IUE TEMPERATURES FOR WHITE DWARF STARS IN AND AROUND THE ZZ CETI INSTABILITY STRIP

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ABSTRACT

We have analyzed all the archival *IUE* images of the DA4 and DA5 white dwarfs with model atmosphere fluxes incorporating the quasimolecular opacities to obtain a consistent set of temperatures for both the variables and nonvariables in and around the ZZ Ceti instability strip. We have found four nonvariable stars inside the instability strip. Taken at face value, this indicates that temperature is not the only parameter that determines if a star pulsates or not, but the large uncertainties in the temperature determinations makes it impossible for us to offer this as more than just a suggestion at the present time.

1. INTRODUCTION

The ZZ Ceti stars, or pulsating DA white dwarf stars (DAV), are the single white dwarfs with hydrogen atmosphere that show multiperiodic light variations (McGraw 1977, 1979). These variations are due to nonradial *g*-mode pulsations (Kepler 1984, and references therein). The periods of the variations range from 109 to 1186 s, and the fractional amplitudes from $\sim 1\%$ to 28%. These variables lie in a narrow instability strip centered near the temperature of maximum photospheric hydrogen opacity—i.e., at the extension of the Cepheid instability strip down to the white dwarf sequence (McGraw 1979). Previous studies of the colors of these stars have concluded that most and perhaps all DA white dwarfs are photometric variables in the temperature range 13 200 K $\gtrsim T_{\rm eff} \gtrsim$ 11 500 K (Fontaine *et al.* 1982; Greenstein 1982). Analyses of the ZZ Ceti instability strip using the *IUE* Observatory images have been conducted previously by Wesemael *et al.* (1986), Lamontagne *et al.* (1987), and Lamontagne *et al.* (1989). A recent analysis of the instability strip using optical line profiles from H8 to Hγ has been presented by Daou *et al.* (1990). Dolez *et al.* (1991), also studying high signal-to-noise optical spectra, found a few nonpulsating DA white dwarfs inside the ZZ Ceti instability strip.

The evidence suggests that except for their photometric variability the DAVs are otherwise normal white dwarfs, and that it is likely that they are broadly representative of *all* DA white dwarfs—i.e., structurally similar to some 80% of the known white dwarfs (Fontaine & Wesemael 1987). If all the stars in the instability strip were found to be variable, then observationally it would be temperature alone that would determine which stars are pulsationally unstable. Further, we could conclude that all the stars have similar total masses and hydrogen-layer masses, as the blue and red edges of the instability strip are functions of stellar mass and the mass of the surface hydrogen layers. For a recent review of the pulsating white dwarfs, see Kawaler & Hansen (1989).

Because the ZZ Ceti stars are relatively cool and therefore old ($\tau_{\rm age} \simeq 5\times10^8$ yr, Wood 1990), and the time scale for gravitational settling is very short compared to their lifetimes, all the hydrogen should be at the surface of the star (Schatzman 1958; Pelletier *et al.* 1989), unless convective mixing with the subsurface helium layer has already taken place. This convective mixing changes the atmospheric abundances at temperatures lower than 11 500 K for stars with H-layer smaller than $10^{-11}\,\mathscr{M}_\odot$ (see Fontaine & Wesemael 1991 for a review).

To determine the boundaries and purity of the instability strip, we analyzed all the archival *IUE* images for all the DA stars with optical colors close to the ZZ Ceti instability strip, plus all DA4 and DA5 stars reported in Wegner & Swanson (1991) as having *IUE* images. The analysis was made with a model atmosphere grid including the quasimolecular opacities responsible for the identified features at 1400 and 1600 Å in the *IUE* spectra of DA white dwarfs (Koester *et al.* 1985; Nelan & Wegner 1985).

In the remaining paragraphs, we will discuss our temperature estimates, the accuracy of the individual effective temperature determination, the determination of the blue and red edges of the instability strip, and the statistics of the purity of the instability strip.

