TEMPERATURE DETERMINATIONS OF HOT DA WHITE DWARFS USING IUE CONTINUUM FLUXES

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ABSTRACT

Effective temperatures of 15 DA white dwarfs hotter than 20,000 K were derived from low-dispersion far ultraviolet spectra which were obtained with the International Ultraviolet Explorer (IUE). The analysis was carried out by comparing the observed far ultraviolet fluxes with model fluxes scaled to the V-band flux. Accurate calibration of the IUE spectra is critical for this analysis We first corrected observations at all epochs to the 1980 IUE calibration using the time-dependent corrections of Bohlin (Refs. 1,2). Taking advantage of the smooth and well-defined continuum fluxes provided by DA white dwarfs, we then used seven white dwarfs for which accurate, independent temperature determinations have been made from line profile analyses to improve the accuracy of the IUE flux calibration The correction to the original calibration is as great as 20% in individual 5-Å wavelength bins, while the average over the IUE wavelength range is 5%. We present both the final calibration correction and the new accurate temperatures for the hot white dwarfs

Keywords: White Dwarfs, IUE, Ultraviolet, Spectrophotometry

1. INTRODUCTION

Accurate temperature determinations for hot DA white dwarfs are necessary for several reasons. Temperatures are needed for deriving the luminosity function of DA's; the luminosity function then serves to check calculations of cooling rates for these stars. Trace element abundances in DA's result from temperature-dependent processes. Successful confrontation of observational abundance determinations with theory requires that the effective temperatures be known with sufficient accuracy. Also, the upper temperature limit for DA's needs to be determined with precision, because this limit will help constrain post main sequence evolutionary calculations. Additionally, upcoming extreme ultraviolet (EUV) photometric survey missions (Refs. 3,4) are likely to discover hundreds of very hot DA white dwarfs (Ref. 5). Non-EUV measurements will be required to make the accurate temperature determinations necessary for interpretation of the EUV photometric data for these stars (Ref 5).

Temperatures of DA white dwarfs have usually been based on optical photometric measurements However, the optical colors become poor temperature indicators for stars hotter than ~25,000 K. Given that FUV continuum fluxes should serve as a more sensitive temperature indicator, an IUE observing program was initiated that specifically targeted DA white dwarfs hotter than 20,000 K (Ref. 6). It was discovered in the course of analyzing the data from that program that the sensitivity degradation of the IUE cameras gave rise to significant errors in the temperatures inferred from the IUE fluxes, compared with optical photometric temperatures. Similar problems had been noted by IUE observers of other object types (Ref. 7). Consequently, the data analysis presented in Ref. 6 was carried out by making a correction to the IUE fluxes which achieved consistency between the FUV-derived temperatures and the optical photometric temperatures. Because of the time dependence of the sensitivity degradation, this correction consisted of using a few well-observed stars from each ~1-year observing epoch to obtain the necessary sensitivity adjustment for that epoch (Ref. 6) Subsequently, efforts were undertaken by other workers to obtain time-dependent corrections which could be used to correct for the time and wavelength-dependent sensitivity degradation of IUE; these corrections are now available (Refs. 1, 2, 8) The stars from the observing program discussed in Ref 6, as well as a number of archive spectra, were analyzed on the basis of these time-dependent corrections This paper presents the results of these analyses.

2 DATA ANALYSIS AND RESULTS

The observations were obtained with the IUE's short wavelength primary (SWP) and long wavelength redundant (LWR) cameras operating in the low-dispersion mode Stars which were sufficiently bright were observed with both cameras Fainter stars requiring long exposures were observed only with the SWP

The IUE spectra were reduced with standard IUE processing techniques. For the analysis, the SWP spectra were truncated at the short wavelength end at 1320 Å to avoid the red wing of Lyman α. The SWP and LWR spectra were cut off at 1940 Å, and the LWR data longward of 3100 Å were omitted because of the unreliability of the fluxes beyond that point. The IUE fluxes were then placed on the original IUE flux scale according to the prescription of Bohlin (Refs. 1, 2). This process only corrects for the variation with time of the IUE sensitivity, and is independent of the absolute flux calibration of the IUE instruments. Bohlin's time-dependent correction data set consists of discrete values which are averaged over 1-year time intervals and 5-Å wavelength intervals Each data point in the observed spectra was modified with a correction value that is linearly interpolated in time but is based on the values for the nearest wavelength. Bohlin estimates that the corrections given by this procedure are accurate to ~1%. This procedure was applied to all the spectra. However, the spectra for WD0004+330, WD0644+375, and WD2309+105 (SWP7747 and LWR6452) were reduced with the old IUE spectral extraction scheme, which was used until November 1980; hence, Bohlin's procedure will not give optimal results for these spectra.

