

HR Diagrams for the Eagle Nebula and the Little Beehive Cluster

Abstract

Our project is the creation of Hertzsprung Russel diagrams for the Little Beehive Cluster and the Eagle Nebula. HR diagrams are used to analyze where a star cluster is along its lifespan. They help approximate the age of a star cluster and for learning more about stellar evolution. The HR diagrams were created by taking images using Las Cumbres Observatory global telescope network's (LCOGT) telescopes in multiple filters. The images were then analyzed in python using astropy and astroalign to extract an estimated photon count of all the stars in the images. The photon count was converted to magnitude using reference stars. The visual magnitudes were then plotted against the difference between the blue and visual magnitudes to create the HR diagram.

Background

Hertzsprung Russel diagrams are scatter plots that show where stars are on their path through stellar evolution. They were independently developed by both Ejnar Hertzsprung and Henry Norris Russell in the early 1900s. A few years prior, there were

many large scale photographic spectrographic surveys. These resulted in the creation of the Henry Draper catalog. Also included in this catalog was a section on divisions of stars by their spectral lines' widths. From this, it was noted that Hertzsprung attributed this to differences in luminosity. Stars with narrower spectral lines have a greater luminosity. Hertzsprung used this to calculate the magnitudes and created an early HR diagram (Hertzsprung, 1911). Russel's early versions of the diagram stemmed from using a moving cluster method to find distances but ultimately resulted in a plot similar to an HR diagram (Russel, 1914).

The HR diagram can have multiple forms. The nomenclature for them is rather undefined but they generally fall into 2 categories: theoretical and observational. The theoretical form is generally plotted with temperature versus luminosity. This is theoretical because one cannot generally measure the temperature of a star. The observational one is made from measured data. It plots the color or spectral type against the star's absolute magnitude.

Theory of the Project

A key part of the HR diagram is how the theoretical and observational ones relate. It is hard to directly relate them but it can be done. To go from color to effective temperature requires knowing more about the star's composition as well as other factors like its rotation and metallicity. To relate luminosity to magnitude is also difficult, but not as many other parameters are needed. It requires a bolometric correction, as well as a correction for extinction which requires a distance value. As such, it is much

easier to calculate the observational HR diagram and use some known parameters to scale it to fit on a theoretical diagram where further analysis can be made.

The important part of the theoretical diagram is it pretty much classifies the star and shows where it is on its path of evolution. There are 3 main sections on an HR diagram. The main diagonal section contains what are known as main sequence stars. Most stars fall under this category. Following along the main sequence, the top left contains brighter hotter stars. It traverses down to the bottom right where the cooler dimmer stars reside. Above the main sequence, there are the super and hypergiants. They are bright and hot. And below the mains sequence there are the white dwarfs, which are cold and dim compared to main sequence stars.

Greater Significance

This project follows a lot of what is known about stellar evolution. An HR digram provides a lot of insight into where a star is at in its current life cycle. The main differences in branches of stellar evolution stem from their mass. But most stars form in similar ways. Stars are formed from the condensation of interstellar particles. The gravitational collapse of massive molecular clouds will form the core of a star. This process generally repeats itself until the star is formed (Aguirre, 2017). Once the temperature of the core is high enough, the fusion of hydrogen will begin to occur and a main sequence star is born. For the majority of the star's life, it will fuse hydrogen into helium and remain on the main sequence.

For main sequence stars, when the hydrogen in the core begins to run out, the core begins to contract. This causes an increase in temperature that ignites the

hydrogen shell around the core. In this phase, the star begins to rapidly expand and increase in temperature and luminosity that changes the stars type to a red giant. Over time the temperature will increase enough to fuse the helium in the core into carbon. If the star has a mass less than approximately $2 M_{\odot}$, its entire core will suddenly ignite. For stars with a larger mass, the fusion of helium has a more gentle start. The helium fusion period is much shorter than the hydrogen one. At the end of this phase, the core will be carbon, surrounded by a burning helium shell and then a burning hydrogen shell. At this point, the main paths branch depending on the mass of the star.

