Determination of Stellar Spectral Classes

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1 Abstract

This project was to determine and verify spectral classes of pre-determined stars. Using a telescope, UVBIR filters, a filter wheel, and a CCD. Data was collected on two stars, and than run through a Python script. The script calculated Light Extinction, the theortical Planck's Black-Body radiation curve, and the data, with a scale factor, was plotted to create a Black-Body diagram was used to analyze the data.

2 Introduction

Black-bodies are objects that emit light simply by being at a temperature, T, above absolute zero. The radiation from the emitted light is called black-body radiation. A black-body emission spectrum is shown in Figure 1. Black-body's surface temperature, T, as it emits energy in all wavelengths with a peak at λ_{max}. [2]

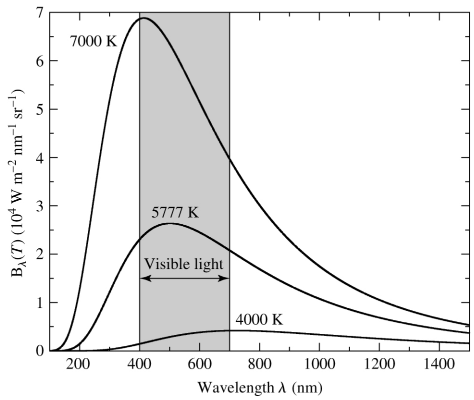

Figure 1: Black-Body Spectrum [2]

T and λ_{max} are inversely related. That means λ_{max} is also inversely related to the star's intensity. This is worth studying because the peak in visible light is how astronomers can classify stars, with Hertzsprung-Russell (H-R) diagram as shown in Figure 2 [2].

The mission of this project is to:

1. To acquire & assemble the equipment required to attempt this project
2. To develop an analysis program to compare data to a Planck Black-Body Diagram
3. Acquire some data for proof-of-concept, so that a later capstone student will be able to get accurate data with little to no restarts.

The surface temperature can be found online. Once temperature is known, λ_{max} can then be calculated before measurements are taken. The calculated λ_{max} will be compared to develop simulated data to compare to the expected data. [2].

3 Theory

Maxwell was the first to realize that light was an electromagnetic wave. [1] In 1884 Joseph Stephan and Ludwig Boltzmann derived the Stephan-Boltzmann equation by using thermodynamics and Maxwell's radiation pressure formula. Assuming the black-body is a perfect sphere with the radius R and surface area of $A = 4\pi R^2$, their equation for luminosity of a black-body became:

$$L = 4\pi R^2 \sigma T_{eff}^4 \tag{1}$$

Because nothing is a perfect black-body T_{eff} is the *effective temperature* of the star. [2]

Planck later discovered that light behaved like a particle. With this assumption, he derived

$$E = h\nu \tag{2}$$

where E is the energy of the photon, ν is the electromagnetic radiation, and h is Planck's Constant which is equal to $6.63 * 10^{-27}$ egr*s. [3]

In 1918, Planck used this new theory to describe the radiation of a black body. Assuming the object ideally follows the laws of thermodynamics, Planck could also assume that the electromagnetic energy of an object is carried by photons. [3]

Following this discovery, Planck then found the relationship of temperature, T, and the radiation intensity given off per volume in frequency, ν,

$$B_\lambda(T) = \frac{\frac{2hc^2}{\lambda^5}}{e^{\frac{hc}{\lambda k_b T}} - 1} \tag{3}$$

with c being the speed of light constant and k being Boltzmann's Constant $(1.38 \times 10^{-16} \frac{erg}{K})$. This equation only works with an ideal black-body, *i.e.* the star is emitting all of its radiation, not absorbing it. Equation 4 later became known as *Plancks's (Black-body Radiation) Law.* [3]

Using a black-body's spectrum, the peak wavelengths, (λ), can be determined using *Wein's displacement law*:

$$\lambda T = 0.002897755 \text{ m K}. \tag{4}$$

To solve for λ equation 9 can be rewritten as:

$$\lambda = \frac{0.00289755}{T} \tag{5}$$

[2]

By knowing the radius and luminosity of the black-body, the effective temperature, T_{eff}, can be found and double checked using an encyclopedia or online trusted database. Then using Wein's displacement law (equation 5) the theoretical λ_{max} can then also be derived. Using a detector and UVBIR filters the actual λ_{max} will be found by using a python script. The transmission grading spectrum of the lenses, as shown in Figure 2, was used to determine the scale factor. Equation 3 was integrated through each filters wavelength to get the stars flux in each filter.

