HUBBLE SPACE TELESCOPE SPECTROPHOTOMETRY AND MODELS FOR SOLAR ANALOGS

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ABSTRACT

Absolute flux distributions for seven solar analog stars are measured from 0.3 to 2.5 μm by Hubble Space Telescope (HST) spectrophotometry. In order to predict the longer wavelength mid-IR fluxes that are required for James Webb Space Telescope calibration, the HST spectral energy distributions are fit with Castelli & Kurucz model atmospheres; and the results are compared with fits from the MARCS model grid. The rms residuals in 10 broadband bins are all <0.5% for the best fits from both model grids. However, the fits differ systematically: the MARCS fits are 40–100 K hotter in $T_{\text{eff}}$, 0.25–0.80 higher in log $g$, 0.01–0.10 higher in log $z$, and 0.008–0.021 higher in the reddening $E(B-V)$, probably because their specifications include different metal abundances. Despite these differences in the parameters of the fits, the predicted mid-IR fluxes differ by only ~1%; and the modeled flux distributions of these G stars have an estimated ensemble accuracy of 2% out to 30 μm.

Key words: stars: atmospheres – stars: fundamental parameters – stars: individual (HD 209458, P041C, P177D, P330E, C26202, SF1615+001A, SNAP-2) – techniques: spectroscopic

1. INTRODUCTION

The James Webb Space Telescope (JWST) requires flux standards in the 0.8–30 μm region. To define reference absolute flux distributions at the longer wavelengths, stellar model spectral energy distributions (SEDs) can be anchored to precision Hubble Space Telescope (HST) spectrophotometry at 0.3–2.5 μm and extrapolated into the mid-IR. A variety of stellar types helps guard against systematic effects in the modeling and extrapolation process, while several standards of each type provide a statistical reduction of the random errors in the measured fluxes and in the fitting process. Three types—white dwarfs (WDs), A stars, and G stars—are chosen because of their specifications include different metal abundances. Despite these differences in the parameters of the fits, the predicted mid-IR fluxes differ by only ~1%; and the modeled flux distributions of these G stars have an estimated ensemble accuracy of 2% out to 30 μm.

2. SOLAR MODELS

Kurucz (2004) has produced a finely sampled solar model SED (fsunallp). Figure 1 compares both this special solar spectrum and the MARCS model to the same CK04 model interpolated in the CK04 grid. All three model SEDs are for the same effective temperature $T_{\text{eff}} = 5777$ K, surface gravity log $g = 4.44$, metallicity $\log [\text{M/H}] = 0$, and the turbulent velocity $v_{\text{turb}} = 2$ km s$^{-1}$, except that the Kurucz fsunallp model has $v_{\text{turb}} = 1.5$ km s$^{-1}$. Shortward of 0.45 μm, where the line blanketing is severe, the MARCS model differs from the CK04 model by more than 5% in the bottom panel of Figure 1, and the Kurucz (2004) and CK04 models differ by up to 3% in the top panel. In this region of severe line blanketing, the models are most sensitive to the input parameters. For example, changing only the $v_{\text{turb}}$ from 2 to 1 km s$^{-1}$ increases the mean flux in the 0.30–0.37 μm range by ~5%, while affecting the fluxes longward of 0.40 μm by <1%.

Longward of 0.6 μm, the Kurucz (2004) and CK04 models differ smoothly by up to 2% in the top panel; however, the ratios in the two panels of Figure 1 match to ~1%. This match between the Kurucz (2004) and MARCS models suggests that the CK04 models may have a slight IR excess with respect to the $V$ band. Furthermore, direct comparisons of the CK04 models with the HST observations show similar residuals in the 1–2.5 μm region. Thus, for solar analog stars with $T_{\text{eff}}$ within a few hundred degrees of the Sun, the first-order correction in the top panel should be an improvement to the CK04 grid models longward of 1 μm. In the 4.2–7 μm region, where the Kurucz (2004) model overestimates the strength of the main CO
band absorption (R. L. Kurucz 2009, private communication), no correction is made to the CK04 grid models. Whenever CK04 is mentioned below, this correction procedure that is based on the Kurucz special solar model is implicit from 1 to 4.2 \( \mu \text{m} \) and longward of 7 \( \mu \text{m} \). The correction is smooth and does not exceed 0.5% beyond 7 \( \mu \text{m} \).

