THE ABSOLUTE FLUX DISTRIBUTION OF LDS749B

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ABSTRACT

Observations from the Space Telescope Imaging Spectrograph (STIS) define the flux of the DBQ4 star LDS749B from 0.12 to 1.0 μm with an uncertainty of ~1% relative to the three pure hydrogen white dwarf primary Hubble Space Telescope standards. With $T_{\text{eff}} = 13,575$ K, log $g = 8.05$, and a trace of carbon at $1 \times 10^{-6}$ of solar, a He model atmosphere fits the measured STIS fluxes within the observational noise, except in a few spectral lines with uncertain physics of the line-broadening theory. The upper limit to the atmospheric hydrogen and oxygen fractions by number are $1 \times 10^{-7}$ and $7 \times 10^{-10}$, respectively. The excellent agreement of the model flux distribution with the observations lends confidence to the accuracy of the modeled IR fluxes beyond the limits of the STIS spectrophotometry. The estimated precision of ~1% in the predicted IR absolute fluxes at 30 μm should be better than the model predictions for Vega and should be comparable to the absolute accuracy of the three primary WD models.

Key words: stars: atmospheres – stars: fundamental parameters – stars: individual (LDS749B) – techniques: spectroscopic

Online-only material: machine-readable tables

1. INTRODUCTION

The DBQ4 star LDS749B (WD2129+00) has long been considered as a flux standard (e.g., Bohlin et al. 1990). To establish the flux on the Hubble Space Telescope (HST) white dwarf (WD) flux scale, Space Telescope Imaging Spectrograph (STIS) spectrophotometry was obtained in 2001–2002. The virtues of LDS749B as a flux standard include an equatorial declination and a significantly cooler flux distribution than the 33,000–61,000 K primary DA standards GD71, GD153, and G191B2B. Full STIS wavelength coverage is provided from 0.115 to 1.02 μm, and the peak in the spectral energy distribution (SED) is near 1900 Å. At $V = 14.674$ (Landolt & Uomoto 2007), LDS749B is among the faintest HST standards and is suitable for use with larger ground-based telescopes and with the more sensitive HST instrumentation, such as the Advanced Camera for Surveys (ACS)/SBC and COS. The bulk of the STIS data was obtained as part of the FASTEX (Faint Astronomical Camera for Surveys) program. Finding charts appear in Turnshek data was obtained as part of the FASTEX (Faint Astronomical Camera for Surveys (ACS)/SBC and COS. The bulk of the STIS data was obtained as part of the FASTEX (Faint Astronomical Camera for Surveys) program. Finding charts appear in Turnshek

The model presented here for LDS749B and archived in the CALSPEC database3 should have a better precision than the Kurucz $T_{\text{eff}} = 9400$ K model for Vega, especially beyond ~12 μm, where the Vega’s dust disk becomes important (Engleke et al. 2006). Vega is also a pole-on rapid rotator, which may also cause IR deviations from the flux for a single temperature model. Our modeled flux distribution for LDS749B should have an accuracy comparable to the pure hydrogen model flux distributions for the primary WD standards GD71, GD153, and G191B2B.

2. THE MODEL

A helium model atmosphere flux distribution for LDS749B is calculated with the LTE code of Koester (e.g., Castanheira et al. 2006) for $T_{\text{eff}} = 13,575$ K and log $g = 8.05$. At such a cool temperature, the differences between LTE and NLTE in the continuum flux distributions should be <0.1% from the far-UV to the IR. For example for a pure hydrogen DA, the difference between the continua of a hot 40,000 K LTE/NLTE pair of models is ~1% between 0.1 and 2.5 μm. The same maximum difference at 20,000 K is only 0.3%. Napiwotzki (1997) did not discuss pure He models but concluded that NLTE effects tend

3 The absolute SEDs discussed in this paper are available in digital form at http://www.stsci.edu/hst/observatory/cdbs/calspec.html.
to become smaller with lower effective temperature. For cool DA WDs, Koester et al. (1998) show that the only NLTE effect that approaches 1% is a deeper line core of Hα. The matter densities in helium-rich WDs are significantly higher, leading to a higher ratio of collisional to radiative transitions between atomic levels. The larger importance of collisions increases the tendency toward LTE occupation numbers because of the robust Maxwell distribution of particle velocities.

$T_{\text{eff}} = 13.575$ K is higher than $T_{\text{eff}} = 13.000$ K published for LDS749B (alias G26−10) in Castanheira et al. (2006), because only UV spectra of lower precision (IUE heritage) were used in that analysis. Voss et al. (2007) found $T_{\text{eff}} = 14.440$ K with large uncertainty, because only line profiles in the optical range were used and log g had to be assumed. A trace of carbon at $10^{-6}$ of the solar C/He ratio is included, i.e., the C/He number ratio is $3.715 \times 10^{-4}$. The model mass is 0.614 $M_\odot$ and the stellar radius is 0.01224 $R_\odot$, which corresponds to a distance of 41 pc for the measured STIS flux.

