

## Hertzsprung-Russell Diagram

### Introduction

The purpose of our project is to observe a star cluster, analyze the images, and create a Hertzsprung-Russell diagram from the resulting data. We chose to observe the Double Cluster, the Eagle Nebula, and the Little Beehive Cluster. These objects are also referred to as Caldwell 14, Messier 16, and Messier 41 respectfully. Each object will be imaged with two different filters. The images will then be analyzed to determine the number of visible stars, their locations in the frame and their brightness's. These values will then be calibrated and compared to give us the visible magnitudes of the stars and their colors. By plotting these values, we will create a Hertzsprung-Russell diagram. These diagrams will give us an idea as to the types of stars in the clusters and where they might be in their life cycles.

### Historical Background

The Hertzsprung-Russell diagram, often referred to as the HR diagram, is one of the most useful plots in astrophysics. The plot depicts the relationship between the luminosity or magnitude of stars versus their effective temperature or spectral class. This plot was first explored by a Danish astronomer named Ejnar Hertzsprung in 1911. He chose his axes to be the color versus the absolute magnitude of the stars. Two years later, American astronomer Henry Russell created a similar plot which compared spectral class and luminosity. Both scientists noticed something interesting happening with their plots. The stars seemed to fall into distinct curves and groups. The most prominent grouping was what we call the main sequence. This

group contains the largest variety of temperatures and brightness's. The main sequence consists of stars that are still fusing hydrogen into helium. Most stars spend the majority of their life fusing hydrogen and thus spend the most time in the main sequence. Above the main sequence are two groups which contain brighter cooler stars better known as red giants and supergiants. These are just stars which fuse heavier elements. The last obvious group on the diagram houses the white dwarfs. This group can be found in the lower left side of the plot due to the star's high temperatures and low luminosities. This diagram gave the astrophysics community a glimpse into the life cycle of stars. It indicates the effects of fusion processes on the brightness and colors of stars.

### Larger Context

The invention of the Hertzsprung-Russell diagram provided very valuable insight into the lifecycle of stars. The diagram itself shows that there is a correlation between the temperature of a star and its luminosity. The relation appeared to be somewhat complex, with the stars falling into a number of separate groups. Upon further investigation it became obvious that the mass of a star plays a role in what groups said star appears in. Our sun, and stars that are less than eight solar masses have a different life cycle than their more massive counterparts due to the type of fusion that occurs within them. These smaller stars only support one kind of nuclear reaction the proton-proton chain which fuses hydrogen into helium. Once a low mass star begins to run out of hydrogen, fusion in the core ceases and the helium shell collapses inward. It is at this point that the star is no longer in its main sequence. The collapse of the helium shell produces energy which sparks fusion but this time it occurs in both the shell and the core producing more heat than it did previously. This change causes the outer atmosphere to expand and cool thus turning the star

into a red giant. The core of the star continues to contract and becomes degenerate, exerting a pressure outward because the electrons refuse to be forced any closer to one another. At this point a large amount of helium in the core gets hot enough to fuse into carbon. This occurs in a matter of seconds and is thus called the helium flash. Once the flash is over, core helium fusion stabilizes, the star's luminosity decreases, and the outer layers begin to shrink towards the core. This period of stability is known as the horizontal branch of the life cycle. Eventually the core runs out of helium to fuse but is not hot enough to fuse carbon. Once again, the outer layers of the star begin to contract and produce thermal energy. This causes the helium in the shell to begin fusing to carbon and the hydrogen in the shell beyond that to begin fusing to helium. All of this fusion pushes the star into its second red giant stage when the atmosphere of the star expands and cools becoming redder again. As the helium shell continues to fuse to carbon it does so in bursts that eject the lighter layers outward creating a planetary nebula. All that is left behind is the carbon core which is known as a white dwarf (Aguirre,2017). Initially the core is still so hot that it burns a bright blue color, but over a period the star will begin to lose its luminosity and cool to a red color.