3. MODEL PARAMETERS FOR THE BEST FIT TO HST FLUXES

Following the technique of Bohlin & Cohen (2008), values for \( T_{\text{eff}} \), \( \log g \), \( \log z \), and the selective dust extinction between the \( B \) and \( V \) bands, \( E(B - V) \), are derived by fitting the \( HST \) observational SEDs with model atmospheres from the grid of CK04. Figure 2 compares the observations to the best-fitting CK04 models. Similarly, Figure 3 shows the ratio of the observations to the best fit from the MARCS grid (Gustafsson et al. 2008). Each reddened model is normalized to the observed flux averaged over 0.6–0.9 \( \mu \text{m} \). The reddening curve used to correct for the extinction as a function of wavelength and \( E(B - V) \) is from Cardelli et al. (1989, CCM) at wavelengths shorter than 2 \( \mu \text{m} \) and is from Chiar & Tielens (2006) at longer wavelengths. Both the level and slope of the two extinction curves are matched at 2 \( \mu \text{m} \).

In Figures 2 and 3, the ratios of the observations to the models appear as small circles at a resolution of \( R = 100 \). The large scatter in these narrowband small circles at the shorter wavelengths demonstrates the Kurucz (2005) claim that exact model fits are currently hopeless because of poor and incomplete atomic line data and because of elemental abundance uncertainties, especially in regions of strong line blanketing. Typically for solar type stars, the model computations show a line blanketing that exceeds 20% below 0.45 \( \mu \text{m} \). However, averages over broad bands should be accurate because of the statistical nature of the uncertainties of the absorption line strengths. For the fainter stars in the three top panels, the signal-to-noise ratio of the observations is poor; and much of the \( R = 100 \) fine structure is just noise. For the four brighter stars, Figure 4 illustrates the source of the fine structure in one narrow wavelength region. Longward of \( \sim 0.42 \mu \text{m} \), the CK04 models in Figure 4 are low, which causes the peaks around 0.43 \( \mu \text{m} \) that often rise above 1.05 in Figure 2. Similarly, the MARCS models are systematically higher than the observations near 0.41 \( \mu \text{m} \), which causes the narrow dips at that wavelength in Figure 3. The use of models for narrowband calibrations is problematic because of deviations from the true observed flux and because of the coarse wavelength grid for the CK04 models. For calibrations in narrow bands with a spectral resolution comparable to the observations, the finite resolution of the observations may also cause errors to the extent that spectral features fall in the bandpass and to the extent there is noise in the observed flux. Whenever possible, narrowband filters and spectroscopic sensitivities are best measured using a standard star with minimal spectral structure in the region of interest. The effects of the resolution and noise can be alleviated by fitting a smooth function to the sensitivity as a function of wavelength in the case of a spectrograph calibration; but narrowband filter calibrations suffer errors directly from all the above problems.

Table 1 lists the broadband regions used to minimize the rms scatter in the fitting procedure. The averages over the first two broad bands show opposite behavior as a function of gravity, in the sense that the flux decreases at 0.300–0.372 \( \mu \text{m} \) and increases at 0.372–0.455 \( \mu \text{m} \) as \( \log g \) increases. These two bands provide a strong constraint on the derived values for \( \log g \) in the temperature regime of the program solar analog stars. For example, an increase of \( \sim 10\% \) in the first to the second broadband flux ratio represents a change of +1 in \( \log g \). Because the uncertainties in the NICMOS data are larger than for STIS, the NICMOS bands are wider. Furthermore, an extra uncertainty of 1%–2% exists where the NICMOS non-linearity correction of Bohlin et al. (2006) is the largest at 1–1.3 \( \mu \text{m} \). Therefore,
Figure 3. As in Figure 2, except that the denominators are interpolated from the MARCS grid.