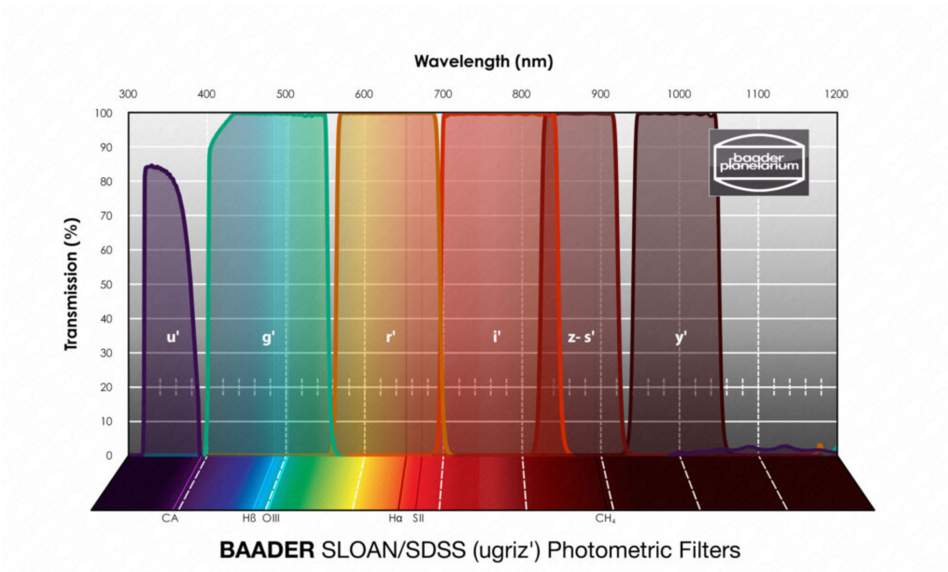

Figure 2: Transmission Grading spectrum of the Lenses [5]

A graph will be created in python to create a black body radiation curve. That curve will then be compared to the known black-body radiation curve to find any correlation.

Light (or atmospheric) extinction due to air mass is when the brightness of a black-body is reduced as its photons pass through the atmosphere. The effects of light extinction depend on transparency, the altitude of the telescope, the zenith angle, and the angle from the zenith to the telescopes line of sight. The higher the zenith angle, the more atmosphere the light from the black-body must pass through, making the black-body's brightness decrease. That equation is shown below. [4]

$$x = \frac{1}{\cos(z) + 0.0025e^{-11\cos(z)}} \tag{6}$$

with x, being the the number of air masses overhead at z, the zenith angle. [4]

4 Methods

Two stars were used for this capstone based off of their magnitude, right ascension, and declination based on Christopher Newport University's location, as well as if they would be in the winter and spring sky. The two stars that were chosen are:

1. Betelgeuse
    - Magnitude: 0.5
    - Right Ascension: $5^h55^m10.3^s$
    - Declination: $7°24'25"$
2. Capella
    - Magnitude: 0.08
    - Right Ascension: $5^h16^m41.4^s$
    - Declination: $45°59'53"$

A CSV file of "The Magnitude 5 Star Catalogue" [6] was used to determine the stars qualifications mentioned above. The items used in this project are:

1. Telescope
2. 12 Volt Lead Acid Battery
3. ZWO - EFW Mini (5 x 1.25" or 5 x 31mm) Five-Position Filter Wheel - 1.25"/31mm - EFWMINI
4. Baader - SLOAN/SDSS (ugriz) Filterset 1.25" - photometric
    (a) g' filter
    (b) r' filter
    (c) i' filter
    (d) z'-s' filter
    (e) y' filter
5. Orion StarShooter G4 Cooled Monochrome Deep Space Imaging Camera

(a) 10' USB cable

(b) 10' 12V DC power cable

(c) Orion Camera Studio software download card

(d) Camera Studio (for taking pictures and gathering data)

6. 12V Sealed Lead Acid (SLA) Battery Charger 1300mA, with Short Circuit Protection

7. RoadPro RPPSAPS 12V Battery Clip-On and Cigarette Lighter Adapter

8. Windows laptop with two USB ports

9. Electrical tape

On a clear night, the telescope and equipment was taken out to Luter Lawn. After the telescope was aligned, all of the equipment was set up, and data was taken. The next morning, The data was then run through the python script to analyze it.