Normalization of the IUE data was accomplished by ratioing the FUV fluxes to the V-band flux, given by

$$f(5490\text{Å}) = 3.61\times10^{-9}/10^{0.4m_V}$$

Determination of the effective temperatures was then accomplished by comparing the observed $f(\lambda)/f(5490\text{Å})$ to that predicted by model atmosphere fluxes for a given effective temperature. The model atmosphere code used was that developed by Basri (Ref. 9). This code, based on Auer's complete linearization method, treats the atmosphere as being plane-parallel and in LTE. The continuum fluxes produced by this code have been checked against model fluxes published by Shipman and by Wesemael (Refs. 10, 11), and have been found to agree within 1% from the FUV through the visible, for effective temperatures greater than 25,000 K. The models allow the presence of trace helium; however, the helium abundance within the DA range of $<10^{-2}$ has an effect on FUV/visible flux ratios only at the <3% level. Therefore, a nominal helium abundance of 10^{-6} was used in the model calculations The effect of surface gravity on FUV/visible flux ratios is less than 1% over the range 10^7 to 10^9; hence a value of 10^8 was used. Temperature determinations were made by comparing the data with a range of models and interpolating to find the best fit model temperature. The best fit temperature was taken to be that for which

$$\sum -2.5 \log \left[(f(\lambda)/f(5490\text{Å}))_{observed}/(f(\lambda)/f(5490\text{Å}))_{model}\right] = 0.$$

Evaluation of the residuals of the fits of the models to the time-corrected data revealed systematic variations as a function of wavelength These variations were of the order of ±15%. The wavelength dependence of the residuals was consistent from spectrum to spectrum Furthermore, comparison of the temperatures obtained from the corrected IUE fluxes with temperatures obtained from hydrogen line profiles (Refs. 12, 13) indicated that the IUE fluxes were low by 5% on the average.

Several factors might account for the observed discrepancy. For instance, the model physics may be wrong. The stellar atmosphere composition may not be pure hydrogen, or the stars may be reddened. Also, the line profile temperatures may be in error. None of these can explain the wavelength-dependent irregularities in the fluxes, those must result from IUE calibration errors. The uncertainties in the model physics affect the average flux level at the <2% level (Ref. 10). Reddening cannot account for the apparently low FUV fluxes, because these are nearby (<100 pc) white dwarfs for which the neutral hydrogen columns are much less than 10^{20}/cm^2. Unless the extinction is highly anomalous, a typical neutral hydrogen column of 3×10^{19} would give $E_{B-V} = 0^m.005$, resulting in an average extinction over the IUE wavelength range of only 1.6%. The temperatures derived from line profiles are subject to small uncertainties due to the statistical errors in the data; Holberg (Ref. 12) quotes formal errors of only ±3,000 K at 55,000 K. Systematic errors due to instrumental calibration errors over the small wavelength ranges of hydrogen lines are unlikely to significantly affect temperature determinations. Therefore, aside from the possibility of the existence of errors in the model line profiles, the effective temperatures for DA white dwarfs that are derived from hydrogen line profiles are the most accurate available. Consequently, the observed systematic variations between the IUE fluxes and the model fluxes are most likely attributable to errors in the IUE calibration.

In order to reconcile FUV continuum temperatures with the line profile temperatures, spectra from seven white dwarfs were used to obtain a flux correction to the IUE data. The stars used were WD 0050-332, 0501+527, 0549+158, 1254+223, 1620-391, 2111+498, and 2309+105 (1982 observation only). Model fluxes were generated for each of these stars using the effective temperatures given by Holberg (Ref. 12). Ratios of the observed FUV/visible flux ratios to the values predicted by the models were calculated for all seven spectra These ratios were then averaged together over the same 5-Å wavelength bins used by Bohlin The resultant flux correction thus consists of the values by which time-corrected fluxes must be divided The flux correction is shown in Figure 1.

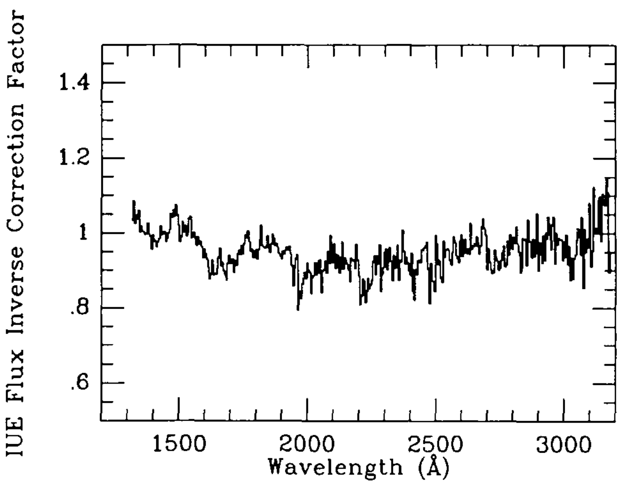

Figure 1. Flux correction to IUE original epoch calibration, binned in 5-Å intervals Spectra to which time-dependent correction has already been applied are to be divided by the flux correction values.