The line broadening theory for the He lines combines van der Waals, Stark, and Doppler broadening to make a Voigt profile. However, the Stark broadening uses a simple Lorentz profile with width and shift determined from the broadening data in Griem (1964), instead of the elaborate calculations of Beauchamp et al. (1997). The Griem method is computationally much faster, and data are available for more lines than are calculated by Beauchamp et al.

The fit of the higher series He lines is much improved, if the neutral–neutral interaction is decreased in comparison to the original formalism of the Hummer–Mihalas occupation probabilities. A similar effect was noted by Koester et al. (2005), and our model uses the same value of the quenching parameter that Koester et al. derived ($f = 0.005$). The model wavelengths are all on a vacuum scale.

3. STIS SPECTROPHOTOMETRY

The sensitivities of the five STIS low-dispersion spectrophotometric modes have been carefully tracked since the STIS commissioning in 1997. After correcting for changing sensitivity with time (Stys et al. 2004) and for charge transfer efficiency (CTE) losses for the three STIS CCD spectral modes (Bohlin & Goudfrooij 2003; Goudfrooij et al. 2006), STIS internal repeatability is often better than 0.5% (Bohlin 2003). Thus, HST/STIS observations of LDS749B provide absolute spectrophotometry with a precision that is superior to ground-based flux measurements, which require problematic corrections for atmospheric extinction.

Observations with a resolution $R = 1000$–1500 in four STIS modes from 1150–1710 Å (G140L), 1590–3170 Å (G230L), 2900–5690 Å (G430L), and 5300–10200 Å (G750L) were obtained in 2001–2002. Earlier observations of LDS749B in 1997 to test the time-tagged mode were unsuccessful. Two observations in the CCD G230LB mode overlap the wavelength coverage of the MAMA G230L but are too noisy to be included in the final combined absolute flux measurement from the other four modes. Table 1 summarizes the individual observations used for the final combined average, along with the unused G230LB data for completeness.

Figure 1 shows the ratios of the three individual G230L and the two G230LB observations to the model fluxes, which are normalized to the STIS flux in the 5300–5600 Å range. The excellent repeatability of STIS spectrophotometry over broad bands is illustrated, and the global average ratio over the 1750–3000 Å bandpass is written in each panel. This ratio is unity to within 0.3%, even for the shorter CCD G230LB exposures despite their almost 3 x higher noise level and CTE corrections. The other CCD modes G430L and G750L also require CTE corrections. Repeatability for all the STIS spectral modes is comparable, i.e., the global ratio deviates rarely from unity by more than 0.6%.

The observations in each of the four spectral modes are averaged and the four segments combined. This composite standard star spectrum extends from 1150 to 10226 Å and can be obtained at http://www.stsci.edu/hst/observatory/cdbs/calspec.html (along with the remainder of the HST standard star library (Bohlin et al. 2001)). This binary fits table named lds749b_stis_001.fits has 3666 wavelength points and seven columns. An ascii file version has 366 wavelength points and seven columns with time (Stys et al. 2004) and for charge transfer efficiency (CTE) corrections. Repeatability for all the STIS spectral modes is comparable, i.e., the global ratio deviates rarely from unity by more than 0.6%.

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Figure 1. Ratio of individual STIS observations to the LDS749B model fluxes. Both the data and the model are binned to the ∼2 pixel resolution of STIS before dividing. The global average and rms for the range between the vertical dotted lines are written in each panel along with the identifying information for each observation: spectral mode, root name, aperture, and exposure time in seconds. The noisier, short-exposure CCD mode G230LB data shown in the bottom two panels are not used in the final average of the observations.

4. COMPARISON OF THE OBSERVATIONS WITH THE MODEL

4.1. The Continuum

To compare the model and observations, a convenient method of removing the slope of the SED is to divide both fluxes by the same theoretical model continuum. Small differences between the observations and the model, either in the lines or in the actual continuum, are easily illustrated in such plots. The theoretical continuum contains only continuum opacities with an extrapolation across the He i opacity edges at 2601, 3122, and 3422 Å, in order to avoid discontinuities. Figure 2 shows an overview of the comparison of the STIS fluxes with the model after division of both SEDs by this same smooth line-and-edge-free continuum. The mean continuum level of the data between the absorption lines agrees with the model within ∼1% almost everywhere.