2. IUE IMAGES

All the *IUE* images were obtained from the archives of the Canadian Astronomical Data Center at DAO, and we used all the SWP, LWP, and LWR images available, together with Strömgren photometry obtained by Wegner (1979, 1983), and Fontaine *et al.* (1985). A list of the images available for each star can be found in Wegner & Swanson (1991). For the stars with no published Strömgren photometry, we used the Johnson photometry reported in McCook & Sion (1987). We use the standard *IUE* calibration (Bohlin & Holm 1980), the correction derived by Hackney *et al.* (1982) to account for wavelength- and exposure-dependent continuum distortions, and the absolute flux recalibration of the *IUE* cameras by Bohlin *et al.* (1990) for the SWP and LWR images, and Oliversen (1988) for the LWP images. We also corrected the fluxes for the sensitivity degradation of the cameras with time, as described by Bohlin & Grillmair (1988) and Teyas & Garhart (1990). Next, we averaged the spectra into 20 Å bins for the SWP camera, and 30 Å bins for the LWP and LWR camera, to give a less noisy continuum with adequate spectral resolution in the region where the quasimolecular features are important. Finally, we transformed the Strömgren and Johnson photometry to fluxes using the calibration of Heber *et al.* (1984).

3. MODEL ATMOSPHERES

The grid of model atmospheres we used is new, and similar to the one reported in Nelan & Wegner (1985). It ranges from 8000 K$\leqslant T_{\rm eff}\leqslant$18 000 K, with 500 K steps, and 7.4$\leqslant$log $g\leqslant$8.6, with 0.6 dex steps. The models have pure hydrogen composition, and include the features at 1400 and 1600 Å detected in the *IUE* spectra of several cool DA white dwarfs, and identified by Koester *et al.* (1985) and Nelan & Wegner (1985) as Ly α satellite absorption from the H_2^+ quasimolecule and as a resonance broadening of Ly α due to the H_2 quasimolecule, respectively. See Wesemael *et al.* (1986) for a comparison of the results obtained with the models by Nelan and Wegner (1985) and Koester *et al.* (1985), as well as a comparison with the temperatures derived from optical photometry and spectrophotometry.

For stars hotter than 18 000 K, we used the grid of models of Wesemael *et al.* (1980).

4. EFFECTIVE TEMPERATURES

We derived effective temperatures by fitting the observed spectra with the new grid by least-squares using the Levenberg–Marquardt method (Press *et al.* 1986). Each pixel was weighted by the inverse of its variance (weight $=1/\sigma^2$), and we excluded the pixels blueward of 1250 Å to prevent contamination by the geocoronal Ly α line; we also excluded saturated pixels. We forced the observed fluxes to match the models at the reddest bin, usually the "*y*" Strömgren magnitude at 5500 Å, for normalization. The computer program used in the analysis was developed by Robert Lamontagne, from the Université de Montréal. We assumed log $g=8.0$—the observed mean gravity for DA white dwarfs—for all the fits (Shipman 1979; Koester *et al.* 1979; Bergeron *et al.* 1991). For example, Bergeron *et al.* (1991) quote $\langle \log g\rangle=7.85\pm0.24$. Note that although a change of $\Delta\log g=0.3$ introduces a change in $T_{\rm eff}$ smaller than 100 K—i.e., smaller than the average internal dispersion of the fit—future work of this kind should use a grid with smaller steps in log g, and the approximation of constant log g should be lifted, even though it will introduce an additional free parameter to the fit.

We derived two sets of temperature estimates. In the first set we use all the *IUE* and photometric data available; in the second we use only the SWP image, and force the theoretical models to match the observations at 1950 Å for normalization. Table 1 lists the results of both techniques. The effective temperatures derived from the SWP image alone (column 5) are hotter than the temperatures derived from all available data (column 3) by an average of $+743\pm563$ K, and this systematic difference indicates that the external error on the temperature determination is much larger than the internal error of the fit (columns 4 and 6). These external errors probably result from one or a combination of the following: the use of different normalization wavelengths for the two methods (5500 Å for all data, and 1950 Å for the SWP fit), possible mismatches of the optical and ultraviolet data, or errors in the flux calibrations.

