ASTR350L Lab 1 Solutions Write-Up Example

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1 Hua

Measuring the physical properties of stars is fundamental to a deeper understanding of their formation mechanisms, their physics, their evolutionary stages, and the structure of the Milky Way itself [Speagle et al., 2025]. Stars have been known for many years to demonstrate a great diversity in luminosities, radii, and temperatures [e.g., Russell, 1913], and precise measurements of these properties can be used to measure both large effects, such as location in the giant branch or white-dwarf cooling track [Althaus et al., 2022], or subtle effects including stellar metallicities, infrared dust emission, and white dwarf ages and equations of state [e.g., Katushkina and Izmodenov, 2019].

Stellar spectral energy distributions (SEDs) can be broadly approximated by the assumption of black body radiation, an idealized model assuming that all radiation produced by the star has been absorbed and reradiated. However, as stars become cooler or higher in metallicity, they begin to produce additional line fluxes, including molecular bands, that strongly deviate from the black-body assumption [Hauschildt et al., 2002].

In recent years, precision measurements of spectral properties have become increasingly important for characterizing the host stars of exoplanets. These can be used to measure the incident UV radiation on planetary atmospheres and the resulting suitability of that planet for life [Huseby et al., 2025], measure the planetary atmosphere via transmission spectroscopy for planets in a transiting configuration [Perdelwitz et al., 2025], and understand accretion and dust attenuation in young stellar systems [Saral et al., 2017]. Variability of stellar photometry can characterize stellar interiors, including convection zones, as well as pulsational modes (see Kurtz, 2022 for a review).

In this lab we infer stellar properties — luminosities, temperatures, and radii — by performing a black body fit to optical-to-infrared photometry. We choose as our sample six stars with a wide range of evolutionary stages. We use these properties to classify each star, gain a better understanding of the diversity of stellar systems, and draw inferences regarding the characteristics of each distinct evolutionary stage. Additionally, we will use these data to understand the ways in which stellar atmospheres deviate from a standard black-body assumption and therefore better understand the physical regimes in which photometry can be used to derive stellar properties, versus those in which spectroscopy is needed.

2 Haʻalele

We analyze stellar photometry for five stars: Aua (Betelgeuse), Ka ʻonohi ali'i (Procyon), Hiku lima (Alioth), Hoku kau ʻopae (Rigel), and Ka maile hope (Alpha cen A). Our data were drawn from the SIMBAD astronomical database and the Wide-field Infrared Survey Explorer (WISE) satellite.

The SIMBAD astronomical database [Wenger et al., 2000] is a compilation of astronomical data and metadata for millions of astronomical objects, including most well-studied stellar sources. Its photometry is compiled from various literature sources, which we detail below:

Figure 1: Optical to infrared data from Aua (Betelgeuse from Johnson et al. [1966] and WISE.

- Aua: Measurements were taken by Johnson et al. [1966], who measured stellar photometry for hundreds of nearby bright stars in *UBVRIJH* filters. Observations were made via telescopes at the Lunar and Planetary Laboratory, and using the Tonanzintla Observatory 40-in telescope.

- Ka ‘onohi ali’i: Photometry is from the *Hubble Space Telescope*’s Wide Field and Planetary Camera 2 [Provencal et al., 1997] using filters approximately equivalent to *UBVRI*. Data were processed using HST pipeline calibration routines in STSDAS, and measured with aperture photometry via IRAF [Tody, 1986].

The remaining three stars had a compilation of 11-band Johnson photometry from [Ducati, 2002]. Infrared data in Ducati [2002] were originally assembled in the NASA infrared catalogs. Note: ideally we’d have slightly more information for these three stars, but this was pretty difficult to dig up.

The WISE satellite [] was a 40-cm space telescope that conducted an all-sky photometric survey in near to mid-infrared bands beginning in 2009. WISE photometry was measured using fitting to stellar point-spread functions (PSFs) and is made available via the NASA/IPAC infrared science archive.

Figure **??** shows the data for Aua as a representative example of our dataset from optical to NIR.

3 Huakaʻi

To measure stellar temperatures, radii, and luminosities, we first converted from Vega magnitudes to physical units. AB corrections were computed from the difference between Vega’s spectrum versus a spectrum with flat spectral flux density integrated over each filter, and here we use those calculations from two separate databases[1]. From the AB system, we converted to Jansky and then to units of erg s^{-1} cm^{-2} Å^{-1} for comparison to the wavelength-dependent version of Planck’s law.