The most significant deviation of the data from the model is in the broad 1400–1550 Å region, where each of the three spectra comprising the G140L average has 350,000 photoelectron events in this 150 Å band. The background level is <0.1% of the net signal, so that neither counting statistics nor background subtraction error could cause the observed ∼1.5% average disparity. Of the five low dispersion modes, G140L shows the worst photometric repeatability of individual spectra in broad bands of σ ~ 0.6%. The three individual spectra comprising the G140L average do show occasional 2–3σ broadband dips within their 550 Å coverage region, but the probability of such a large excursion as 1.5% in their average is extremely unlikely at any particular wavelength. However,
the probability is much greater that such a large excursion could occur in some 150 Å band. Individual G140L spectra of the monitoring standard GRW+70° 5824 often show a broad region differing by 1–2% from the average. The cause of such excursions could be flat field errors, temporal instabilities in the flat field, or other detector effects that might make the flat field inapplicable to a narrow spectral trace.

4.1.1. Uncertainties in $T_{\text{eff}}$ and $\log g$

The uncertainty in the model $T_{\text{eff}}$ is determined by the uncertainty in the slope of the UV flux distribution. For a constant $\log g$ model that is cooler or hotter by 50 K and normalized to the measured 5300–5600 Å flux, there are increasing differences with the data from 1% near 2000 Å to 2% at the shorter wavelengths. Such a large change in the modeled continuum level in Figure 2 (red line) is inconsistent with the STIS flux (black line). This 50 K uncertainty of the model $T_{\text{eff}}$ is an internal uncertainty relative to the temperatures of the primary WD standards GD71, GD153, and G191B2B. If a re-analysis of the Balmer lines in these primary DA standards produced a systematic shift in the temperature scale, this shift would be reflected in a revised $T_{\text{eff}}$ for LDS749B that is independent of the 50 K internal uncertainty. A 50 K temperature difference causes a $<0.5\%$ flux change in the IR longward of 1 μm.

To estimate the uncertainty in $\log g$, models are computed at the 13,575 K baseline temperature but with an increment in $\log g$. Positive and negative increments produce nearly mirror image changes in the flux distribution. For a decrease of 0.7 in $\log g$, the flux decreases by a nearly uniform 1.5% below 3600 Å after normalizing to unity in the 5300–5600 Å range. Increasing $T_{\text{eff}}$ by the full 50 K uncertainty to 13,625 K can compensate for this flux decrease below $\sim$2000 Å. However, the +50 K increase compensates little in the 2500–3600 Å range, leaving a disparity of $\sim$1%. Because this 2500–3600 Å range includes some of the best S/N STIS data, a 1% disparity establishes the uncertainty of 0.7 dex in $\log g$ as barely compatible with the STIS flux distribution. The IR uncertainty corresponding to this limiting case of $T_{\text{eff}} = 13,625$ K and $\log g = 7.35$ is $\sim$1% longward of 1 μm, because the fractional percentage changes in the IR from the higher temperature and from the lower $\log g$ are both in the same direction.

4.1.2. Interstellar Reddening

Another source of error in the model $T_{\text{eff}}$ is interstellar reddening. The standard galactic reddening curve has a strong broad feature around 2200 Å, and a tiny limit to the extinction $E(B-V)$ is set by the precise agreement of STIS with the model in this region of Figure 2. For the upper temperature limit of $T_{\text{eff}} = 13,625$ K and $\log g = 7.35$, the model is $\sim$1% high at 1300 Å and $\sim$1% low at 2200 Å. Thus, for standard galactic reddening, $E(B-V)$ must be less than 0.004, and $T_{\text{eff}}$ is less than 13,675 K. In this case of $T_{\text{eff}}$ and $E(B-V)$ at these allowed limits, the IR flux beyond 1 μm is still the same as for the unreddened baseline $T_{\text{eff}} = 13,575$ K within 0.5%.
However, Bohlin (2007) presented arguments for reddening with a weak 2200 Å bump for other lines of sight with tiny amounts of extinction. Reddening curves measured in the Small Magellanic Cloud (SMC) (e.g., Witt & Gordon 2000) are missing the 2200 Å feature and can cause larger uncertainty in \( T_{\text{eff}} \). Additional evidence for extinction curves more like those in the Magellanic Clouds is presented by Clayton et al. (2000) for the local warm intercloud medium, where the reddening is low. Changes in the shape of the flux distribution after reddening with the SMC curve of Witt and Gordon are similar to the change in shape with \( T_{\text{eff}} \). For example, reddening a model with \( T_{\text{eff}} = 14,130 \) K by SMC extinction of 0.015 is required to make an equally unacceptable fit as for 13,575 K and galactic extinction of \( E(B-V) = 0.004 \). In this extreme limiting case of SMC extinction, the IR flux beyond 1 \( \mu \)m is still the same within \( \sim 1\% \) as for \( T_{\text{eff}} = 13,575 \) K and \( E(B-V) = 0 \).