This life cycle is very different for a high mass star, that is stars which have a mass over five solar masses. Although large mass stars have much more fuel than their low mass counterparts, they burn through that fuel much faster and thus have shorter life spans. This means they spend less time in the part of their lives known as the main sequence. Just like low mass stars, high mass stars leave the main sequence once they have fused all the hydrogen in their core into helium. Once a high mass star begins to run out of hydrogen, fusion in the core ceases and the helium shell collapses inward. It is at this point that the star leaves the main sequence and enters the

horizontal branch. The collapse of the helium shell produces energy which sparks fusion but this time, rather than the helium in the core fusing to carbon quickly in a “helium flash” like a low mass star, the triple-alpha process begins gradually. This collapse and subsequent fusion of helium in the core causes the star’s atmosphere to expand outward causing it to become a red supergiant. From this point on the life of a high mass star diverges from that of its low mass counterparts. The fusion of elements in the core will not stop at carbon. High mass stars burn much hotter and thus can continue to fuse heavier elements each time the core runs out of the element it is currently fusing the outer layers collapse inward and spark the fusion of the next element. This continues on as the core fuses the carbon, oxygen, neon, silicon. Each successive element produces less energy upon its fusion and thus is burned through much faster than the last. Once the core has fused to iron the iron begins to photo disintegrate. This reaction where the iron releases a photon, protons and helium nuclei produces less energy than it absorbs. This causes the outward pressure in the core to drop, and subsequent high speed core contraction and raised core temperature. Now the core’s electrons which maintain its degeneracy pressure begin to react with the protons produced by the iron photodisintegration and cause the core to contract further. This continues until neutron degeneracy pressure puts a stop to it. Although the core stops contracting, all of the outer layers do not. When the layered material slams into the solid core it rebounds outward in a massive shockwave that is known as a supernova.

These different states and stages in a star’s life are all visible on an Hertzsprung-Russell diagram. To the untrained eye the diagram simply shows brightness and color, but for those who know what they’re looking for it predicts mass, age and what is happening in it’s core.

## Object Information

The first object we attempted to image was an open cluster in the Perseus constellation named the Double Cluster or Caldwell 14. The two clusters that make up the Double Cluster are NGC 869 and NGC 884. Caldwell 14 itself has a magnitude of They sit quite close together with only These clusters are only about 14 million years old which is quite young when compared to the clusters that surround it which are all over five times it's age (Currie, 2010).

The Little Beehive Cluster, also known as Messier 41, is an open cluster located just four degrees south of Sirius, the north star (Kambic, 2009). It is roughly 2,300 ly away from earth and is approximately 190 million years old.

The Eagle Nebula, or Messier 16, houses a very young open cluster of stars that can be found in the Serpens constellation (Burnham, 1978). It is a distance of approximately 5,700 ly from Earth. Some of the stars in the Eagle Nebula are less than 3 million years old which is unsurprising considering the massive amount of star-forming dust (Hillenbrand, 1993).

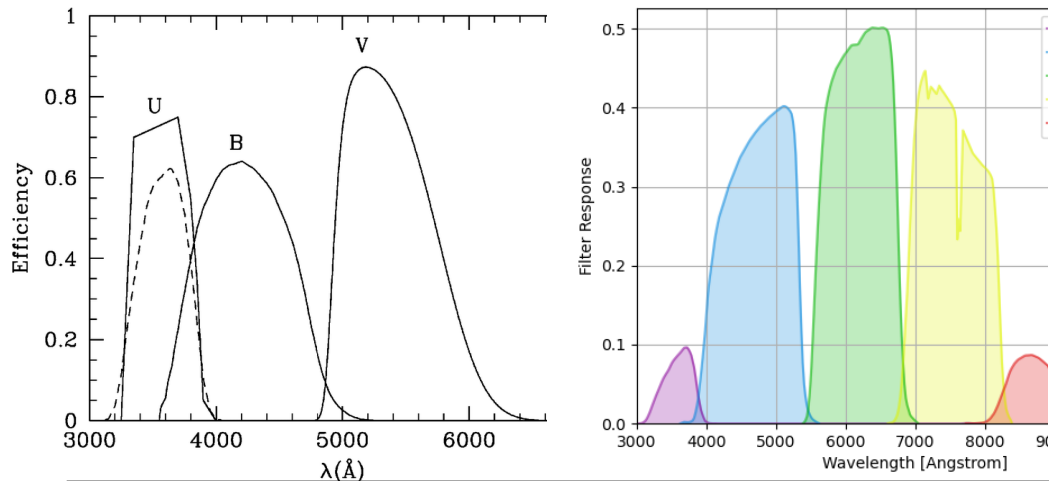
The Little Beehive Cluster is an open cluster in the constellation Canis Major. It is almost exactly  $4^\circ$  south of the star Sirius (Kambic, 2009). The cluster contains several red giants, the brightest of which is the star HIP 32406 (HD 49091) (Stoyan, 2010). The star cluster is estimated to 190 million years old and has the expected lifespan of 500 million years (Stoyan, 2010).