5. TIME SERIES PHOTOMETRY

Because beating between pulsation modes can reduce the photometric variations of a real ZZ Ceti star to undetectable levels for up to ~60 min (Hesser *et al.* 1976; McGraw 1977; Kepler *et al.* 1983), in determining whether a star is variable or not (column 2 of Table 1) we obtain at least 3 consecutive hours of time series photometry data with a time resolution of typically 10 s. In addition to the beating down of the light curve amplitude, we observe DAVs with amplitudes as small as 0.6% ($\simeq$6 mmag), and the 3 h runs are needed to give detection limits a factor two or more smaller than this. In Table 2 we present the limits for the nonvariable stars we have observed.

In our program of time series photometry we have also found a new variable star, WD 1236−495 (Kanaan *et al.* 1992). Most of these observations were obtained with a 2-star photometer (target and comparison star, Nather 1973) on the 1.6 m telescope of Laboratório Nacional de Astrofísica (LNA), in Brazil.

The other nonvariable stars listed in Table 1 are from the observations of Robinson & McGraw (1976), McGraw (1979), Lawrence *et al.* (1967), Hesser, *et al.* (1969), Hesser & Lasker (1971, 1972), Richer & Ulrych (1974), and Dolez *et al.* (1991). Note, however, that these other searches for new variables did not, in general, obtain 3 h runs; most runs did not have a detection limit lower than 0.6%, and the sample is known to be contaminated by variable stars (Kepler *et al.* 1983; Kanaan *et al.* 1992).

6. INSTABILITY STRIP

The first obvious conclusion of the analysis of Table 1 is that there is indeed a well-defined instability strip, i.e., a region of effective temperatures in which most stars are variable. Also, we find that the observed extent and limits of the strip depends systematically on the data used in obtaining the temperature estimates. Specifically, if we adopt the temperatures estimated by fitting to all the data

TABLE 1. Best-fit effective temperatures.

Star	Variable	$T_{\rm eff}$	$\sigma_{T_{\rm eff}}$	$T_{\rm eff}^{\rm SWP}$	$\sigma_{T_{\rm eff}}$	Alias
WD 1108+325		39 100	230			Ton 60
WD 1033+464		25 900	93			GD 123
WD 1247+553		21 500	240	21 700	310	PG, GD319
WD 1026+002		18 200	400	19 900	390	PG[1]
WD 0413−077	NV	16 800	220	19 400	320	40 Eri B
WD 1143+321		16 020	54	17 000	110	G148-7
WD 1105−048		15 870	35	16 720	68	G163-50
WD 0406+169		15 740	89	16 100	150	LP414-101
WD 2126+734	NV	15 440	92	16 800	140	G261-43
WD 1311+129				15 400	180	PG[2]
WD 2007−303		15 080	41	16 390	93	LTT7987
WD 1919+145		15 080	45	15 700	230	GD 219
WD 1327−083	NV	14 670	24	15 520	69	W485A
WD 2047+372		14 660	54	15 100	210	G210-26
WD 0352+096	NV	14 420	32	15 000	150	HZ4
WD 0148+467		14 130	35	14 800	120	GD279
WD 0943+441	NV	13 790	79	15 080	38	SA29-130
WD 1213+528	NV			13 500[1]	120	Case 1[1]
WD 0713+584				13 400[1]	29	GD294
WD 0231−054	NV	12 840	25	12 910	22	GD31
WD 2341+322	NV	12 490	27	13 170	18	G130-5[3]
WD 1425−811	V	12 230	44	12 640	39	L19-2
WD 0401+250	NV	12 180	27	12 870	33	G8-8
WD 1647+591	V	12 120	11	12 260	15	G226-29
WD 1053−550	NV			12 000[1]	520	BPM20383
WD 1855+338	V	12 040	90	12 060	18	G207-9
WD 1935+276	V	11 970	91	12 370	31	G185-2
WD 0921+354	V	11 840	91	13 150	56	G117-B15A
WD 0133−116	V	11 830	75	12 400	130	R548
WD 1022+050	NV	11 700	40	13 350	62	PG,LP550-52
WD 2326+049	V	11 380	30	11 780	41	G29-38
WD 1236−495	V	11 200	55	11 560	52	BPM37093[4]
WD 0858+363	V	11 100	60	12 000	55	GD 99
WD 0255−705	NV	11 010	38	12 000	160	BPM2819
WD 1559+369	V	10 880	30	11 560	41	R808
WD 1307+354	V	10 300	110	11 740	62	GD154
WD 2105−820	NV	10 300	44	10 020	21	BPM1266
WD 2246+223	NV	10 280	45	10 230	26	G67-23
WD 1544−377		10 000	130	10 610	25	L481-60
WD 0839−327		8800	26	9630	12	L532-81
WD 2359−434		7760	46	8150	24	BPM45338