After application of both the time-dependent and flux corrections to the spectra, the effective temperatures were recomputed The complete listing of the results obtained is given in Table 1. The absence of any significant variation with temperature of the FUV continuum temperatures compared to the line profile temperatures indicates that any temperature dependent effects which may affect the modeling of either the line profiles or the continuum fluxes are not significant.

Temperatures are given both for spectra which were time- and flux-corrected (Method 1) and for spectra subjected to individual epoch corrections (Method 2) calculated as per Ref. 6. In the current instance, the individual epoch corrections were based on line profile temperatures, rather than on optical photometric temperatures, as had been done in Ref. 6. The epochs for which the corrections were obtained, and the stars used, were 1980.0 (WD2309+105), 1981.4 (WD0501+527, 1254+223, 2111+498), and 1982.6 (WD0050-332, 0549+158, 1620-391, and 2309+105). It is seen that the two methods are equivalent, giving effective temperatures which differ only trivially. Note also that, although the time-dependent correction cannot be strictly applicable to spectra reduced prior to November 1980, the effective temperatures that are derived using that scheme are very close to the temperatures obtained from the individual epoch corrections.

The errors shown for the IUE continuum measurements are the combined errors arising from uncertainties in the V magnitude, the spectral-signal-to-noise ratio, the values of stellar parameters other than effective temperature, small reddening effects, and errors in the flux correction. In addition, the flux correction error included the published uncertainties in the effective temperatures used for obtaining the flux correction. (Uncertainties in the model fluxes have no effect; the models are used to obtain the flux corrections and to fit the corrected data. Hence, any systematic model-dependent effects would cancel out) The magnitude of the flux correction error averaged over the IUE wavelength range (for the correction derived from all seven stars) was only ±1.3% (1 σ),

Table 1 Temperatures of Stars Derived from Different Measures

	IUE Continua				Line Profiles			Optical Photometry	
	Method 1[a]		Method 2[b]						
WD Name	T_{eff}[c]	Error[d]	T_{eff}	Error	T_{eff}	Error	Ref.	T_{eff}	Error
0004+330	42.58[e]	$^{+3.46}_{-2.83}$	42.84	$^{+5.60}_{-4.13}$	--	--	--	56.5	$^{+19.7}_{-10.7}$
0050-432	34.15	$^{+1.64}_{-1.37}$	34.68	$^{+1.84}_{-1.52}$	36.85	±1.39	HWB	33.51	$^{+1.57}_{-1.25}$
0346-011	39.10	$^{+2.21}_{-1.90}$	38.33	$^{+2.22}_{-1.89}$	47.5	±2.5	K	40.33 31.44	$^{+6.97}_{-4.32}$ $^{+2.04}_{-1.52}$
0501+527	66.37	$^{+8.76}_{-7.13}$	63.82	$^{+8.69}_{-7.05}$	62.25	±3.52	HWB	71.7	$^{+16.0}_{-11.4}$
0549+158	34.03	$^{+1.62}_{-1.35}$	34.32	$^{+1.76}_{-1.46}$	33.30	±0.83	HWB	37.77	$^{+3.53}_{-2.56}$
0644+375	21.76[e]	$^{+0.29}_{-0.29}$	21.84	$^{+0.43}_{-0.41}$	--	--	--	22.72	$^{+0.34}_{-0.33}$
0651-020	35.50	$^{+2.47}_{-1.96}$	35.84	$^{+2.65}_{-2.08}$	--	--	--	36.73	$^{+4.76}_{-3.06}$
1031-114	25.67	$^{+0.36}_{-0.34}$	25.81	$^{+0.39}_{-0.37}$	--	--	--	25.03	$^{0.49}_{-0.48}$
1033+464	28.38	$^{+4.81}_{-2.30}$	--	--	--	--	--	"27.2"	
1254+223	40.67	$^{+2.65}_{-2.22}$	40.20	$^{+2.77}_{-2.29}$	42.375 42	±1.48 ±2	HWB K	41.91	$^{+3.42}_{-2.77}$
1403-077	45.98	$^{+8.18}_{-5.78}$	--	--	--	--	--	41.04	$^{+7.37}_{-4.59}$
1615-154	31.76	$^{+0.85}_{-0.76}$	31.40	$^{+0.88}_{-0.78}$	--	--	--	30.83	$^{+0.68}_{-0.60}$
1620-391	24.83	$^{+0.39}_{-0.39}$	24.92	$^{+0.41}_{-0.41}$	24.50	±0.14	HWB	24.37	$^{+0.47}_{-0.46}$
2111+498	37.36	$^{+2.32}_{-1.91}$	36.76	$^{+2.34}_{-1.90}$	36.125	±0.94	HWB	37.15	$^{+2.57}_{-2.01}$
2309+105	50.30[f] 52.69[e,g]	$^{+4.25}_{-3.57}$ $^{+4.74}_{-3.98}$	52.03[f] 53.54[g]	$^{+4.91}_{-4.08}$ $^{+7.23}_{-5.63}$	53.60	±2.94	HWB	65.2	$^{+10.1}_{-7.7}$