Table 1
Broad Bands for Fitting Models

| Wavelength Range ($\mu$m) |
|--------------------------|
| 0.300–0.372              |
| 0.372–0.455              |
| 0.455–0.550              |
| 0.550–0.650              |
| 0.650–0.750              |
| 0.750–0.850              |
| 0.850–1.000              |
| 1.300–1.550              |
| 1.550–1.900              |
| 1.900–2.400              |

Figure 4. Detailed comparison of the STIS absolute fluxes (black circles) for the four brightest stars with their best-fitting CK04 (red squares) and MARCS (green) models in a narrow wavelength region of 0.41–0.44 $\mu$m. The CK04 SED is shown at the resolution of the sparse grid of 1221 points that covers the full 0.009–160 $\mu$m wavelength range, while the finely sampled MARCS models are smoothed to match the $R \sim 1000$ resolution of the black circle STIS data. The bulk of the fine structure in Figures 2 and 3 is not due to missing strong absorption lines in the models; but instead, the few percent differences between observation and theory are caused by small errors in the total strength of the heavy line blanketing.

Table 2 summarizes the results of the best fits for the two sets of models. The residual broadband rms values are all <0.5% for both the CK04 and MARCS model fitting.

4. COMPARISON OF CK04 AND MARCS RESULTS

There are systematic differences in the models; the MARCS and the CK04 best fits differ by up to +100 K in $T_{\text{eff}}$, +0.8 in log $g$, +0.10 in [M/H], and +0.021 in $E(B - V)$, even though both grids are computed for plane-parallel structure and with $v_{\text{turb}} = 2$ km s$^{-1}$. These differences are probably due largely to different adopted abundances. The MARCS models use the relative abundances and the $Z = 0.012$ fractional abundance by mass of chemical elements heavier than helium from Grevesse et al. (2007), while CK04 adopt the abundances of Grevesse & Sauval (1998) with $Z = 0.017$.

The low values from the CK04 grid for log $g$ with respect to the MARCS results and with respect to the 4.44 solar value may indicate that the metallicities adopted for the MARCS models are more realistic in the heavily line blanketed 0.3–0.455 $\mu$m region that is of primary importance for the determination of log $g$. Whatever the true cause of the low values for log $g$ for the CK04 fits, there is little effect on the mid-IR flux, which is the main goal of this work. For example, in the worst case of P177D with the lowest log $g$ of 3.60, increasing log $g$ to the canonical solar value of 4.44 makes large changes of a few percent in the two shortest wavelength broad bands, as expected. The 0.3–0.372 $\mu$m ratio drops by $\sim$6%, while the next band at 0.372–0.455 $\mu$m increases by $\sim$3%. In these heavily line blanketed regions, such deviations can be explained by abundance errors and uncertainties in the atomic physics used by CK04. However, at the longer wavelengths, where the goal is to accurately predict the flux, the maximum difference between the log $g$ of 3.60 and 4.44 models is 0.2%. The values for $T_{\text{eff}}$ and the reddening
Table 2
Solar Analog Stars