[1]Spectra and colors indicate a composite with a cool object. PG1026+002 and Case 1 are known binary stars.
[2]The star is classified as a DBA3 in McCook & Sion (1987).
[3]G130-5 is a binary system with a 9″ separation, composed of a DA4 and a dM5 (Oswalt *et al.* 1988).
[4]New variable ZZ Ceti star (Kanaan *et al.* 1992).

TABLE 2. Limits on pulsation from time series photometry.

Star	Limit (mmag)
WD 1327−083	2.8
WD 0352+096	4.5
WD 1213+528	1.5
WD 1022+050	1.4
WD 0401+250	4.0
WD 1053−550	1.2
WD 0255−705	2.8
WD 2105−820	2.9
WD 1123+189	3.3

on the star, the instability strip spans the temperature range 12 230$\geqslant T_{\rm eff}\geqslant$10 300, with the star L19−2 defining the blue edge, and GD 154 defining the red edge. Using this temperature scale (see column 3 of Table 1), the instability strip contains known 11 variable stars (the other known 11 variables have not been observed with *IUE*) and 4 nonvariables: PG1022+050, G8-8, BPM20383, and BPM2819. In Sec. VIII we will discuss the accuracy of the temperatures. If instead we adopt the temperatures estimated using the SWP images only (column 5 of Table 1) the instability strip spans 13 150$\geqslant T_{\rm eff}\geqslant$11 560 K, with G117-B15A at the blue edge and R808 at the red edge. Again, there are 11 variables and 4 nonvariable stars—GD 31, G8-8, BPM20383, and BPM 2819—inside the instability strip, the latter three being common with the

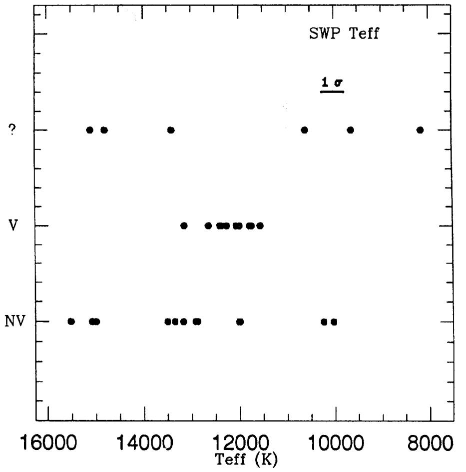

FIG. 1. Effective temperatures derived from the *IUE* SWP images only. On the y axis, the question mark designs stars that have not been looked for variability yet, V represents variable stars, and NV represents nonvariable stars. The 1 σ bar is the mean standard deviation for the four nonvariable stars inside the instability strip, 462 K. The instability strip ranges $(13150\pm400)\geqslant T_{\rm eff}\geqslant(11560\pm400)$ K.

nonvariable list determined using all the data. Figure 1 displays the temperatures derived from the SWP data for variable and nonvariable stars.

7. MODELS WITH REDDENING

To test the solutions obtained with the two different normalizations—i.e., at the red bin of the SWP camera (1950 Å) or the Strömgren "y" magnitude (or Johnson "V" magnitude for WD0406+169, WD2007−303, WD1247+553, and WD1307+354), at 5500 Å—we included an extra parameter in our fit, the color excess E_{B-V}, adopting the extinction law of Seaton (1979). The effect of a small extinction coefficient is to depress considerably the ultraviolet flux relative to the optical. For example, even an extinction coefficient of $E_{B-V}=0.01$ causes a reduction in the UV flux by 5% (Thejll *et al.* 1991).

With the inclusion of this ad hoc parameter, the agreement of the effective temperatures obtained with the two normalizations was better, suggesting that the reddening, or mismatching of the ultraviolet and optical fluxes, could be the main effect causing the differences in Table 1. The mean difference between $T_{\rm eff}$ obtained from the SWP image only and $T_{\rm eff}$ from all the data, including the optical photometry, was then $\Delta T_{\rm eff}=273\pm380$ K, consistent within 1 σ. We will use the value of 380 K as the external error on the temperature.