If a star has less than $8 M_{\odot}$, its core will continuously contract but it will never reach a temperature high enough to fuse carbon. It does still have the 2 burning shells of hydrogen and helium though. These shells begin burning out of phase and this causes the characteristic thermal pulsing of some giant stars. The star's carbon core will continue to condense until the limit is reached. At this point, the star is now a white dwarf. The hydrogen and helium layers will still burn and expand which causes a loss of mass. Over time the layers are completely ejected and will eventually form a planetary nebula (Aguirre, 2017).

Stars with masses greater than $8 M_{\odot}$ follow a different path. The core will reach a high enough temperature to begin carbon fusion and it will then form a burning layer of carbon. This process of fusion and layer generation will continue with heavier elements until it reaches iron because the fusion of iron doesn't produce energy (Aguirre, 2017). The star begins to run out of energy and begins to collapse due to its own gravity. Stars with a core that has a mass less than $3 M_{\odot}$ will have the collapse stopped due to neutron pressure. These stars will eventually form a neutron star that

will later become a supernova. Stars with a more massive core will completely collapse into a stellar blackhole.

Project Details

The first step is to find what object is being represented in the HR diagram. A key factor in choosing what object to image is whether or not it is even visible this time of year. We initially chose Caldwell 14 as the object of our study but we couldn't find a way to calibrate the B magnitude for the diagram. This resulted in the use of our backup objects: the Little Beehive Cluster, and the Eagle Nebula.

Caldwell 14, also known as the Double Cluster, is located in the Perseus Arm of the Milky way galaxy. The Double Cluster contains the 2 clusters NGC 869 and NGC 884. They are approximately 7 kly from Earth and are only a few hundred ly apart. The star clusters are also both relatively young; they are approximately 14 million years old. The other neighboring star clusters have ages of 75 to 150 million (Currie et al., 2010).

The Eagle Nebula (also known as Messier 16, M16, NGC 6611, and the Star Queen Nebula) is a younger open cluster of stars (Burnham, 1978). It is approximately 1-2 billion years old (Hillenbrand et al., 1993). It is in the constellation Serpens and in the Sagittarius arm of the Milky Way (Burnham, 1978). The Eagle nebula gets its name from the prominent silhouette in its center. This also contains the famous Pillars of Creation imaged by Hubble. The nebula has large dust clouds which form these pillars. These are composed of galactic hydrogen and gas which are incubating new stars. Inside some of the dust clouds, protostars may even be forming.

The Little Beehive Cluster is also known as Messier 41, M41, and NGC 2287.

The Little Beehive Cluster is an open cluster in the constellation Canis Major. It is almost exactly 4° 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 be 190 million years old and has an expected lifespan of 500 million years (Stoyan, 2010).

To image our clusters, the telescopes at LCOGT were used. The telescope available for our use at LCOGT is their 0.4 m one. It is a specially modified Meade telescope. The attached imaging device is an SBIG STL-6303. This imaging device has a field of view of approximately 30 by 20 arc minutes (Brown et al., 2013). All the images from the LCOGT science telescopes are processed through the BANZAI pipeline. The Banzai pipeline processes all of the image frames taken and calibrates the images. The following calibrations are made: bad-pixel masking, bias subtraction, dark subtraction, Flat field correction, source extraction and astrometric calibration. These make the received frames better in quality and more easily processed for other work (Brown et al., 2013).