| Star     | R.A. 12000 | Decl. 12000 | V  | T_eff | log g | [M/H]     | E(B−V) | rms (%) | T_eff | log g | [M/H]    | E(B−V) | rms (%) |
|----------|------------|-------------|----|-------|-------|-----------|--------|---------|-------|-------|-----------|--------|---------|
| P041C    | 14 51 58.19| +71 43 17.3 | 12.01 | 5960 | 3.95 | 0.02  | 0.027 | 0.31 | 6020 | 4.65 | −0.03  | 0.038 | 0.34     |
| P177D    | 15 59 13.59| +47 26 41.8 | 13.48 | 5780 | 3.60 | −0.17 | 0.031 | 0.24 | 5860 | 4.30 | −0.08  | 0.049 | 0.29     |
| P330E    | 16 31 33.85| +30 08 47.1 | 13.01 | 5820 | 4.60 | −0.30 | 0.035 | 0.28 | 5920 | 4.60 | −0.20  | 0.056 | 0.41     |
| HD 209458| 22 03 10.8 | +18 53 04 7 | 7.65  | 6080 | 4.00 | −0.10 | 0.005 | 0.15 | 6160 | 4.45 | −0.04  | 0.021 | 0.24     |
| C26202   | 3 32 32.88  | −27 51 48.0 | 16.64 | 6100 | 4.30 | −0.55 | 0.035 | 0.34 | 6200 | 4.55 | −0.48  | 0.054 | 0.47     |
| SF1615+001A | 16 18 14.23 | +60 00 08.4 | 16.75 | 5800 | 4.10 | −0.78 | 0.104 | 0.29 | 5840 | 4.45 | −0.73  | 0.112 | 0.43     |
| SNAP-2   | 16 19 46.13| +55 34 17.7 | 16.2  | 5740 | 4.05 | −0.36 | 0.036 | 0.34 | 5800 | 4.85 | −0.31  | 0.048 | 0.46     |

$E(B−V)$ are much more important than $\log g$ for determining the IR fluxes with respect to the 0.6–0.9 $\mu$m normalization region.

The MARCS models are indexed by a quantity $\log z = [\text{Fe/H}]$, which represents the logarithm of the number of iron atoms relative to hydrogen by number; and $[\text{Fe/H}] = 0.0$ indicates a solar abundance. The upper ($Z$) and lower ($z$) cases must not be confused; but as long as models with enhanced alpha elements are not considered, then the fraction of metals by mass, $Z$, scales directly with the total metal number density relative to the Sun, $\log z = [\text{Fe/H}] = [\text{M/H}]$, where $M$ represents the total metallicity. A quirk of the MARCS grid is that for $[\text{Fe/H}] < 0$, a solar relative metallicity among the heavy elements is classified as “alpha-poor,” while models with enhanced oxygen and alpha elements with respect to iron are denoted as “standard.” Hence, for the six stars with metallicities lower than solar, the “alpha-poor” MARCS grid is utilized.

Despite the differences in the models, the comparison in Figure 5 of the best-fitting CK04 and MARCS models for each star typically agrees to $\sim 1\%$ in broad continuum bands. The systematically higher temperatures for the MARCS fits are partially compensated by higher reddenings. Unfortunately, this comparison between CK04 and MARCS extends only to 20 $\mu$m, which is the long wavelength limit of the MARCS grid. Because JWST requires flux standards to 30 $\mu$m, the CK04 models are the baseline, while the agreement with the independent MARCS grid sets a lower limit of $\sim 1\%$ to the uncertainty in the modeled IR SEDs.

In addition to this systematic uncertainty in the G star models, the systematic uncertainty in the SEDs of the primary pure hydrogen WDs that are the basis for the HST flux scale must be included in the error analysis. The error model of Bohlin (2003) assigns a 1% uncertainty in the flux relative to the 0.55 $\mu$m flux for these WDs longward of 1.5 $\mu$m. For models in the range of the results of Table 2, a delta of 18 K, e.g., for models with $T_{\text{eff}} = 5800$ versus 5818 K, the change in the 1.5/0.55 $\mu$m flux ratio is 1%. However, this possible error in the HST flux scale causes little extra error in the extrapolated G star fluxes, because the ratio of these two $\sim 5800$ K models is rather flat beyond 1.5 $\mu$m, increasing to an error of only 1.2% at 30 $\mu$m. Thus, combining the $\sim 1\%$ uncertainty in the G star models with a $\sim 1\%$ uncertainty in the primary WD models, a limit of 2% to the systematic uncertainty for the modeled mid-IR fluxes relative to the V band is conservative, except in the unlikely case that both model grids have errors in the mid-IR that are large and of similar amount.

