White Dwarfs as Absolute Flux Standards

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Abstract

Hot DA white dwarfs can serve as excellent calibration sources through the far ultraviolet (FUV) and visible spectral regions. Accuracies of temperature and gravity determinations and of modeling are such that the relative flux may be predicted for an individual star with an accuracy of typically better than 2 percent. By making certain restrictions, the relative fluxes can easily be determined to better than 1 percent. The absolute flux level is determinable by visible photometry or spectrophotometry to an accuracy of 3 percent or better. Thus the overall accuracy of the calibration that can be provided by white dwarfs is dominated not by errors in parameter determinations or flux modeling, but rather by observational uncertainty in the absolute fluxes in the visible.

I. Motivation

Hot DA white dwarfs are the most suitable class of object for use in absolute flux calibrations. Their atmospheres consist of pure (or nearly pure) hydrogen. Number abundances for He are typically $< 10^{-5}$ with respect to H, and even "metal rich" DA have total heavy element number abundances that are $< 10^{-4}$ relative to H. The atmospheres are plane-parallel, and there are no detectable winds. The atmospheres do not significantly depart from LTE; the only NLTE effects seen are very narrow features in the H line cores that are only observable at high resolution. Above about 16,000 K, convection becomes negligible. Above 20,000 K, the quasi-molecular Lyman α satellite features that are peculiar to DA below 20,000 K disappear. Furthermore, the bright WD that are suitable for calibration purposes (V ~ 13) are also nearby, and have negligible reddening ($N_{HI} < 1 \times 10^{19}$ cm^{-2}). The purity of the DA atmospheres is such that the only spectral features detectable are the H lines; outside those lines, a very pure continuum is obtained (excepting the metal-rich DA above about 50,000 K).

Historically, an early suggestion that white dwarfs could serve as useful primary flux standards for *IUE* was made by Greenstein and Oke (1979). Later, a correction to the *IUE* flux standard based on white dwarfs was presented by Finley, Basri and Bowyer (1990). White dwarfs have now been used by the *IUE* Project to establish the relative flux scale for the *IUE* calibration (González-Riestra et al, this volume). White dwarfs were also used for the calibration of the Hopkins Ultraviolet Telescope (Kruk, this volume). An outcome of this meeting has been a decision to obtain spectra of

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additional white dwarfs for the purpose of improving the absolute calibration of the *HST* FOS.

The purpose of this presentation is to demonstrate that these calibration efforts rest on a sound theoretical footing, and that the use of the white dwarfs for calibrating critical instruments will not introduce any systematic biases in the flux scales.

II. Accuracy of Flux Predictions

The technique suggested for obtaining absolute fluxes for white dwarfs consists of determining accurate temperatures and gravities by detailed fitting of the hydrogen line profiles (Balmer, and Lyman if available), generating synthetic spectra using model atmospheres for those input parameters, and scaling the model spectra to match visible photometry or spectrophotometry. Thus there are two error terms: a slope error, due to the uncertainty in the temperature determination, and a "zero point" error, due to the uncertainty in the visible photometry or spectrophotometry used to set the absolute level. (Gravity errors affect the relative fluxes by less than 0.3 percent above 30,000 K).

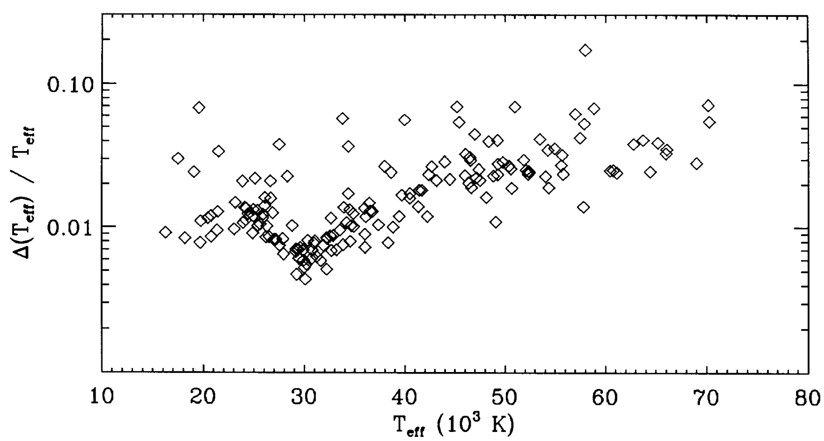

Figure 1: Fractional T_{eff} error obtained from Balmer line profile fitting for our sample of hot DA white dwarfs.

