. We interpret this as a very strong indication of the overall reliability of the spectroscopic method.

We have now analyzed in the same rigorous and homogeneous fashion high-S/N optical spectroscopy for 103 DA stars known to be nonvariable and all of the 34 known ZZ Ceti stars. The picture that emerges for the empirical ZZ Ceti instability strip has been described in Figure 3. Most of the nonvariable stars fall well outside the strip, and only 20 of them are within the range of effective temperature of immediate interest, i.e., within $13,000\ {\rm K} \geq T_{\rm eff} \geq 10,500$ K. Allowing for the uncertainties in the derived atmospheric parameters (especially near the edges of the strip), the distributions of 20 nonvariable and 34 variable stars shown in Figure 3 imply that the strip is pure. There are no nonvariable stars inside the strip, and all DA white dwarfs, upon cooling, must become ZZ Ceti pulsators. The empirical ZZ Ceti instability strip has a trapezoidal shape in the $\log g$–$T_{\rm eff}$ diagram, and the blue edge appears to have significantly stronger dependence on the surface gravity (mass) than the red edge does. The strip is narrow ($\sim$1200 K wide when $\log g \sim 8.0$), an attribute that must be largely responsible for the (incorrect) past reports of a possible mixed (variable and nonvariable) population inside the instability region.

The empirical strip that we present here will have to be explained by nonadiabatic pulsation theory, which still remains unsatisfactory for ZZ Ceti stars, although recent progress has been made (see, e.g., the review of Fontaine, Brassard, & Charpinet 2003).

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REFERENCES

Bergeron, P., & McGraw, J. T. 1990, ApJ, 352, L45
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bergeron, P., Saumon, D., & Wesemael, F. 1995a, ApJ, 443, 764
Bergeron, P., Wesemael, F., Lamontagne, R., Fontaine, G., Saffer, R. A., & Allard, N. F. 1995b, ApJ, 449, 258 (B95)
Billères, M., & Fontaine, G. 2003, in Asteroseismology Across the HR Diagram, ed. M. J. Thompson, M. S. Cunha, & M. J. P. F. G. Monteiro (Dordrecht: Kluwer), in press
Billères, M., Fontaine, G., Brassard, P., Charpinet, S., Liebert, J., Saffer, R. A., & Vauclair, G. 1997, ApJ, 487, L81
Bragaglia, A., Renzini, A., & Bergeron, P. 1995, ApJ, 443, 735
Dolez, N., Vauclair, G., & Koester, D. 1991, in White Dwarfs, ed. G. Vauclair & E. M. Sion (NATO ASI Ser. C, 336; Dordrecht: Kluwer), 361
Fontaine, G., Bergeron, P., Brassard, P., Billères, M., & Charpinet, S. 2001, ApJ, 557, 792
Fontaine, G., Bergeron, P., Lacombe, P., Lamontagne, R., & Talon, A. 1985, AJ, 90, 1094
Fontaine, G., Brassard, P., & Charpinet, S. 2003, in Asteroseismology Across the HR Diagram, ed. M. J. Thompson, M. S. Cunha, & M. J. P. F. G. Monteiro (Dordrecht: Kluwer), in press
Fontaine, G., McGraw, J. T., Dearborn, D. S. P., Gustafson, J., & Lacombe, P. 1982, ApJ, 258, 651
Fontaine, G., & Wesemael, F. 1984, AJ, 89, 1728
Giovannini, O., Kepler, S. O., Kanaan, A., Costa, A. F. M., & Koester, D. 1998, A&A, 329, L13
Greenstein, J. L. 1976, AJ, 81, 323
Jordan, S., et al. 1998, A&A, 330, 277
Kepler, S. O., & Nelan, E. P. 1993, AJ, 105, 608
Kepler, S. O., Giovannini, O., Kanaan, A., Wood, M. A., & Claver, C. F. 1995, Baltic Astron., 4, 157
Koester, D., & Allard, N. F. 2000, Baltic Astron., 9, 119
Koester, D., & Holberg, J. B. 2001, in ASP Conf. Ser. 226, 12th European Workshop on White Dwarfs, ed. J. L. Provencal, H. L. Shipman, J. MacDonald, & S. Goodchild (San Francisco: ASP), 299
Koester, D., & Vauclair, G. 1997, in White Dwarfs, ed. J. Isern, M. Hernanz, & E. García-Berro (Dordrecht: Kluwer), 429
Koester, D., et al. 2001, A&A, 378, 556
Lamontagne, R., Wesemael, F., Fontaine, G., Wegner, G., & Nelan, E. P. 1989, in IAU Colloq. 114, White Dwarfs, ed. G. Wegner (LNP 328; New York: Springer), 240
Landolt, A. U. 1968, ApJ, 153, 151
Maxted, P. F. L., & Marsh, T. R. 1999, MNRAS, 307, 122
McGraw, J. T. 1977, Ph.D. thesis, Univ. Texas at Austin
Mukadam, A. S., Kepler, S. O., Winget, D. E., & Bergeron, P. 2002, ApJ, 580, 429
Silvotti, R., Bartolini, C., Cosentino, G., Guarnieri, A., & Piccioni, A. 1997, in White Dwarfs, ed. J. Isern, M. Hernanz, & E. García-Berro (Dordrecht: Kluwer), 489
Vauclair, G., Dolez, N., Fu, J.-N., Homeier, D., Roques, S., Chevreton, M., & Koester, D. 2000, A&A, 355, 291
Wesemael, F., Bergeron, P., Fontaine, G., & Lamontagne, R. 1991, in White Dwarfs, ed. G. Vauclair & E. M. Sion (NATO ASI Ser. C, 336; Dordrecht: Kluwer), 159
Wesemael, F., & Fontaine, G. 1985, ApJ, 288, 764
Wesemael, F., Lamontagne, R., & Fontaine, G. 1986, AJ, 91, 1376
Winget, D. E., & Fontaine, G. 1982, in Pulsations in Classical and Cataclysmic Variables, ed. J. P. Cox & C. J. Hansen (Boulder: JILA), 46
Wood, M. A. 1995, in White Dwarfs, ed. D. Koester & K. Werner (LNP 443; Berlin: Springer), 41