The CK04 fits often show somewhat lower rms residuals in Table 2; and the CK04 fits are usually closer to the canonical solar values of $T_{\text{eff}} = 5777$ K, while the MARCS models are closer to the solar $\log g = 4.44$. A difference common to all seven stars in Figure 5 is the rise of $\sim 2\%$ from 4 $\mu$m to the maximum of the CO fundamental band strength at 4.6 $\mu$m, where the modeling is severely challenged by the difficulties of the molecular physics and the tenuousness of the solar atmosphere at the height of the temperature minimum where CO is most abundant. Precision JWST/NIRSPEC spectrophotometry of the G stars relative to the WD and A stars should determine the true strength of the CO bands, which will enable better estimates of the SEDs of the G type standards in this region of greatest uncertainty.
5. HD 209458

HD 209458 has a planetary transit that reduces the flux by \(\sim 1.6\%\) (Wittenmyer et al. 2005). However, the length of the transit is only \(\sim 3\) hr from phase \(\sim 0.98\) to 1.02 in the 3.5 day orbital period. The ephemeris is precisely known; and any observation of HD 209458 can be checked for dimming caused by a transit. The STIS and NICMOS observations utilized here are all obtained outside of transit. The precise period is \(P = 3.52247554\) days with an uncertainty of 0.016 s, so that an uncertainty of the time of zero phase is less than 1 minute for 36 years after 2003, when the time of zero phase was measured precisely. The heliocentric phase at any time \(T\) is the fractional part of \((T - T_0)/P\), where \(T_0 = 52, 854.82545\) is the Reduced Julian Date, i.e., with 2,400,000 days subtracted. For example, the STIS observation at 2001 October 28 22:13:24 UT is at \(T = 52221.4260\) JD or at a phase of \(-0.54\), i.e., +0.46. For precise estimates, the difference in light travel time to the Earth instead of the Sun must be accounted. For the ecliptic latitude of 28.7 for HD 2090458, this time difference is in the range \(\pm 7.3\) minutes, i.e., \(\pm 0.001\) in phase.

During secondary eclipse at phase 0.5, Knutson et al. (2008) report flux decreases of 0.09%, 0.21%, 0.30%, 0.24%, and 0.26% at 3.6, 4.5, 5.8, 8.0, and 24 \(\mu\)m, respectively, while Rowe et al. (2006) constrain the planetary flux contribution to \(< 0.01\%\) in the 0.4–0.7 \(\mu\)m band. Thus, the model predictions for the SED of HD 209458 are in error by small fractions of a percent as a function of wavelength due to the contribution from the hot Jupiter planet. Outside of eclipse, Cowan et al. (2007) constrain the variation with phase to be \(< 0.15\%\) at 8 \(\mu\)m.

Also, the temperatures for HD 209458 of 6080 and 6160 K in Table 2 are near those summarized by Wittenmyer et al. (2005), especially the \(T_{\text{eff}}\) value of 6099 \(\pm 44\) K of Fischer & Valenti (2005), who find \(\log g = 4.38\), and [Fe/H] = 0.01. The special model with \(T_{\text{eff}} = 6100\) K and \(\log g = 4.38\) for HD 209458 constructed by Kurucz in 2005 agrees with the best-fit CK04 model to within about 2% longward of 0.4 \(\mu\)m, when the two models are normalized at 0.6–9 \(\mu\)m.

6. THE SUN AS A SOLAR ANALOG STAR

Figure 6 shows the comparison between the solar observations and the models, in analogy with the stellar observations in Figures 2 and 3. The flux of the Sun is from Thuillier et al. (2003, hereafter Th03), where observations from the ATLAS and EURECA missions with the Space Shuttle are referenced to the Heidelberg Observatory blackbody absolute flux standard. Rieke et al. (2008) have adopted the Th03 flux distribution for their solar SED below 2.4 \(\mu\)m. The agreement between the shapes of the observed and modeled SED does not achieve the