## Data Collection

All of the imaging we have done for our HR diagrams has been through the Las Cumbres Observatory on a 0.4-meter telescope with a SBIG STL-6303 imaging device. The SBIG STL-6303 has a field of view which is 30 by 20 arc minutes (Brown, 2013). Before receiving any of our

images they were processed through the BANZAI pipeline. This just means they were put through a series of calibrations to improve quality (Brown, 2013). We took images of the objects in six different filters. Initially Aaron and I planned on using the Double Cluster as the main focus of our HR diagram project but upon comparing reference stars in the cluster to our photos we realized the image only captured half the cluster. This seemed fine considering the Double Cluster is made up of two separate clusters, NGC 869 and NGC 884, and we just happened to fully capture NGC 869. It wasn't until we got into the analysis of the cluster that we ran into some problems. At that point we decided to choose some new objects, the Eagle Nebula, also known as Messier 16, as well as the Little Beehive Cluster or Messier 41. We attempted to take Bessel-B and Bessel-V filtered photos for both objects. To ensure that we obtained a good quality image for each filter we had 10 images taken per filter. We were easily able to obtain the Bessel images for the Little Beehive Cluster but when we went to take images for the Eagle Nebula we quickly realized that it was no longer in view at this time of year. Luckily earlier in the term Aaron and I took SDSS filtered images of Messier 16 while it was still visible to produce colored images of the nebula. While the Bessel filters are more useful when it comes to creating an HR diagram, we figured it would still be worth it to attempt building an HR diagram using the SDSS-r and SDSS-g filters. The only relevant filters for this project are the Bessel-V, Bessel-B, SDSS-r, and SDSS-g filters, although we also have SDSS-u and SDSS-i images for Messier 16. Bessel-B spans a wavelength of light from around 375 to 575 nanometers which is violet through green light with its peak in blue. Bessel-V has a wavelength range from about 475 to 650 nm which is blue through more yellow/orange light. The SDSS filters are a bit different. SDSS-g ranges from about 400 to 550 nm which is violet through green light and SDSS-r ranges from

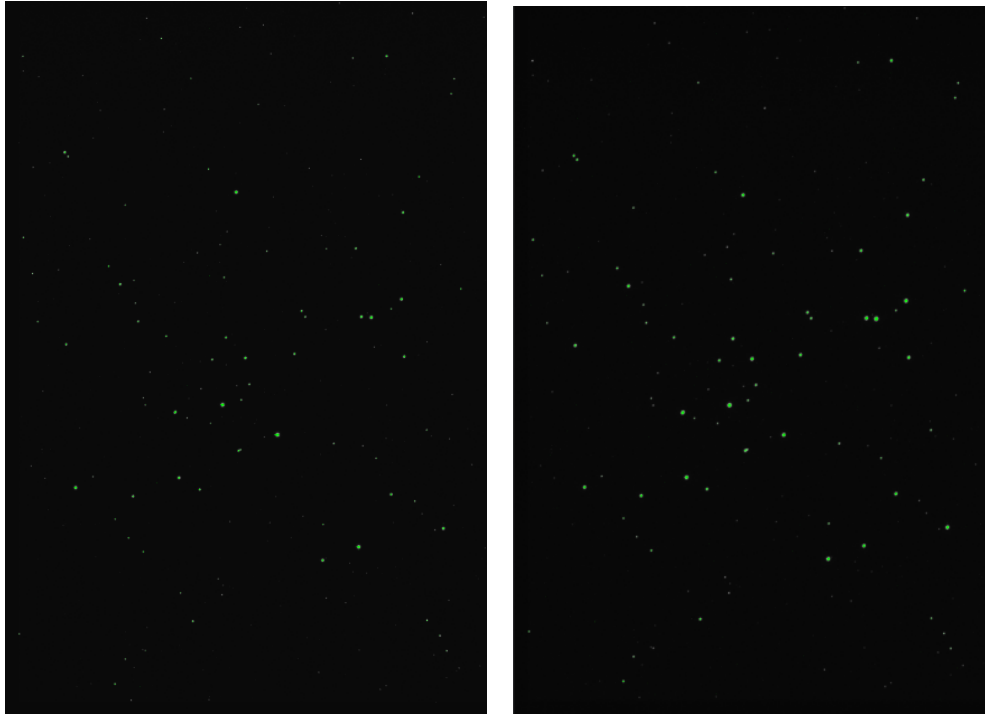
about 550 to 700 nm which is yellow into red light. As you can see, we're getting a slightly different range of wavelengths here.