Generally for creating an HR diagram, you take images in 2 filters. The filters we used so far are the SDSS and Bessel ones. The SDSS filters used are: g' , and r' (figure 1). The SDSS g' filter generally covers the blue light and the r' filter generally covers the visual light. The Bessel filters used are B and V (figure 2). For the Eagle Nebula, we took images using the 3 SDSS filters at the LCOGT node at Cerro Tololo Inter-American Observatory. The images of the Little Bee Hive cluster were taken in Bessel B and Bessel V at the LCOGT node at Tenerife. All the images taken were done with a 50

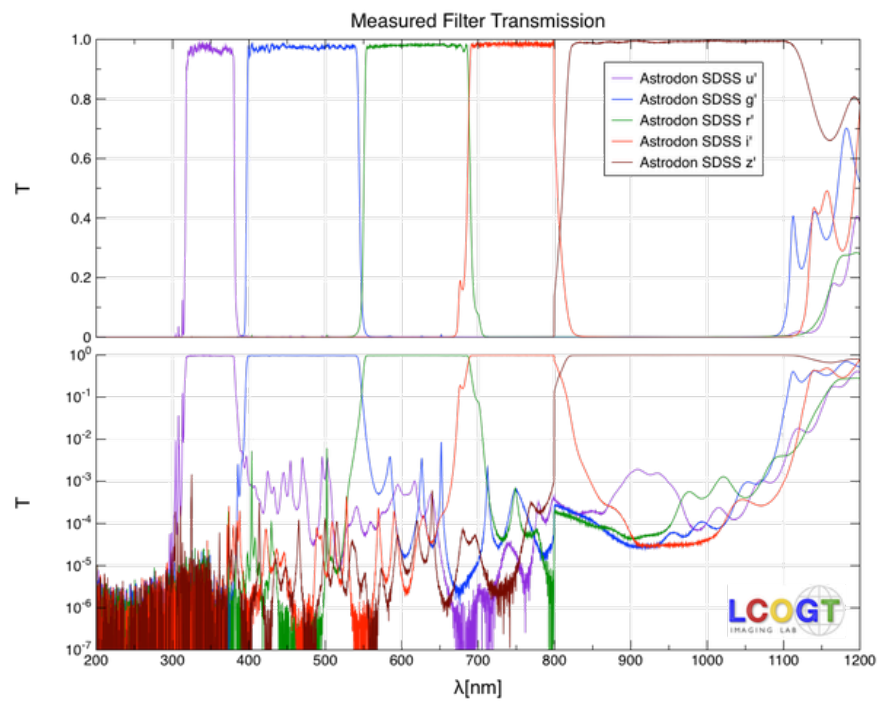


Figure 1: SDSS filter transmissions from LCOGT

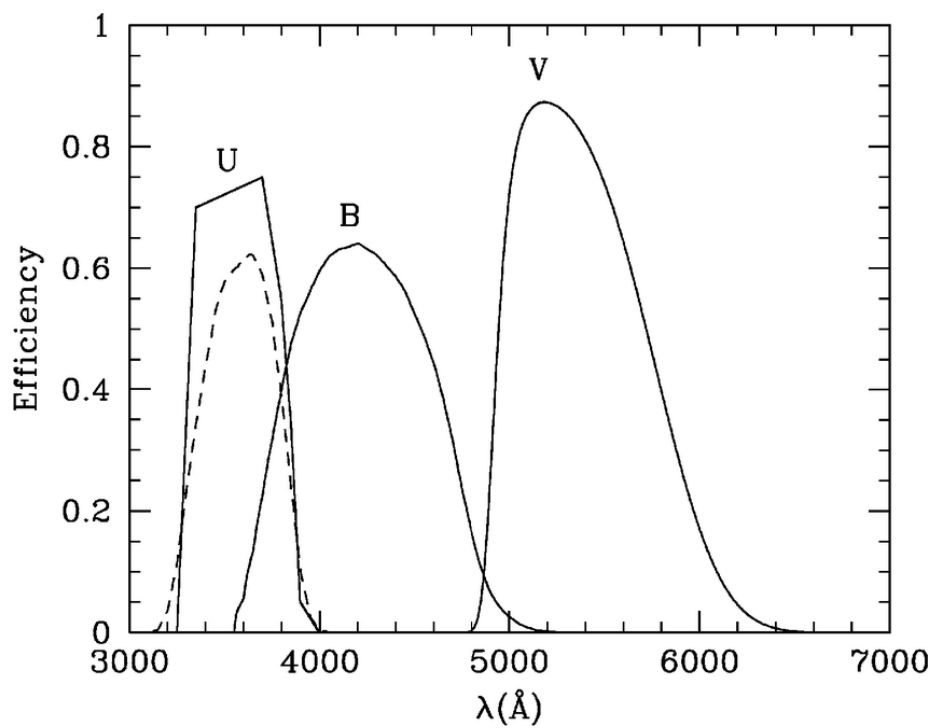


Figure 2: Bessel filter transmissions. (Rovilos et al., 2009)

second integration time. Once we received the images, some preprocessing needed to be done. We flipped the images vertically and then rotated them by 90° clockwise using Astroart.

A key piece of information needed is a way to calibrate the magnitudes of the images. This is generally done by using a reference star with a known magnitude for the V filter. Generally, given magnitudes are from the v filter. Using Astroarts' star atlas function, I was able to find the visual magnitudes of a few of the brightest, round stars and make them reference stars for the Little Beehive Cluster. These reference stars were then marked on a png form of the image for later referencing (figure 3). The visual magnitudes in the star atlas were from the Gaiadr3 catalog. For the Eagle Nebula, we were able to find a finder chart with visual magnitudes so there was no need to make our own (figure 4).

Using the astropy module in python, it is possible to detect stars and then estimate the number of photons they emitted. This is then calibrated to a reference star with a known magnitude. The reference star is found in the image by using a short code script. The script loads the image using astropy and outputs it using matplotlib and astropy. A key section of the script is shown below.

```
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)
```

This section allows the location of a click to be output to the command line from the plotted image. This was used by clicking on the star that matches the reference star from the figures. By comparing this x y location found to the list of positions found in the astropy photometry, it is possible to find which star found corresponds to the