A real-world example of the temperature determination accuracy that is obtainable is shown in Figure 1, which is a plot of the fractional 1σ errors obtained from fitting the Balmer line profiles for 170 hot DA white dwarfs that I observed with typically 100:1 S/N at 5 Å resolution. Errors are derived from χ^2 analyses, and are due to the S/N of the spectra. In most cases, parameters are obtained from simultaneously fitting H β, γ, δ, and ϵ. The T_{eff} errors range from significantly less than 1 percent at 30,000 K to about 3 percent at 60,000 K. Some fraction of the targets were less well observed, and have significantly larger errors for their temperatures than the typical values. Note that the brighter objects that are best-suited for calibration purposes have temperatures that are determined much more accurately than in the "typical" cases.

The largest error in the predicted flux is in the FUV, so I have calculated the error in the predicted flux at 1400 Å relative to the flux at 5490 Å (the isophotal wavelength for the Johnson V band) for the same set of objects, given those temperature errors.

The result is plotted in Figure 2. It is seen that as long as the temperature range is restricted to ≥ 27,000 K, the error in the predicted 1400 Å flux (relative to the visible) will typically be of the order of 0.5 percent to 1.5 percent.

The wavelength dependence of the predicted flux error is shown in Figure 3, in which I have plotted the ratio of the model flux for T_{eff} = 51,000 K so that for a 50,000 K model, representing a fairly typical 2 percent T_{eff} error for that temperature range. The errors are negligible in the Paschen continuum, are less than 0.5 percent at the red end of the Balmer continuum, and monotonically increase toward shorter wavelengths to about 1 percent in the vicinity of Lyman α.

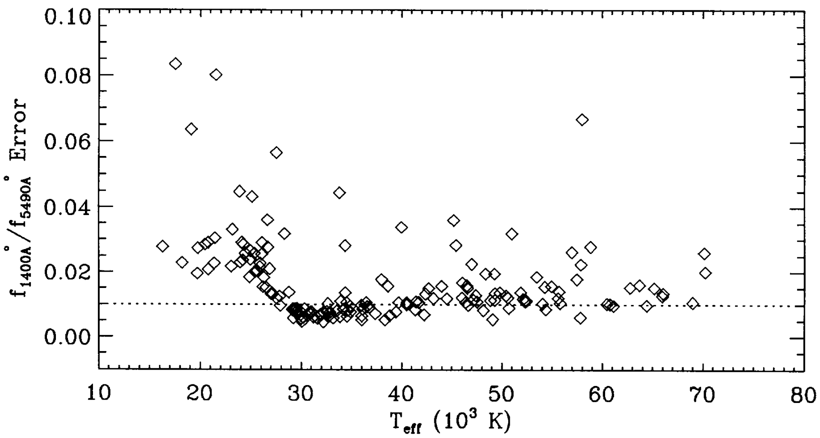

Figure 2: Error in predicted flux at 1400Å relative to flux at 5490Å based on T_{eff} errors shown in Figure 1.

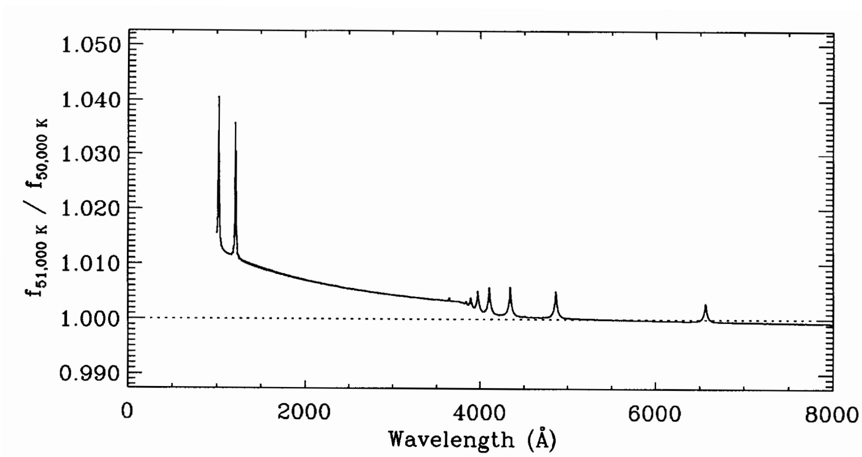

Figure 3: Relative flux error vs. wavelength (normalized at 5490Å) given a 2 percent error in T_{eff} at 50,000K