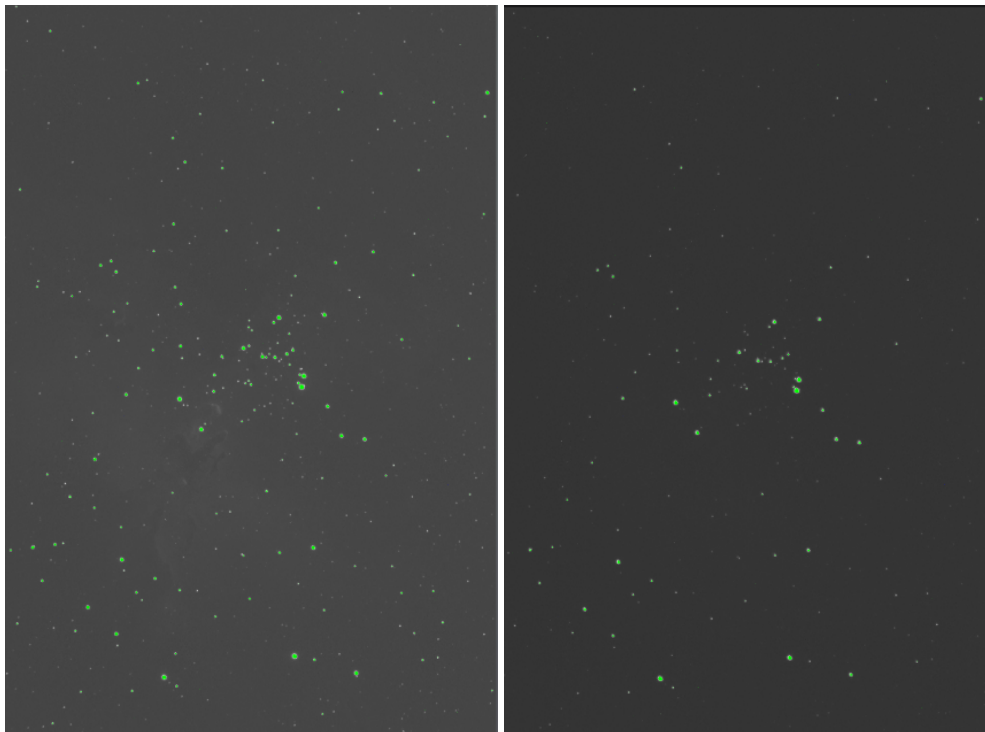
The transmission curves: Bessel filters left (Rovilos, 2009), SDSS filters right  
 \*\* SDSS-g is the blue curve and SDSS-r is the green curve

## Summary Images

First are the Bessel Filter images of Messier 41: (V filter on the left and B on the right.)



SDSS Filter images: (SDSS-r on the left and SDSS-g on the right)



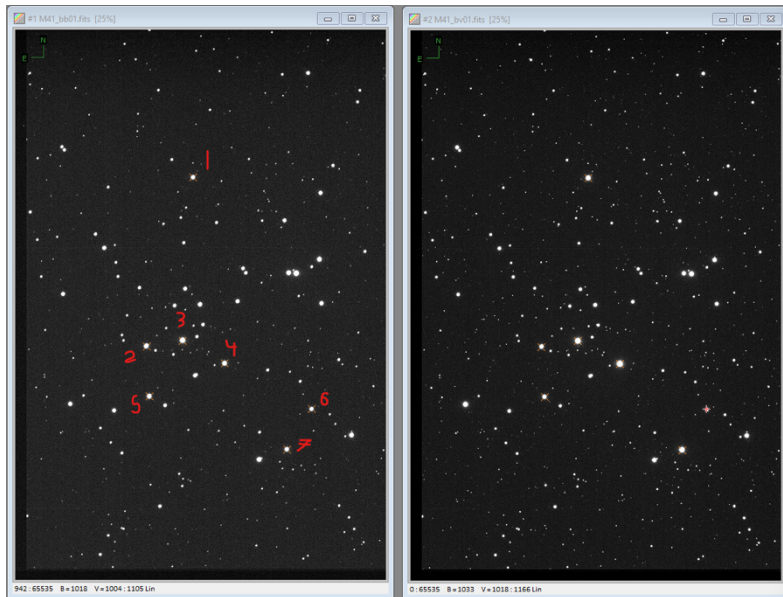


## Data Analysis

The first step in our analysis process was to use python to determine which of the 10 photos we took using each filter had the highest star count. We would use these photos to construct our Hertzsprung-Russell diagram. In order to do this, we used an astropy code which blocked out background noise and filtered stars by brightness and pixel count so that the discernable stars in the image could be marked and counted. We had a large variance in star count from object to object. This was due to the fact that while the Eagle Nebula is known to contain over 6,000 stars, the Little Beehive Cluster only has approximately 300 stars in it. DAOSTarFinder is one of the many modules we used in our code to filter the stars in our image. It works by filtering bright spots in an image by number of pixels and brightness in standard deviations above the background. I spent a good deal of time selecting an ideal number of standard deviations the brightness should be above the background. By choosing a value of 10 standard deviations I was able to taper the 6,500 stars originally detected in M16 down to a reasonable 338.