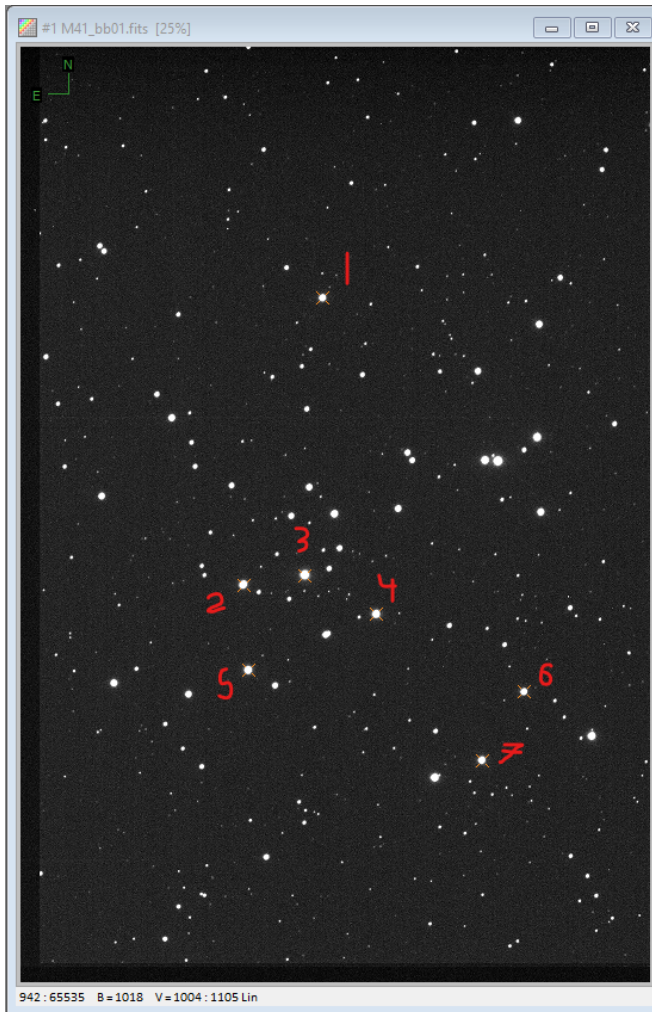


Figure 3: Little Beehive Cluster reference stars. We only used reference stars 1, 4 and 7. Star 1 has M_v 7.48, star 4 has M_v 6.9, and star 7 has M_v 7.08 (Gaia Collaboration et al., 2021). Star 4 is known as HIP 32406 with spectral class K3III (Stoyan, 2010). This is also the Bessel B image that was used to create the HR diagram.

reference star. Since the reference stars are generally the brightest ones in the image, if there are stars in a similar location, the reference star is likely is the one with the highest photon count.

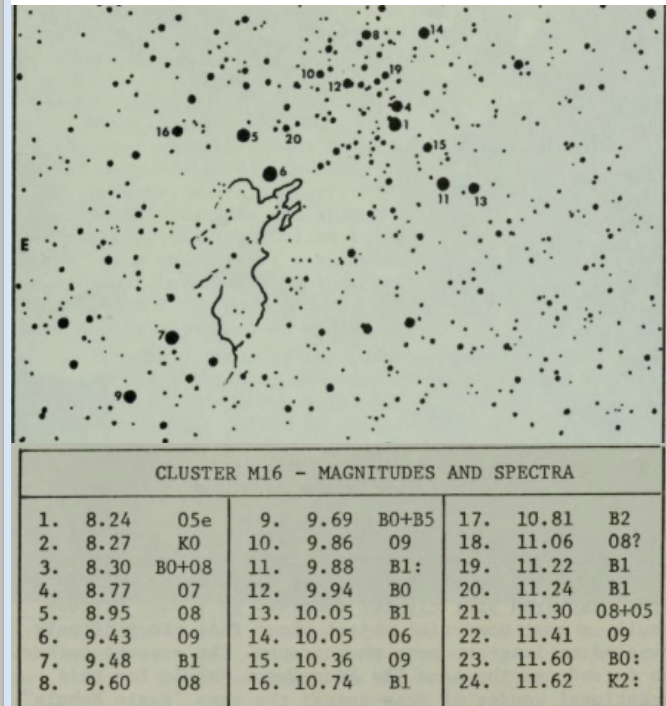


Figure 4: Eagle Nebula Reference stars with their magnitudes and spectral classes. (Burnham, 1978)

Another key section of the code is aligning the images in the 2 filters. Even though the images were taken around the same time, the images don't perfectly align. Using the `astroalign` module, the images in different filters were aligned and then the exact positions from the photometry function are the same for stars found in the 2 different filters. Now that the images are aligned, I had the entire list of stars with their location, index, and estimated photons output to the command line. Using the positions found previously, it was easy to find the index of the reference star in the list. Now we have all the values we need to calibrate the magnitudes.

Now that the reference magnitudes are known, the photon counts from the images need to be calibrated into magnitudes. This is done using the equation:

$$M_v = M_{v,ref} - \left(2.5 \log_{10} \left(\frac{b_v}{b_{v,ref}} \right) \right)$$

where M_v is the calibrated visual magnitude, $M_{v,ref}$ is the magnitude of the reference star, b_v is the photon count of the unknown star, and $b_{v,ref}$ is the photon count of the reference star. Calibrating the other magnitude is a bit more difficult. For the Little Beehive Cluster, we were able to identify one star's spectral class. The star is HIP 32406 (aka HD 49091) and it corresponds to reference star 4 (Stoyan, 2010). Once the visual magnitudes were calibrated with one reference star, the calibrated magnitudes were compared to other reference stars with known magnitudes. If they were roughly similar, we could move on, otherwise, there was likely an error.