\[ \text{http://kurucz.harvard.edu/stars/hd209458/} \]
1% goal, as illustrated in the bottom two panels, where the ThO3 measurements differ from both models by \( \sim 4\% \) near 2 \( \mu \)m. Thus, either the measured ThO3 fluxes or both special solar models have the wrong \( K \) band to \( V \) band flux ratio. The ThO3 uncertainty at 2 \( \mu \)m is quoted as 1.3% in Table III of Th03 but grows to \( \sim 2\% \) in the Conclusions section, which also quotes a 2%–3% uncertainty below 0.85 \( \mu \)m. Thus, an error of 4% in the ratio of the 2 to the 0.55 \( \mu \)m ThO3 fluxes is conceivable. If the ThO3 solar SED does actually have errors as large as 4%, then the \( HST \) SEDs may be more accurate with their estimated uncertainty of 2% in relative flux.

Conversely, if the models have small systematic errors, for example, in the abundances, then somewhat different models will fit the ThO3 fluxes better. In the upper two panels, the best fits from the respective grids suggest that a model with a somewhat lower metallicity may be required for the Sun, i.e., \( \log z = -0.29 \) and \( -0.23 \) for the best fits from the CK04 and MARCS grids, respectively.

At the longer wavelengths, Figure 7 illustrates the ratio of three other candidate solar SEDs to the baseline CK04 model. In the bottom panel, the agreement of the MARCS SED with CK04 is generally within 1%, except in the problematic CO band around 4.6 \( \mu \)m. In the middle panel from 0.5 to 2.4 \( \mu \)m, the comparison with Rieke et al. (2008) is the same as shown for the comparison with ThO3 in the bottom panel of Figure 6, except for the more drastic smoothing. Longward of 2.4 \( \mu \)m, the agreement of CK04 with the model used by Rieke et al. (2008) is excellent, i.e., within the estimated uncertainty of 2%. In the top panel, the comparison is with the best-fit CK04 model from Figure 6. The ratio of this cooler model SED with lower gravity and lower metallicity to the baseline CK04 model rises to 1.06 at 30 \( \mu \)m. Such a large discrepancy as 1.06 seems unlikely given the excellent agreement among the standard CK04, MARCS, and Rieke models longward of 2.4 \( \mu \)m. Thus, the most likely conclusion seems to be that the ratio of the ThO3 flux at 2 \( \mu \)m to the ThO3 flux shortward of 1 \( \mu \)m is too high by \( \sim 4\% \). The only other possibility is that all the models are wrong by a similar amount in their \( V \) to \( K \) band and \( K \) band to 30 \( \mu \)m flux ratios.

7. SUMMARY

Absolute flux standards with spectral types of G are required for \( JWST \) calibration. None of the seven \( HST \) stellar G type stars is a true “solar analog” in the sense that the shape of the SED matches either the ThO3 solar flux measurements or the standard Kurucz (fsunallp) or MARCS solar model to 1% over the whole 0.3–2.5 \( \mu \)m observed range. However, STIS and NICMOS spectrophotometry measure the flux distributions of these seven G stars, which fit CK04 and MARCS model atmospheres from 0.3 to 2.4 \( \mu \)m within an rms scatter of <0.5% in broad wavelength bands. These models are normalized to the \( HST \) SEDs and are used to extend the measured fluxes to longer wavelengths. The seven composite observed plus model SEDs are archived in the CALSPEC database of \( HST \) flux standards\(^5\) as *_stisnic_003.fits*.

Emission from dust rings like the one around Vega often contribute added mid-IR flux; but \( JWST \) observations can identify discrepancy large cases of excess emission longward of 10 \( \mu \)m, if no other mid-IR data are available before \( JWST \) operations begin. A separate paper with additional authors is planned, which will compare the SEDs of some of these G stars and a set of \( HST \) WDs and A stars with the revised \textit{Spitzer} calibration of Rieke et al. (2008).

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\(^5\) http://www.stsci.edu/hst/observatory/cdbs/calspec.html

\(^6\) This STScI internal document can be found at http://www.stsci.edu/hst/nicmos/documents/isrs/.