One of the possibilities for inaccuracies for the faint stars in miscentering in the *IUE* aperture which causes the measured *IUE* flux to be lower than the true value. The reason we suspect miscentering is that stars fainter than $V=15.5$ (Sonneborn *et al.* 1987; Grady & Taylor 1989)—the minority of our sample—are too faint to be seen on the *IUE* guide sensors and therefore had to be centered by using an offset from a nearby bright star, an operation which is sometimes less than successful (Sonneborn *et al.* 1987). Another problem is that, as the star is faint, the scatter in the observed fluxes is large in both the ultraviolet and optical, increasing the uncertainty of matching UV and optical fluxes. For the fainter objects (Ton 60, PG 1311+129, and G117-B15A), miscentering of the star in the *IUE* aperture is possible. For these faint stars the effective temperatures derived from the SWP image alone should be more accurate, because the fit is only to the shape of the spectra, and does not rely on its overall flux calibration.

8. ACCURACY OF THE OBTAINED TEMPERATURES

As we discussed above, we assume a surface gravity of $\log g=8.0$ for all our fits, and for stars in this temperature range, we expect a scatter of $\Delta \log g=0.3$ (Daou *et al.* 1990). For these objects, a change in the surface gravity of $\Delta\log g=0.3$ gives $\Delta T_{\rm eff}\simeq 100$ K.

The main uncertainty in the absolute temperature determination comes from the 10% systematic external uncertainty in the absolute flux calibration of the *IUE* cameras (Bohlin *et al.* 1991). This 10% uncertainty in the flux results in an uncertainty of $\Delta T_{\rm eff}=240$ K for the stars in the temperature range of the ZZ Ceti stars, when using the normalization at the Strömgren "y" or Johnson "V" magnitudes. When we use the normalization at the red bin of the SWP camera, there is no uncertainty from this effect, since we then fit only the shape of the spectra, not its absolute calibration.

There is another uncertainty affecting our fitted temperatures, the mixing length parameter used in the models to describe the efficiency of convection. Winget *et al.* (1982), Fontaine *et al.* (1984), and Tassoul *et al.* (1990) demonstrate that the change of parameters from ineffective ML1 to effective ML3 changes the position of the theoretical instability strip for the ZZ Ceti stars by up to 500 K. Bergeron *et al.* (1992) indicates that the derived effective temperature could change systematically by about 1000 K if we change from ML1 to ML3, in the temperature range of the ZZ Ceti stars. The grid of models used in this study was calculated with a mixing length $l=1.5\ H_P$, where H_P is the pressure scale height. We do not have at the moment grids of models calculated with different mixing length parameters, or theories, to compare its effect on the observed flux in the ultraviolet, and its consequent uncertainty in the temperatures derived here.

9. STATISTICS OF THE NONVARIABLES

Due to the large internal and external errors on the obtained temperatures, as well as the narrowness of the instability strip, we must estimate the significance of the result that there are nonvariable stars inside the instability strip. To estimate the significance of each of the nonvariables' temperature determinations, we first calculated

$$\sigma_{\rm Total}=[\sigma^2_{\rm internal}+\sigma^2_{\Delta\log g}+\sigma^2_{\rm external}]^{1/2},$$

TABLE 3. Probabilities for nonvariables stars.

Star	P_{out}
SA29-130	0.997
Case 1	0.987
GD 294	0.982
G130-5	0.821
G8-8	0.472
BPM20383	0.395
PG 1022+050	0.179
BPM2819	0.128
BPM1266	0.500
G67-23	0.514
L481-60	0.693

for all the temperatures obtained using the SWP images only. It is a conservative estimate of the total uncertainty in the temperature caused by (i) the formal uncertainty for the temperature fit (internal error, column 7 of Table 1) (ii) the uncertainty given by a possible $\Delta \log g = 0.3$ change in the surface gravity ($\sigma_{\Delta \log g} = 100$ K), and (iii) the external error, which we will assume to be $\sigma_{\rm external} = 380$ K. We did not include the standard deviation due to the absolute flux calibration because it should affect only the absolute temperatures, and be included in the external error. We consider $\sigma_{\rm Total}$ a conservative estimate because, for the temperatures derived from the SWP images only, there is no match between optical and *IUE* fluxes. $T_{\rm eff}^{\rm SWP}$ are the temperatures we will use in our statistical estimate of the purity of the instability strip.