Using the spectral class, the B-V index is easily found. The B magnitude can then be easily be found for the reference star with the equation:

$$M_b = M_v + I_{b-v}$$

where M_b is the calculated blue magnitude for the reference star, and I_{b-v} is the B-V index. Then the first equation can be used to calculate all the B magnitudes. For the Eagle Nebula, there were a few reference stars with known spectral classes, so the above equations were similarly used to calibrate the HR diagram. The Final step is to simply plot the calibrated V magnitudes versus the difference between the B magnitudes and the V magnitudes.

Plots (add in the images)

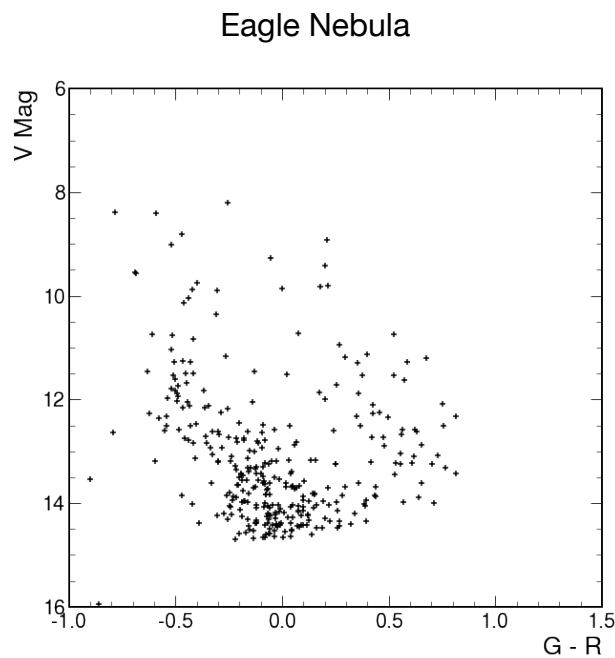


Figure 5: HR diagram for the Eagle Nebula (M16)

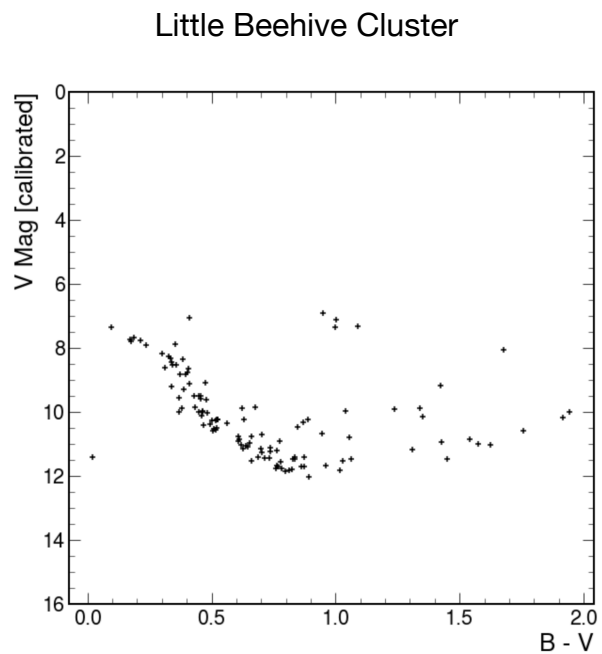


Figure 6: HR diagram for the Little Beehive Cluster (M41)

Our generated plots can be seen in figures 5 and 6 for the Eagle Nebula and the Little Beehive Cluster respectively. There are some errors with both but the Little Beehive HR diagram turned out fairly well.