We then fit Planck’s law to our data for each sta using a Levenberg-Marquardt algorithm as implemented in `Scipy`. The Levenberg-Marquardt algorithm solves nonlinear least squares problems by interpolating between a Gauss-Newton procedure — which minimizes a sum of squares — and a gradient descent method, which takes repeated steps opposite of the gradient of the function, in order to minimize the derivative. The Levenberg-Marquardt routine is more robust than alternative minimization algorithms to local minima.

From the Planck fit, we then integrate over the best-fit black body curve and use the inverse square law to derive the luminosity. Distances are from the Hipparchos satellite, which measured precision stellar astrometry to derive parallaxes and proper motions of thousands of nearby stars – and were queried via SIMBAD.

Lastly, we use the Stefan-Boltzmann law to derive radii for each star.

4 Hoʻina

Parameter results for each star are given in Table **??**. For each, we compare to literature measurements in the final column, finding agreement at the level of 10-20% accuracy.

The significant diversity among luminosity and radius demonstrates that these stars span three distinct evolutionary stages: the main sequence, where stars spend the majority of their lifetimes, the giant branch, where stars have evolved following their main-sequence lifetimes and in which they burn heavier elements than Hydrogen, and the white dwarf cooling track, where the hot, earth-sized stellar remnant is supported by electron degeneracy pressure (for a review of stellar evolutionary stages, see Silva Aguirre, 2018).

[1] `https://www.astronomy.ohio-state.edu/martini.10/usefuldata.html` and `https://irsa.ipac.caltech.edu/data/WISE/docs/release/All-Sky/expsup/sec4_4h.html` for ground-based/optical and WISE data, respectively.

The stars analyzed here are representative examples of each of these three classes:

- **Main-Sequence Stars:** Hiku lima and Ka maile hope are main-sequence stars with spectral types A1 and G2, respectively. Ka maile hope is consistent with a typical stellar radius of approximately solar, but we find that Hiku lima is inflated by a factor of two compared to typical A-type stars, which have radii ∼2 times solar [Shallis and Blackwell, 1979]. It is likely that the star's strong magnetic field or known photometric variability is due to significant pulsations in the star [Babu and Shylaja, 1983].

- **Giant Stars:** ʻAua and Hoku kau ʻopae are giant stars; ʻAua is a red giant, while Ka maile hope is a blue supergiant. The contrast between the colors of these two stars are indicative of their different masses, with Ka maile hope being significantly more massive [Moriya and Menon, 2024].

- **White Dwarfs:** Ka ʻonohi aliʻi (B) is a white dwarf, the remnant of a solar-mass star, with radius similar to an earth radius and typical of white dwarf radii at ∼1-2% solar [Provencal et al., 1997].

Comparisons to classmates show dispersion at the level of 10-20%, likely due to inclusion of WISE data, removal of photometric outliers, and alternative choices in fitting methodology or algorithm. In general, we found that the identification of stars as white dwarfs, giant branch, or main sequence was robust across the class results, while measurement of spectral subtypes might not be possible given our current level of precision.

5 Hāʻina

The primary assumption made in this analysis is the treatment of our stars as a perfect black body. For hot main-sequence stars and white dwarfs, this is typically an accurate assumption, but in the case of Hiku Lima, the chemical peculiarity of this star may have caused additional uncertainties; accordingly, our results differed from literature values by x% in this case [Baines et al., 2023].

Additionally, incompleteness of our photometry caused additional uncertainties in some cases. For the bluest stars, ultraviolet photometry would have better constrained the declining slope of the Planck function, while for the brightest stars some of the WISE or SIMBAD photometry may have been saturated; significant outliers in the case of Betelgeuse in particular were inconsistent with typical black-body curves. Lastly, the accuracy of photometric calibration for our older sources (e.g., Johnson et al., 1966) may have been erroneous at the level of a few percent or more.

Several sources were also known binaries; while most photometry were likely dominated by the source of interest, it is possible that the fainter binary companion could have biased our results at the few-percent level.

Notably, the deviations from black body curves are sensitive to spectral type. While white dwarfs are known to be relatively accurate black bodies [Suzuki and Fukugita, 2018], although they do have significant gravitationally broadened absorption features, cooler main-sequence stars and giant branch stars contain broad molecular features in their atmospheres that deviate significantly from black bodies at the level of ∼10s of percent. Additionally, ʻAua has occluding dust attenuation that was not accounted for in this analysis [Cannon et al., 2023], causing excesses in the WISE band and systematically reducing the calculated luminosity in the optical bands.

In this analysis, we have measured basic stellar parameters at 10-20% accuracy, and highlighted cases in which photometric analysis is insufficient for precision studies of these properties. However, with more sophisticated modeling of stellar atmospheres, it is likely that the precision of these measurements could approach the few-percent level.

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