III. Systematic Errors

The above results show that the internal errors in the effective temperatures obtained from Balmer line profile fitting are such that the relative model fluxes we predict will be in error by at most about 1.5 percent at the shortest FUV wavelengths, and much less than 1 percent in the optical. Those accuracies are obtainable for DA white dwarfs with effective temperatures ≥ 27,000 K. However, there are also external, systematic effects that can affect the results.

Due to the advent of modern detectors on medium to large telescopes, we now commonly obtain spectra for white dwarfs fainter than 16th magnitude with S/N exceeding 100:1. This has led to the realization that the current treatment of Stark broadening in the higher Balmer lines is not completely satisfactory (Bergeron 1993, Bergeron, Saffer and Liebert 1992). The wings in the higher lines are predicted by current theory to be too strong, thus requiring lower temperatures to achieve a fit, relative to the lower Balmer lines. (This is only a few percent effect in the Balmer lines, which is why it was not noticed in the days of lower S/N optical spectra). A provisional method for removing this inconsistency, in lieu of the development of a more sophisticated Stark theory, has been suggested by Bergeron (1993). The method consists of, in effect, doubling the strength of the field due to adjacent charged particles that is required to “dissolve” a given atomic level of hydrogen. The relevant parameter employed in the Hummer-Mihalas occupation probability formalism (Hummer and Mihalas 1988) is referred to as β_{crit}. Doubling that parameter has the effect of reducing the probability of finding electrons in quasi-bound states, thus reducing the strength of the pseudo-continuum that overlies the Balmer line series. Functionally, that has the same effect as reducing the strengths of the overlapping wings of the Balmer lines, and allows consistent fits to be obtained for the full Balmer series. (It remains to be conclusively shown whether or not that approach introduces any significant systematic biases in the temperatures and gravities obtained).

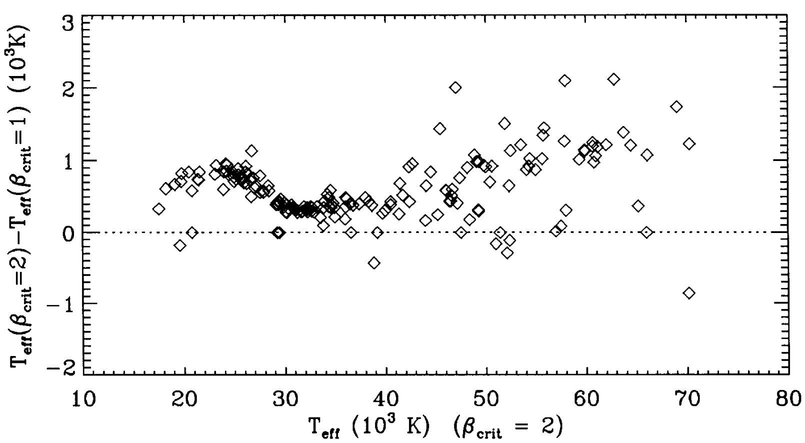

Figure 4: T_{eff} differences obtained from fitting Balmer line profiles using models with β_{crit} = 1 or 2.

The question of the proper Stark broadening treatment (or Hummer-Mihalas parameter values) to use is being addressed by the author's ASTRO-2 program that will involve the observations of the full Lyman series for several hot DA white dwarfs. The effects in the Lyman lines are expected to be several times larger than in the Balmer lines, thus allowing fine tuning of the Hummer-Mihalas formalism and testing of new, improved Stark broadening theories. However, for now, we can obtain an overestimate of the effect of the Stark uncertainties on the predicted fluxes by comparing the results obtained for β_{crit} = 1 with those obtained for β_{crit} = 2. (The values ultimately obtained after the Stark question is settled are expected to be much closer to those we obtain with β_{crit} = 2). A check was made by deriving T_{eff} and log *g* for the full sample of objects described above, using both values of β_{crit} and (usually) simultaneously fitting H β, γ, δ, and ε. The differences in T_{eff} are shown in Figure 4. Temperatures obtained with β_{crit} = 2 are consistently higher than for β_{crit} = 1, by several hundred K just above 20,000 K, decreasing to a few hundred K around 30,000 K, and slowly increasing to about 1000 K around 60,000 K.