5 Results

Table 1: Betelgeuse Data Table

Camera Data						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	**Altitude**
night 1	47988	49777	48997	7163	24066	40
night 2	47127	47902	48462	47876	5266	34
night 3	47450	48075	65535	15614	6675	30.75
Flux Calculations						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
	-55316.12155	4447.382091	6633.917676	7138.664314	7138.664314	
Scale Factor						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
	102443.1216	43454.61791	41828.08232	40737.33569	-1872.664314	
Scaled Data						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
night 1	150431.1216	93231.61791	55630.91768	47900.33569	22193.33569	
night 2	149570.1216	91356.61791	90290.08232	88613.33569	3393.335686	
night 3	149893.1216	91529.61791	107363.0823	56351.33569	4802.335686	

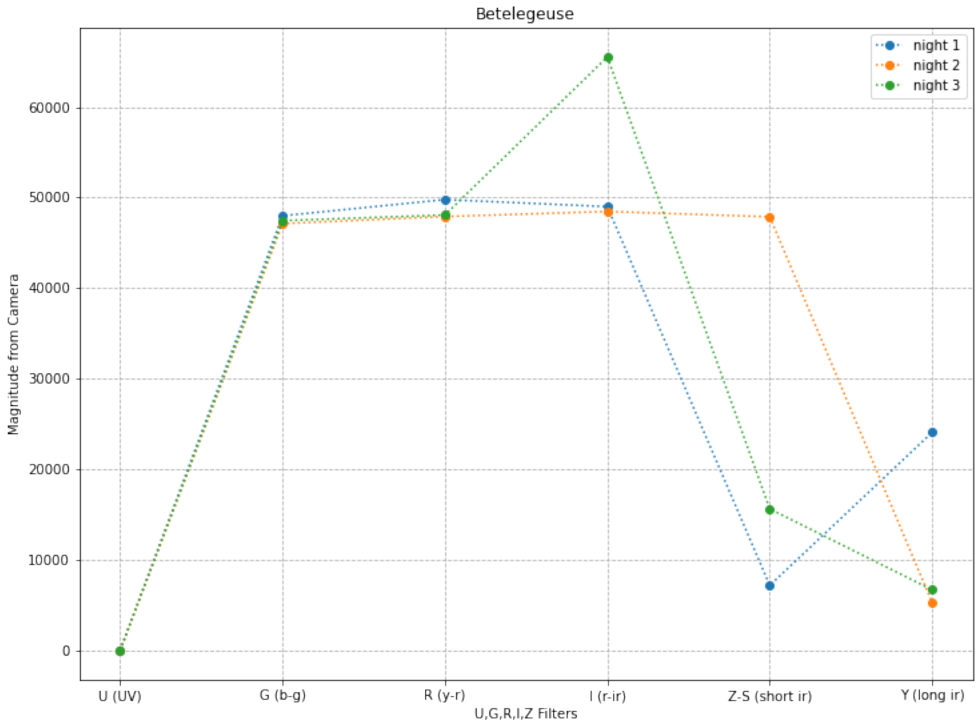

Figure 3: Betelgeuse Data Graph Before Scale Factor

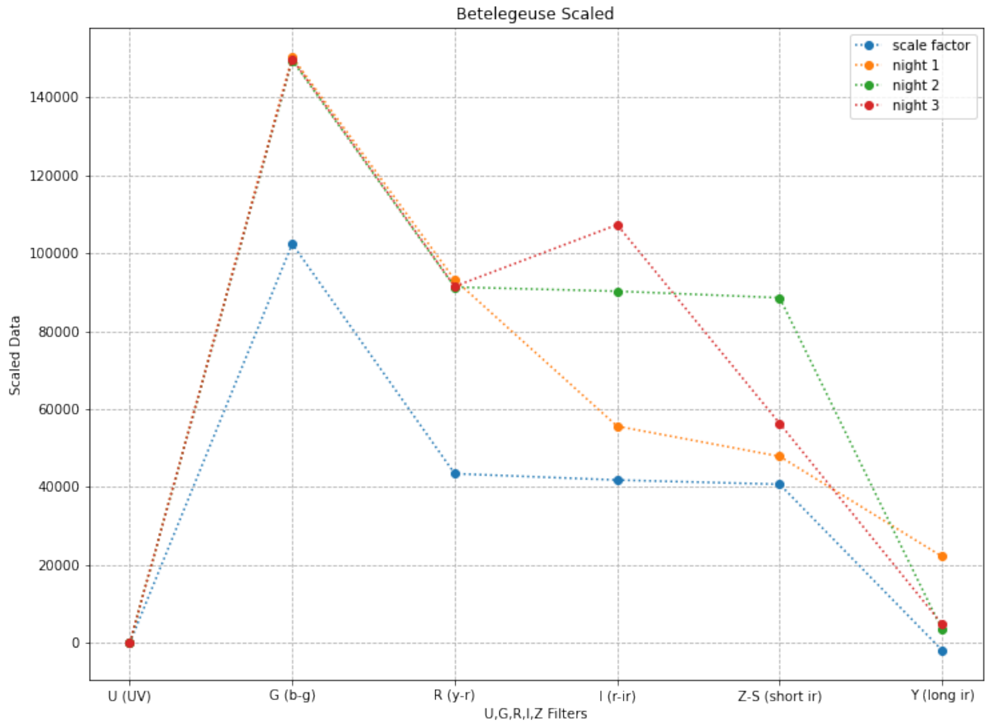

Figure 4: Betelgeuse Data After Scale Factor

The light extension due to air mass for Betelgeuse on each night is:

- Light Extinction on Night 1 = 0.3154
- Light Extinction on Night 2 = 0.0364
- Light Extinction on Night 3 = 1.2717

Table 2: Capella Data Table

Camera Data						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	**Altitude**
night 1	4733	26338	25272	3519	266	47.75
night 2	47921	47727	42157	5391	814	40.5
night 3	57169	47971	48297	11826	6168	38
Calculations						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
	1118392.811	39565.74431	37294.6514	31263.17209	31263.17209	
Scale factor						
	g' filter	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
	1166313.811	8161.255687	4862.348603	-25872.17209	-30449.17209	
Scaled Data	**g' filter**	**r' filter**	**i' filter**	**z-s' filter**	**y' filter**	
night 1	1171046.811	34499.25569	30134.3486	-22353.17209	-30183.17209	
night 2	1214234.811	55888.25569	47019.3486	-20481.17209	-29635.17209	
night 3	1223482.811	56132.25569	53159.3486	-14046.17209	-24281.17209	