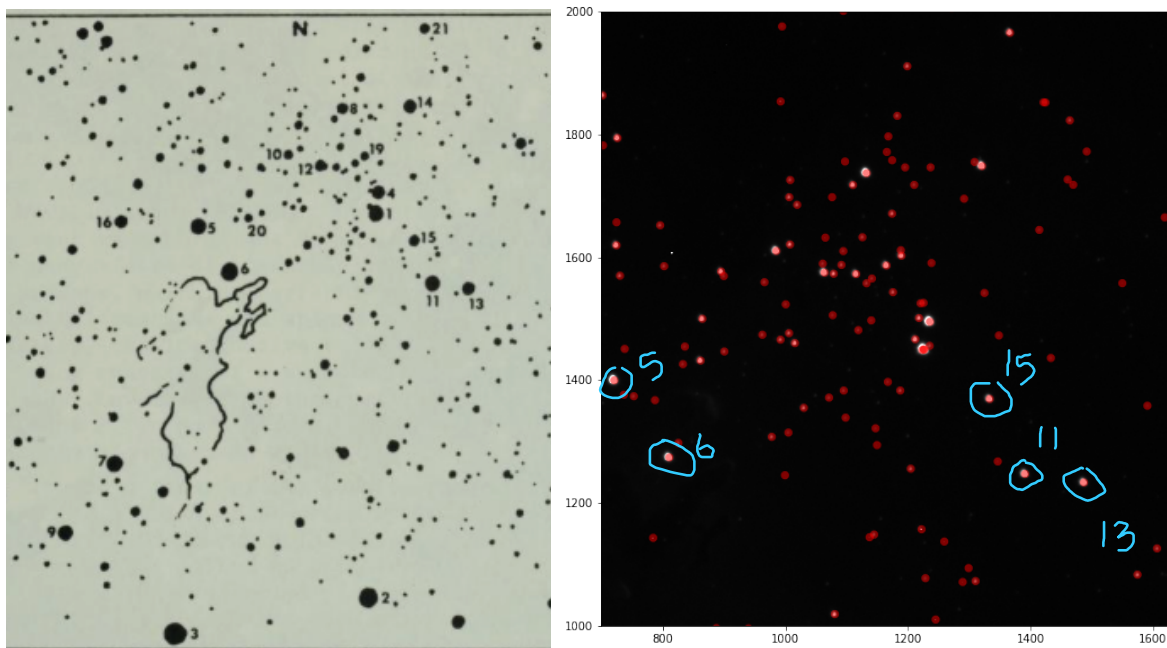
Once we selected images for each object, we used python to process all the images. The information that our code produced was the number of stars, their locations in our images, and their respective photon counts. We could not proceed any further until we were able to calibrate the photon counts to produce accurate magnitudes. The way we chose to do this was to find reference stars in each cluster that had available visual magnitudes and color spectra. It was at this point that we realized we could not proceed with our analysis of NGC 869 as we were unable to find any data for the spectra of stars in this cluster. We got our reference star data from two different sources.

For Messier 41 we were able to use astroart star atlas and the Gaia database to pinpoint the stars in our images and their necessary magnitude values.



For M41  
 Star:magnitude (GAIA)  
 1: 7.48  
 2: 9.19  
 4: 6.90  
 5: 8.43  
 6: 9.06  
 7: 7.08  
 (Gaia Collaboration, 2021).

For the Eagle Nebula we were able to find star charts and data in “Burnham’s Celestial Handbook: An Observer's Guide to The Universe beyond the solar system, volume 3”.



CLUSTER M16 - MAGNITUDES AND SPECTRA								
1.	8.24	05e	9.	9.69	B0+B5	17.	10.81	B2
2.	8.27	K0	10.	9.86	09	18.	11.06	08?
3.	8.30	B0+08	11.	9.88	B1:	19.	11.22	B1
4.	8.77	07	12.	9.94	B0	20.	11.24	B1
5.	8.95	08	13.	10.05	B1	21.	11.30	08+05
6.	9.43	09	14.	10.05	06	22.	11.41	09
7.	9.48	B1	15.	10.36	09	23.	11.60	B0:
8.	9.60	08	16.	10.74	B1	24.	11.62	K2:

For the Little Beehive Cluster we chose to use reference star #4 also known as HIP 3206 (Stoyan, 2010). It has a visual magnitude of 6.9 and is of the spectral type K3 so its B-V index is 0.95 (Stoyan, 2010). We chose to use reference star 15 for the Eagle Nebula. Star 15 has a visual magnitude of 10.36 and is of the O9 spectral type which means its B-V index is -0.31 (Burnham, 1978).