[a]Method 1 involved using time and flux corrections to IUE spectra as per section 5.3.6.2

[b]Method 2 involved using individual epoch corrections as per section 5.3.6.1

[c]Temperatures are given in 10^3 K

[d]Errors are 1σ uncertainties

[e]Temperatures obtained using Method 1 on these observations are not strictly accurate. See text

[f]IUE temperatures were obtained from 1982/142 observations

[g]IUE temperatures were obtained from 1979/355 observations

References HWB = Holberg, Wesemael, and Basile (Ref 12) K = Kahn *et al* (Ref. 13)

excepting possible flux errors due to uncertainties in the model physics. Shipman has estimated, however, that the model uncertainties are of the order of 2% or less (Ref. 10). The errors in the temperatures of the individual objects were dominated by observational uncertainties in the V magnitudes.

Also listed in Table 1 are the published line profile temperatures and temperatures calculated from published optical photometry. The optical photometric temperatures are taken from Ref. 5. The temperatures obtained from the different measures are consistent in all cases except that of WD0346-011. For this star, the three different measures give three different temperatures, indicating that the atmosphere of this star might not be homogeneous.

3. CONCLUSIONS

The original epoch calibration of IUE produces fluxes for DA white dwarfs which systematically vary with respect to fluxes predicted by model atmospheres. The variations with wavelength are of the order of ±15%. Based on predicted fluxes using effective temperatures of DA white dwarfs derived from fitting hydrogen line profiles, the IUE flux levels after correction for the time-dependent sensitivity degradation are 5% low (averaged over the range 1320 to 3100 Å). DA white dwarfs may be used to derive a flux correction which can be applied to achieve an absolute overall accuracy for IUE spectra of the order of ±2%.

4. ACKNOWLEDGMENTS

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5. REFERENCES

1. Bohlin R & Grillmair C 1988, The ultraviolet calibration of the Hubble space telescope: II. A correction for the change in sensitivity of the SWP camera on IUE, *Ap. J Suppl*, 66, in press.
2. Bohlin R & Grillmair C 1988, in preparation.
3. Bowyer S 1983, The extreme ultraviolet explorer, *Adv. Space Res*, 2, 157.
4. Pye J P & Page C G 1987, The XUV wide field camera on ROSAT: Plans for the data handling and analysis, *Proceedings, Astronomy from Large Databases*, 447.
5. Finley D S 1988, Studies of hot white dwarfs and instrumentation for stellar extreme ultraviolet photometry, Ph.D. thesis, University of California, Berkeley.
6. Finley D, Basri G & Bowyer S 1984, Self-consistent recalibration of IUE and determination of hot DA white dwarf effective temperatures, *Proceedings of the Third Goddard IUE Symposium: Future of Ultraviolet Astronomy Based on Six Years of IUE Research*, NASA CP-2349, 277.
7. Hackney R L, Hackney K R & Kondo Y 1982, Spectral anomalies in low-dispersion SWP images, *Advances in Ultraviolet Astronomy: Four Years of IUE Research*, NASA CP-2238, 335.
8. Clavel J, Gilmozzi R & Prieto A 1986, A correction method for the degradation of the LWR camera (II). erratum and final results, *NASA IUE Newsletter*, No 31, 83
9. Malina R F, Bowyer S & Basri G 1982, Extreme-ultraviolet spectrophotometry of the hot DA white dwarf HZ 43: Detection of HE II in the stellar atmosphere, *Ap J*, 262, 717.
10. Shipman H L 1979, Masses and radii of white-dwarf stars. III. Results for 110 hydrogen-rich and 28 helium-rich stars, *Ap. J*, 228, 240.
11. Wesemael F et al. 1980, Atmospheres for hot, high gravity stars, *Ap J Suppl, 43, 429*
12. Holberg J B, Wesemael F & Basile J 1986, DA white dwarf effective temperatures determined from IUE Lyman alpha profiles, *Ap J*, 306, 624
13. Kahn S M et al. 1984, Photospheric soft x-ray emission from hot DA white dwarfs, *Ap. J*, 278, 255.