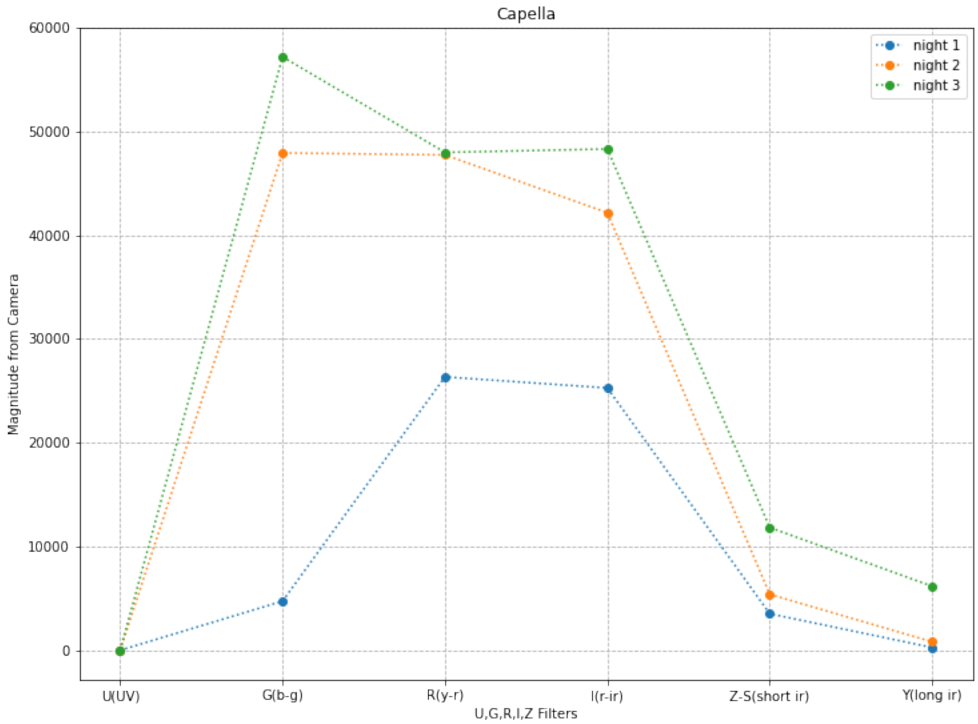

Figure 5: Capella Data Graph

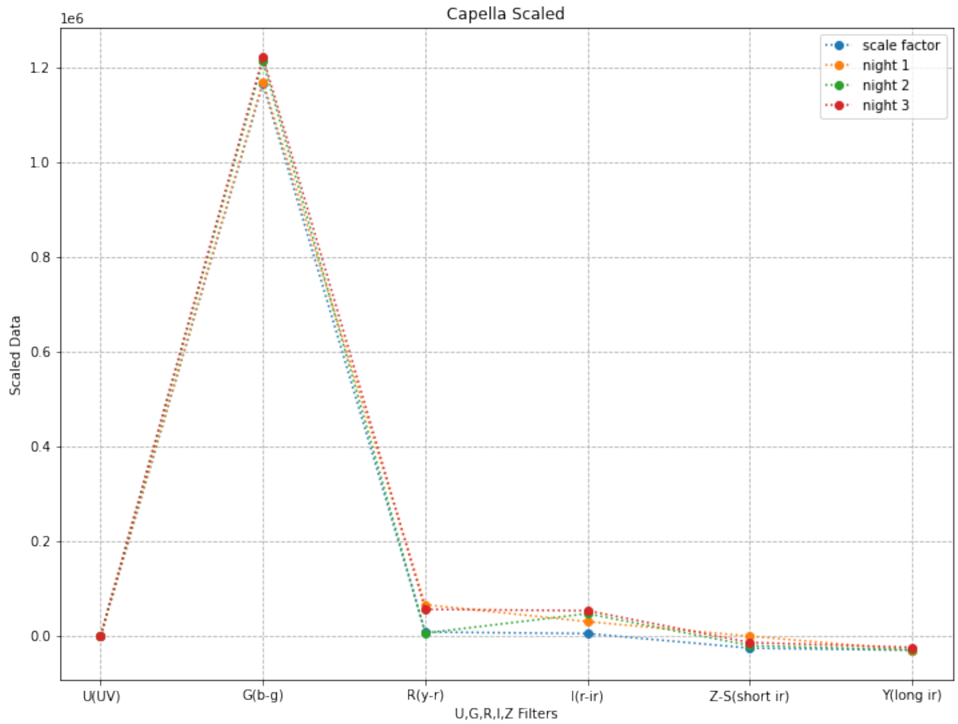

Figure 6: Capella Data After Scale Factor

The light extinction due to air mass for Capella on each night is:

- Light Extinction on Night 1= 0.0563
- Light Extinction on Night 2= 0.0127
- Light Extinction on Night 3 = 1.047

6 Discussion and Analysis

6.1 Analysis

To create some correlation between 16 bit pixel values and wavelength a scale factor had to be created. That was found by integrating equation 3 through each filters wavelengths to get the stars flux. The data for night 2 (it was closest to the theoretical fit) was subtracted from the flux to create the scale factor. That scale factor was then added to each data point to create the scaled factor. As you can see, the g' filter had a negative flux for Betelgeuse. Integrating its Planck's distribution with a delta function ($\sum f(\lambda)T(\lambda)\Delta(\lambda)$) to take into account the transmission percentage, is once source of error I could not solve. Humidity, background noise in the camera, as well as possibly over-saturating the CCD are all points of error that, if more time was available, would have been looked into.

6.2 Setbacks and Resolutions