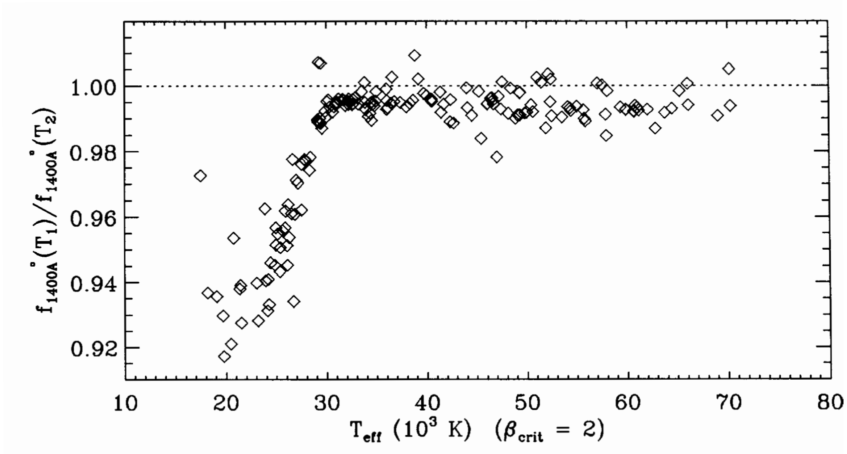

Figure 5: Ratio of FUV fluxes (normalized to 5490Å) for β_{crit} = 1and 2. T_1 refers to T_{eff} obtained for β_{crit} = 1etc.

The effect of that temperature difference on the predicted FUV flux (relative to the visible) is shown in Figure 5. For the temperatures obtained for a given value of β_{crit} we used the models for the same value of β_{crit} to predict the fluxes at 1400 Å (normalized in all cases to 5490 Å). For each object, we then calculated the ratios of the normalized 1400 Å fluxes based on the different values of β_{crit}. It is clear from Figure 5 that above about 30,000 K, the systematic error in the predicted fluxes that is due to the current uncertainty in the Stark broadening treatment is no more than 1 percent. However, given the rapid increase in the systematic (and random) errors in the predicted fluxes below that temperature, we suggest a lower limit of about 30,000 K for white dwarfs that are to be used for high precision absolute flux calibrations.

IV. Metals

The question of the presence of metals in white dwarfs invariably arises in the context of considering white dwarfs as flux standards. Previously, our knowledge of that subject was rather limited. Now, however, we have the two EUV all-sky surveys, by the *ROSAT* Wide Field Camera (WFC) and by the Extreme Ultraviolet Explorer (*EUVE*), and most importantly, we now have *EUVE* spectra of a significant number of hot DA white dwarfs. We now know that those DA WD that are heavily absorbed in the EUV have significant concentrations of trace elements; metals are essentially ubiquitous in the region of the $T_{eff} - \log g$ plane above about 50,000 K and below $\log g \sim 8$. Furthermore, the distribution of relative abundances is apparently consistent with the presence of metals being due to radiative support.

Metals have a profound effect in the EUV, where overlapping bound-free continua and line blanketing start reducing the flux below about 260 Å. G191-B2B is one of the DAs that has the highest concentrations of heavy elements, and its flux at 100 Å is reduced by 4 orders of magnitude relative to a pure H DA of the same effective temperature. The effects outside the EUV are much more subtle, though. Models with metals do not accurately reproduce the hydrogen line profiles unless, in addition to the bound-free opacity that dominates the EUV spectrum, one also self-consistently includes hundreds or thousands of metal lines that lie in the EUV and FUV and provide significant cooling that counteracts the upper atmosphere heating caused by the bound-free opacity. Models that have that capability are in progress. Furthermore, metals (particularly of the Fe group) have large numbers of lines that can overlap and reduce the apparent continuum level. This is shown in Figure 6, which includes the flux for a 60,000 K, log g = 7.5 model that matches both the Balmer line profiles and the observed continuum flux level for G191-B2B, and a 57,000 K model that includes a few hundred of the strongest Fe lines, with an abundance of Fe/H = 3×10^{-6}, as well as C. (Note that the CIV doublet at 1550 Å is unresolved, given the assumed instrument resolution of 3 Å FWHM. Also, note that the metal spectrum has been lowered by 0.5 percent so that the continua of the two spectra overlap.) Thus, in the more metal rich DA, we can expect to have some portions of the EUV spectra reduced by order of a few percent due to overlapping metal lines.

