Data Reduction Notes on the MUSCLES SED for Proxima Centauri

1. Data Extraction

We use archival XMM-Newton and HST data to construct a MUSCLES-like panchromatic SED for Prox Cen. Prox Cen was not observed as part of the MUSCLES Treasury Survey, and the available Prox Cen archival data were taken with observational specifications different from MUSCLES. STIS E140M and G230LB data are used in place of COS G130M, G160M, and G230L and STIS G230L (the LB versus L data use the STIS CCD instead of MAMA detector). There also exist several archival spectra for Prox Cen that extend to substantially longer wavelengths than the MUSCLES observations. These include Faint Object Spectrograph (FOS) G570H and G780H data and STIS G750L data.

The STIS G230LB, G430L, and G750L used an unsupported observing configuration that prevented the automatic extraction of 1D spectra from these data by the CalSTIS pipeline. Thus, we custom-extracted these spectra with CalSTIS v3.4 as directed by the STIS Data Handbook. The resulting G230LB data contained a large number of “dropout” pixels (pixels with either negative or very low flux considering nearby flux and noise levels). We cleaned the spectrum of these dropouts by

1. low pass filtering the data with an exponential filter (>3 dB suppression for signals with 0.02 Å periodicity and lower) to create a “smoothed” spectrum
2. flagging pixels >5-sigma from the low-pass curve
3. iterating 1 and 2 to convergence to create a low-pass curve that approximated the spectral continuum (i.e. that wasn’t biased by the dropouts and emission lines)
4. removing points >5-sigma below the low-pass curve and with S/N < 1 or negative values.

The resulting gaps in the spectrum were later filled with polynomial fits to the surrounding continuum as described in Loyd et al. (2016). We also culled data from G230LB below 2000 Å because fluxes were systematically high and replaced it with a quadratic polynomial fit. Because this gap is very large compared to those made by removing dropouts, it required modification of the quadratic fitting scheme. We fit the quadratic to the E140M data from 1250 Å onward and the G230LB data from 2000 – 2500 Å, with major emission lines removed and, because the gap was abutted by data with much different resolution and S/N, we modified the data errors to be proportional to (pixel width)^-2 for the purposes of the fit.

We corrected the STIS G750L data for IR fringing (also described in the STIS Data Handbook), but possible fringing remained at the red end of the spectrum, so we culled data redward of 9000 Å. The wavelength solutions of the STIS and FOS data differed by several hundred km/s. The
FOS data nearly matched the rest wavelengths of major spectral features, so we shifted the STIS data to match.

The XMM-Newton data were reduced in the same manner as described in Loyd+ 2016 and with more detail in Brown+ 2017 (in prep.).

2. Effective Temperature, Bolometric Flux, and an Appropriate PHOENIX Spectrum

We appended a PHOENIX spectrum with effective temperature, $T_{\text{eff}} = 2800$ K, to the MUSCLES SED for Prox Cen beyond 9000 Å. The $T_{\text{eff}}$ we used is substantially lower than those quoted in the literature, so we provide an explanation of this choice and a discussion of its significance below.

Boyajian et al. (2012) determine a value of $T_{\text{eff}} = 3054$ K for Prox Cen based on a direct measurement of the stellar radius via interferometry (Demory et al. 2009). Other, non-interferometric values published in the literature include

- 3042 K (Ségransan et al. 2003)
- 2900 K (Rajpurohit et al. 2013)
- 2883 K (Gaidos et al. 2014)

We found that a PHOENIX spectrum with $T_{\text{eff}} = 3054$ K showed poor agreement with the HST STIS and FOS visible (4500 – 7000 Å) and near-IR (7000 – 9000 Å) data. A comparison of these spectra, along with PHOENIX spectra for other $T_{\text{eff}}$ values to be discussed, is shown in Figure 1. A key difference to note is the disagreement in the overall slope of the spectra. Similar disagreements between HST data and PHOENIX spectra using literature $T_{\text{eff}}$ values were found for the MUSCLES stars (Loyd+ 2016), motivating us to directly fit PHOENIX spectra to literature photometry in that work. We used the same process for Prox Cen and found a best fit $T_{\text{eff}}$ of 2752 K. We used photometry from Girard et al. (2011); Zacharias et al. (2013); Cutri et al. (2003); Soubiran et al. (2016); Anglada-Escudé & Butler (2012); de Bruijne & Eilers (2012); Neves et al. (2013); Hosey et al. (2015); Gaidos et al. (2014).

We also used the HST STIS and FOS spectra from 4500 to 9000 Å to constrain the PHOENIX model $T_{\text{eff}}$. We found the minimum $\chi^2$ value was achieved for $T_{\text{eff}} = 2691$ K. This fit was independent of literature photometry. Thus, it supports the conclusion that the higher $T_{\text{eff}}$ values reported in the literature produce poor fits when used to select a PHOENIX model from the Husser et al. (2013) grid of models used for MUSCLES. We note, however, that we have not attempted to determine whether the source of this issue is the models or the literature $T_{\text{eff}}$ value. The majority of the STIS and FOS visible and IR data for Prox Cen overlap, and the excellent agreement between the spectra.
Fig. 1.— A comparison of HST data with PHOENIX spectra of various $T_{\text{eff}}$ all normalized such that the integrals in the displayed range are identical to that of the HST data.
in this overlap serves as evidence against the possibility that the disagreement between \( \sim 3000 \) K PHOENIX models and the data is due to systematic errors in the data, unless such errors equally affected both the STIS and FOS data, taken nearly 20 years apart.

The choice of \( T_{\text{eff}} \) is significant because it has a strong effect on the bolometric flux of the spectrum. We found that varying \( T_{\text{eff}} \) between 2700 and 3050 K and using two normalization methods for the resulting PHOENIX model, either normalizing to the STIS and FOS data or the literature photometry, produced a factor of three range in bolometric flux. Differences between the two normalization methods were as large as 50%. Factor of three differences in observed flux from Prox Cen result in 30% variations in the calculated equilibrium temperature of orbiting planets, which has major ramifications for the inferred habitability of systems like Proxima b.

We chose to use a PHOENIX spectrum with \( T_{\text{eff}} = 2800 \) K for the Prox Cen SED released with v2.0 of the MUSCLES spectra. This \( T_{\text{eff}} \) results in a bolometric flux of \( 3.17 \times 10^{-8} \) erg s\(^{-1}\) cm\(^{-2}\) when normalized to the STIS and FOS data and \( 2.68 \times 10^{-8} \) erg s\(^{-1}\) cm\(^{-2}\) when normalized to photometry. In comparison to other values for \( T_{\text{eff}} \), this produces a model that fits the data well and compares favorably with the Boyajian et al. 2012 bolometric flux of \( 2.961 \times 10^{-8} \) erg s\(^{-1}\) cm\(^{-2}\). Further, the discrepancy between the two normalization methods is less for this than for other values of \( T_{\text{eff}} \). It is also worth noting that Prox Cen has been deemed an M5.5 star (Bessell 1991), for which Rajpurohit et al. (2013) derive a nominal \( T_{\text{eff}} \) of 2800 K, although they specifically report a \( T_{\text{eff}} \) of 2900 K for Prox Cen.

For the final data product, we normalize the PHOENIX spectrum such that it produces an integrated flux (a few percent below the final computed bolometric flux due to the limits of the spectrum) of \( 2.95 \times 10^{-8} \) erg s\(^{-1}\) cm\(^{-2}\).

**REFERENCES**


Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, 2246