Looking at the images for both objects it was obvious which stars were our reference stars but we still did not know the coordinates of the stars in our images. To solve this issue, I wrote a code that would print our image as a plot you could interact with.

```
imagefile = "eagle_sdss_g.fits" #Here I am assuming the image is in the same
# imagefile = r"C:\Users\Sam Whitebook\Test_Image.fits" #Replacing the path w
#Now we will use astropy to open the file. Note that sometimes LCO files come
image = fits.open(imagefile)[0].data
header = fits.open(imagefile)[0].header

plt.rcParams["figure.figsize"]=[10,10]
plt.rcParams["figure.autolayout"] = True

def mouse_event(event):
    print('x: {} and y: {}'.format(event.xdata, event.ydata))

fig = plt.figure()
cid = fig.canvas.mpl_connect('button_press_event', mouse_event)

plt.imshow(np.log(image), origin='lower', cmap = "gray", vmin=4, vmax = 11)
```

When we clicked on our reference stars it would give us the coordinates we needed. Once we had the stars coordinates it was easy to look them up in our star data lists. Though some other stars had similar locations it was usually obvious which star was our reference as the photon count would be exponentially larger. The next step in our process was to use a reference stars visible magnitude to convert the photon counts from the visible spectrum image to magnitudes.

Below is the formula we used to calibrate the photon count to get our V magnitudes using the reference magnitudes.

$$m = m_{ref} - 2.5 \log \left( \frac{f}{f_{ref}} \right) \quad (1)$$

It wasn't until this point that I realized SDSS magnitudes are not the same as Bessel magnitudes and the spectral types have different indexing for the different filters. This made calculating the magnitudes for the Eagle Nebula different and more complicated. I could not find the SDSS color indices, (g-r) values, for the spectral types and transformations between Bessel and SDSS magnitudes are not certain. I will discuss further the effects of this issue in the error analysis.

Once we had all of our magnitudes for the visible, we could use our reference star's spectral class and visual magnitude to determine its B magnitude. Each spectral class has a color index value which is equal to the B magnitude minus the visual magnitude so we could use that relation to calculate a reference B magnitude. Below is the formula we used to get our reference B magnitudes.

$$m_B = index + m_v \quad (2)$$

With the reference B magnitude, we could then calibrate the photon counts for the Bessel-B image to give us B magnitudes for each star using equation (1) again. Below is the formula we used to get our reference B magnitudes.

Now that we have magnitudes for both the Bessel-V and Bessel-B images we could move onto calculating the color index for each star. This was done by rearranging equation (2).

```

ref_vmag=10.36 #float(input('input star 1 magnitude:'))
ref_vp=sums_v[157]
ref_index=-.31 #for 09 star
ref_bmag=ref_index+ref_vmag
ref_bp=sums_b[157]
#print(ref_p)