Despite small uncertainties in the interstellar reddening and consequent uncertainty in \( T_{\text{eff}} \), our modeling technique still predicts the continuum IR fluxes to 1% from 1 \( \mu \)m to 30 \( \mu \)m. Discounting the most pathological case of SMC reddening, the worst far-IR uncertainty is from the combined 50 K temperature and 0.7 log \( g \) uncertainties, because the changes in the slope from the visual band normalization region into the IR due to higher temperature and lower log \( g \) are both in the same direction. In the absence of modeling errors or other physical complications like IR excesses from dust rings, the measured fluxes of LDS749B relative to the three primary WDs should be the same as predicted by the relative fluxes of the respective models to a precision of 1% in the IR.

### 4.2. The Stellar Absorption Lines

#### 4.2.1. Hydrogen

An upper limit on the equivalent width for \( \text{H} \alpha \) of \( \sim 0.1 \) Å constrains the fraction by number of hydrogen in the atmosphere of LDS749B to \( < 1 \times 10^{-6} \) of helium. However, a stricter limit of \( < 1 \times 10^{-7} \) is provided by the weak Ly\( \alpha \) line. Because interstellar absorption at Ly\( \alpha \) could be significant, zero hydrogen is consistent with the observations and is adopted for the final best model for LDS749B. After normalization in the V band, the continuum of a model with \( 1 \times 10^{-7} \) hydrogen composition and the baseline \( T_{\text{eff}} = 13,575 \) K and log \( g = 8.05 \) agrees with the zero hydrogen baseline continuum to \( \sim 0.5\% \) from Ly\( \alpha \) to 30 \( \mu \)m.

#### 4.2.2. Helium

Figure 3 compares the observed He i lines with the baseline model after correcting the model wavelengths by the radial velocity of \( -81 \) km s\(^{-1}\) (Greenstein & Trimble 1967). The model is smoothed with a triangular profile of FWHM corresponding to a resolution \( R = 1500 \) for the MAMA spectra shortward of 3065 Å and to \( R = 1000 \) for the CCD spectra longward of 3065 Å. In general, the model underestimates the line strengths, even for the quenching of the neutral–neutral interactions with \( f = 0.005 \). There is a suggestion of some systematic asymmetry with stronger absorption in the short wavelength side of the line profile. This asymmetry could be in the STIS line-spread function, or perhaps a more exact treatment of the Stark line-broadening theory would reproduce the observed asymmetries.
4.2.3. Carbon

With a C/He ratio of $1 \times 10^{-6}$ solar, i.e. a C/He number ratio of $3.715 \times 10^{-9}$, the modeled C i and C ii lines reproduce the observations within the observational noise, as shown in Figure 4. In particular, the agreement of the modeled C i(1329)/C ii(1335) line ratio with the observed ratio means that the carbon ionization ratio corresponds to the photospheric temperature of the star. With this small amount of carbon, the spectral classification of LDS749B should more properly be DBQ (Wesemael et al. 1993).

4.2.4. Oxygen

The oxygen triplet at 1302.17, 1304.87, and 1306.04 Å constrains the fraction of oxygen in the LDS749B atmosphere. This triplet absorption feature extends over 4 Å or about seven STIS pixels, but no obvious absorption feature appears above the noise level. After binning the STIS data by seven pixels, the rms noise in the 1300 Å region is 0.8%. The corresponding 3σ upper limit to the equivalent width is 0.10 Å, which implies an upper limit to the atmospheric oxygen fraction by number of $7 \times 10^{-10}$ of helium.

5. CONCLUSION

In the absence of any interstellar reddening, a helium model with $T_{\text{eff}} = 13,575$ K $\pm 50$, $\log g = 8.05 \pm 0.7$, and a trace of carbon at $1 \times 10^{-6}$ of solar fits the measured STIS flux distribution for LDS749B. The noise-free, absolute flux distribution from the model after normalization to the observed broadband visual flux is preferred for most purposes. This normalized model SED is a high fidelity far-UV to far-IR calibration source, and the flux distribution is available via Table 3 in the online journal. Both the observed flux distribution and the modeled fluxes are also available from the CALSPEC database (see footnote 3).

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**Table 3**

| Wavelength | Flux        | Continuum        |
|------------|-------------|------------------|
| 900.000    | $8.7713311 \times 10^{-15}$ | $8.763803 \times 10^{-15}$ |
| 900.250    | $8.775207 \times 10^{-15}$ | $8.795087 \times 10^{-15}$ |
| 900.500    | $8.785346 \times 10^{-15}$ | $8.805789 \times 10^{-15}$ |
| 901.000    | $8.795857 \times 10^{-15}$ | $8.821295 \times 10^{-15}$ |
| 901.500    | $8.806439 \times 10^{-15}$ | $8.836236 \times 10^{-15}$ |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
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4 This STScI internal document, and that of Stys et al., can be found at http://www.stsci.edu/hst/stis/documents/isrs/.