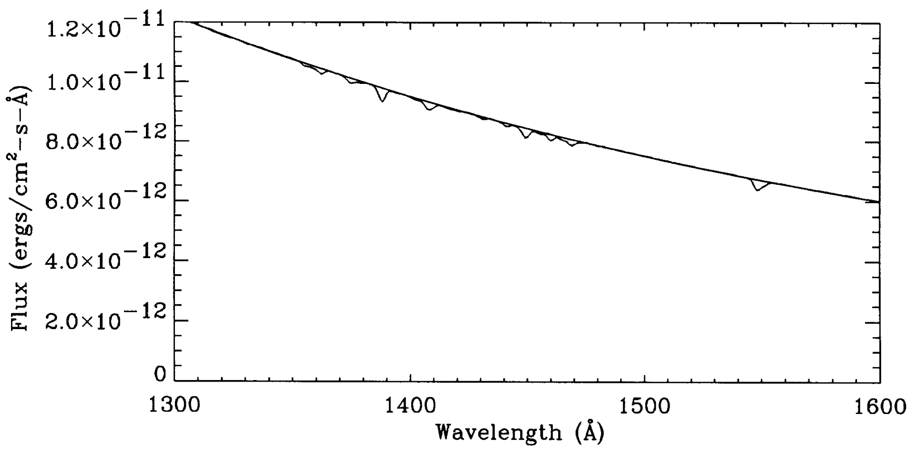

Figure 6: Pure H model, 60,000K, and metal-rich model, 57,000K, including a few hundred of the strongest Fe lines, and the CIV 1550Å doublet. Metal model spectrum is shifted downward by 0.5 percent, and convolved with instrumental resolution of 3Å FWHM.

V. Recommendations

At effective temperatures below 30,000 K, the Balmer continuum slope starts becoming a more sensitive function of T_{eff}, without a corresponding increase in the accuracy of the temperatures obtained from Balmer line profiles. Thus, the internal uncertainty in the predicted FUV flux at 1400 Å rapidly increases from about 0.5 percent at 30,000 K to at least a few percent at cooler temperatures. Furthermore, the systematic errors due to uncertainties in the current treatment of Stark broadening and the hydrogen equation of state are such that systematic errors in the predicted FUV fluxes may approach several percent below 30,000 K.

Above 50,000 K, metals are apparently nearly always present. Although the case of G191-B2B suggests that even for very metal-rich DA, one may use pure H Balmer fit temperatures to model the relative fluxes to an accuracy of a few percent or better, prudence suggests that DAs hotter than 50,000 K should only be used as secondary standards, or avoided altogether, until fully self-consistent models including large numbers of metal lines are in hand, and fairly accurate abundance determinations have been made.

If one restricts potential DA WD calibration standards to the range of about 30,000 K to 50,000 K, though, the results shown here indicate that by determining T_{eff} from high S/N optical spectroscopy, relative fluxes may be predicted with accuracies of 1.5 percent or better. Furthermore, the uncertainties in modeling hydrogen (of which we are currently aware) are such that systematic errors in the predicted relative fluxes should be less than 1 percent in this T_{eff} range. Given an assumed accuracy of 3 percent for the absolute flux level as set by optical photometry or spectrophotometry, by selecting a sample of hot DA in the 30,000 K to 50,000 K range that have accurate visible fluxes and accurate temperatures, one can in principle establish an absolute flux standard from the red wing of Lyman α through the near IR with an overall accuracy of the order of 2 percent.

Much of the work described here is being carried out in collaboration with Detlev Koester. Additionally, all models discussed here were calculated using Koester's WD model atmosphere codes. This work was supported by NASA grants NAGW-2478 and NAS5-29298.

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