If this project was to be repeated, getting a new camera that works with the same application so that date collection can run much more smoothly. Another is to learn how to used the tracker on the camera so that the telescope does not need to be realigned every few minutes to keep the star in view. Recording the humidity of each night and getting a bigger filter wheel so that there is an empty spot would also make things run much more smoothly. Another is figuring how to get the CCD and filter to recognize a lower magnitude star.

The last and biggest suggestion, is making this a two person capstone. The telescope not only requires two people to set it up, but there are many moving parts of this project, as well as some tricky coding. Having a second person to help with both the execution and analysis would make this project much more smooth.

6.3 Conclusion

Even though there are still many things to work on in the analysis and error reduction, this capstone still accomplished this main missions.

References

[1] Stephen Blundell and Katherine M. Blundell. *Chapter 23: Photons*, page 247–261. Oxford University Press, 2019.

[2] Bradley W Carroll and Dale A Ostlie. *'An introduction to modern astrophysics; 2nd ed.'*. Addison-Wesley, San Francisco, CA, 2007.

[3] Leslie M. Golden. *Experiment 17 Blackbody Radiation*, pages 473–498. Springer New York, New York, NY, 2013.

[4] Mike Luciuk. Atmospheric extinction and refraction.

[5] Team Baader Planetarium. Now available: New baader ubvri and sloan/sdss (ugriz') photometric filters, Oct 2021.

[6] John Pratt. The mag 5 star catalog, Dec 2015.