We calculated the difference in temperature to the blue and red edges, including the uncertainties in the temperature of the edges themselves ($\sigma_{\rm Total}^{\rm edge} = 400$ K), and the total probability that the star would lie either to the blue or to the red of the instability strip.

For the temperature fits using the SWP images only, the probability that the nonvariable stars GD31, G8-8, BPM20383, and BPM2819 are outside the instability strip are 34.2%, 31.8%, 34.7%, and 24.8%, respectively. There is also a probability of 27.4%, 36.2%, and 48.4% that Case 1, PG1022+050, and G130-5 are inside the instability strip. The compound probability that the instability strip is pure, i.e., contain only variable stars, is 2.2×10^{-3}, equivalent to outside of 2.8 σ, or 1 chance in 450.

For the temperatures derived using both the *IUE* images and the optical photometry, *the probability that the nonvariable stars are outside the instability strip* $P_{\rm out}$ are found in Table 3.

The compound probability that the instability strip is pure, i.e., contain only variable stars, is 6.0×10^{-4}, equivalent to outside of 3.2 σ.

The very simple confidence estimate derived here might be misleading as the large temperature uncertainties for each star puts every nonvariable less than two standard deviations from the boundaries of the instability strip.

10. DISCUSSION

The main conclusion of our analysis is that most but not all—75%—stars inside a narrow temperature range are variable, and therefore the conclusion of Fontaine *et al.* (1982) that the temperature is the main parameter for determining whether a star is variable or not still holds. The temperature of the instability strip itself is uncertain by at least 273 ± 380, the external error on our fit.

We have, on the other hand, found four stars inside the instability strip that are not observed to be variables. They constitute 27% of the stars in the instability strip, independent of which of the two temperature scales is adopted. The scale obtained by fitting to the SWP images only has the smaller uncertainties because here the fitting is essentially to the *shape* of the spectra and the absolution flux calibration is unimportant. By contrast, although the scale using all the *IUE* images and optical photometry data is the one having the greatest leverage on the energy distribution, it is subject to uncertainties on the absolute flux calibration of the *IUE* images through, for example, problems of centering faint stars in the *IUE* aperture using blind offsets.

There are a few effects that must be taken in account when analyzing such statistics:

(1) Certain combinations of the indices of the spherical harmonics l and m, when viewed from certain aspects, show no luminosity variations, because the surface brightness distribution over the observable hemisphere of the star averages out in time. For example, when the rotation axis of a variable star is seen pole on, the pulsation modes which are symmetrical about the pole cancel out, and we see no observable variations, even though the star is variable. If the modes are rotationally split, on the other hand, the effect will make modes with different m values have different amplitudes, but probably not cancel out all the variations (Pesnell 1985). This factor cannot explain such large percentage of nonvariables because it requires very specific orientations (Fontaine *et al.* 1982).

(2) There is an observational limit on the detectable pulsational amplitude. Considering that some known pulsators have very small amplitudes ($0.6\% \simeq 6$ mmag for G226-29, $0.4\% \simeq 4$ mmag for BPM37093), we could claim that a *pulsating* star is nonvariable if its amplitude is below our detection limit.

Our conclusion is that, taken at face value, there is a significant number of nonvariable stars inside the ZZ Ceti instability strip. The relatively large remaining uncertainties in the temperature determinations make it impossible for us to offer this conclusion as more than just a suggestion at the present time. If these nonvariables are indeed inside the instability strip, these stars could have different hydrogen surface layer mass, and or different stellar masses. A statistical analysis with a larger number of stars, both variable and nonvariable, is necessary, and we are in the processes of observing such stars with both the *IUE* satellite and optical spectroscopy, as well as with time-series photometry to improve the statistical significance of our conclusions. A study of the masses (surface gravities) and the effects of convective efficiencies on the *IUE* spectra should also be undertaken.

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