```

```

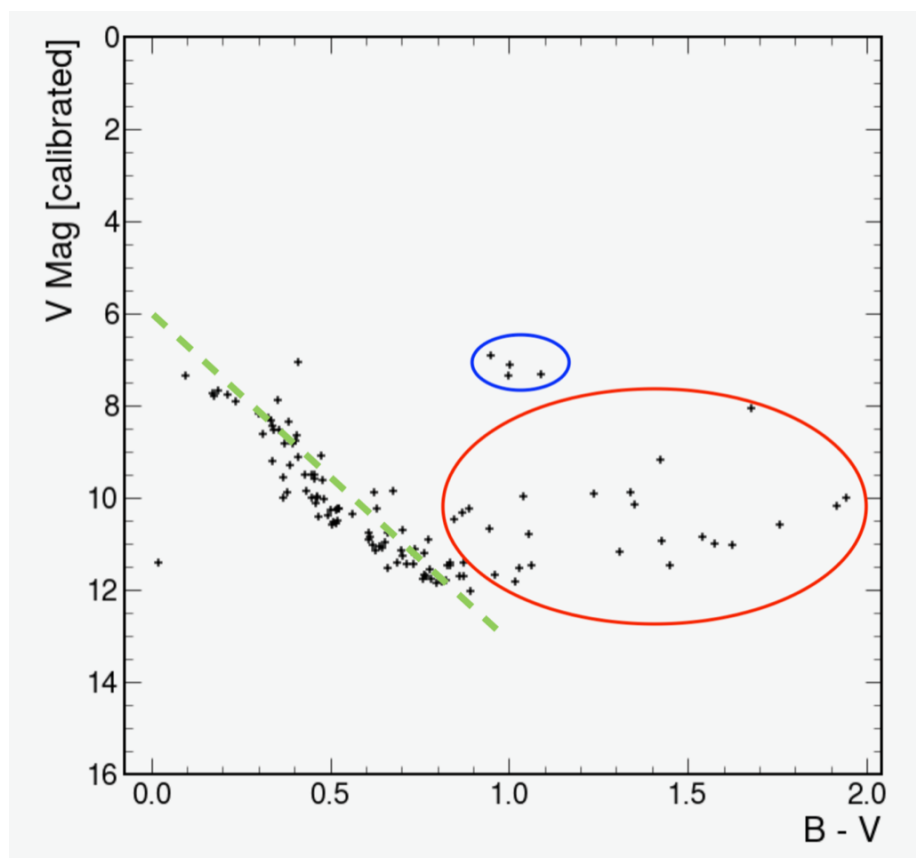
color = []
Vmag = []
Bmag = []
for i in range(len(positions)):
    mag_v = ref_vmag - 2.5 * np.log10(sums_v[i] / ref_vp)
    mag_b = ref_bmag - 2.5 * np.log10(sums_b[i] / ref_bp)
    color.append(mag_b - mag_v)
    Vmag.append(mag_v)
    Bmag.append(mag_b)

```

The last step of creating the HR diagram is plotting the color indices versus V magnitudes.

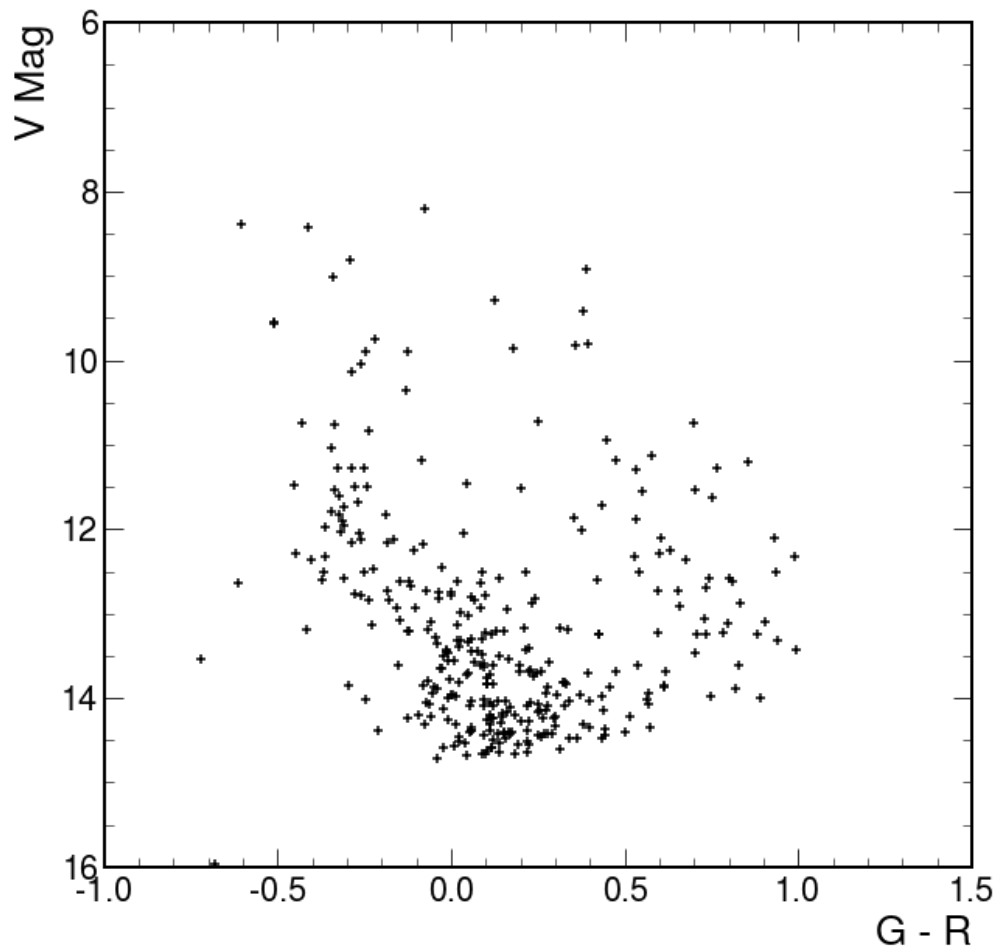
### Plots

Little Beehive Cluster (Messier 41) Hertzsprung-Russell diagram:



[ you can see a clear main sequence for this cluster and the color indices are appropriate for the stars in the cluster]

Little Beehive Cluster (Messier 41) Hertzsprung-Russell diagram:



[This diagram was created before we realized that the SDSS filter produce asinh magnitudes instead of Pogson magnitudes. Note how there is no clear definition of a main sequence or horizontal branch as well as the fact that color indices are inappropriately low.]

### Error Analysis

Now is a great time to discuss the issues with the SDSS images for creating an HR diagram. Bessel filters are compatible with the standard magnitudes, also known as Pogson magnitudes. Because of this fact, calibrating the photon values using given magnitudes is quite simple for the Bessel images. In order to calibrate the SDSS photon values we would have to

convert our reference star magnitudes to asinh magnitudes and then back to Pogson magnitudes to do the color index calculations. In theory this sounds doable the only issue is that transformations between these types of magnitudes are unreliable and the formulae given are not helpful for our particular purposes. Below are the transformation equations between Bessel magnitudes and SDSS magnitudes:

$$B = g + 0.3130(g - r) + 0.2271$$

$$V = g - 0.5784(g - r) - 0.0038$$

My code accurately calculated the Pogson magnitudes for the SDSS-r image but using the common B-V indices for the calculation of our reference star's B magnitude yielded an incorrect value which in turn made all of the calibrated B magnitudes and color indices wrong as well. The B-V indices I was calculating were all between 0 and -0.5. At first, I found the large number of very blue stars surprising, but when I considered the fact that all the stars in the Eagle Nebula are very young it seemed appropriate. Due to inexperience with observational astrophysics, I was slow to correct this error in judgement. I used the magnitude for star 15 in "Burnham's Celestial Handbook" for my calculations and checked the code using star 11 and 13.

```
print('Reference Star Visible Magnitudes:')
print('Burnhams star number: 13', 'id: 143')
print('calibrated magnitude:', Vmag[143], "given magnitude: 10.05")
print('Burnhams star number: 11', 'id: 145')
print('calibrated magnitude:', Vmag[145], "given magnitude: 9.88")
```

```
Reference Star Visible Magnitudes:
Burnhams star number: 13 id: 143
calibrated magnitude: 10.046340509234835 given magnitude: 10.05
Burnhams star number: 11 id: 145
calibrated magnitude: 9.885931766135302 given magnitude: 9.88
```

---

I am confident that I could have found an appropriate approach to create an HR diagram using SDSS filtered images had I not realized my mistake so late. We were using a method that was not compatible with SDSS data.

The whole process for producing an Hertzsprung-Russell diagram was much smoother and more successful for the Little Beehive Cluster. Our code produced a beautiful diagram with an obvious main sequence and appropriate magnitudes. The calculation of the visible magnitudes was not quite as accurate as the Eagle Nebula values but they were still very close.

**Reference Star Visible Magnitudes:**

Reference star number: 1

calibrated magnitude: 7.321901064210279 given magnitude: 7.48

Reference star number: 4

calibrated magnitude: 6.9 given magnitude: 6.39

Reference star number: 7

calibrated magnitude: 7.115196387251935 given magnitude: 7.08

Overall, the Messier 41 HR diagram was satisfactory. The final diagram on page 12 shows the main sequence, and horizontal branches for both low mass and high mass stars distinctly which is exactly what we were hoping to achieve.

Conclusion (what I would redo)

We ran into many roadblocks with this project. There were so many I could create a numbered list. My main regret is not having the foresight to realize SDSS filters would require a different approach. I put a great deal of time into getting all the relevant data for the Eagle Nebula and tailoring the code for it before I realized my mistake. Although I would love to learn how to properly make a HR diagram using SDSS images I would recommend using Bessel filters to anyone who wishes to successfully and efficiently complete this project. The next lesson learned is that you should be sure to pick an object that has many reference stars with listed magnitudes and spectral types and is visible. We wasted time analyzing data that we could get no further



with due to lack of information on a particular object. As someone who has no experience with telescopes, I was slow to request images at the beginning of the term because I was afraid of the unknown. My recommendation to students taking this class in the future would be to request and analyze your images earlier rather than later because you never know if you will run into problems and need to change course.

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