Discussion / Analysis

For the Little Beehive Cluster, there are points on the HR diagram that probably shouldn't be there. The star finding algorithm that was used wasn't perfectly refined so there are some stars that the diagram shows that likely shouldn't be there. A marked up version of this HR diagram is shown in figure 7. The markups were made while referencing a previously made HR diagram of the cluster. For the Little Beehive Cluster HR diagram, there is clearly a main sequence and a few giant stars. The B-V values found are also appropriate for the cluster. The HR diagram was calibrated using only

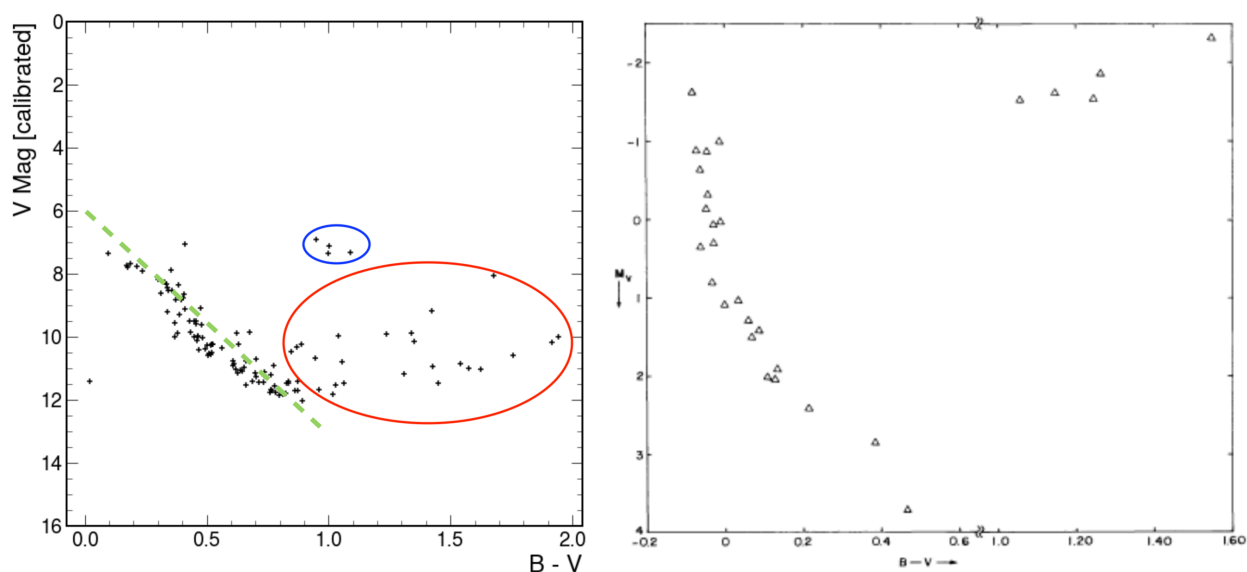


Figure 7: On the left is a marked up version of figure 6 showing the Little Beehive cluster HRD. The red circle contains stars that are likely noise. The blue circle contains the reference stars. The dashed green line shows the main sequence. On the left is a previously created HR diagram for the Little Beehive cluster by Kucuk and Eryurt-Ezer (1988).

reference star 4 and its B-V index from its spectral class. The other reference stars were used to check the calibrated magnitudes against the known magnitudes. The output from checking is shown below:

```
print('calibrated values versus known values')
print("star 1:", Vmag[id1], "7.48")
print("star 3:", Vmag[id3], "7.02")
print("star 7:", Vmag[id7], "7.08")
```

```
calibrated values versus known values
star 1: 7.321901064210279 7.48
star 3: 7.058768137424425 7.02
star 7: 7.115196387251935 7.08
```

The differences are fairly small however only 3 were checked. The average difference was close to 3%.

The results of the HR diagram for the Eagle Nebula are quite off. However, the visual magnitude calibration was very accurate. The comparison of 2 known stars to the calibrated magnitudes is shown below:

```
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
```

The visual magnitudes were well calibrated but the calibration for the color index was done incorrectly because the index used was specifically for Bessel type filters.

Errors and Problems Encountered

Our original project was to recreate the 1919 Eddington experiment using more modern images of a solar eclipse. However, we were unable to find any such data for that analysis. We were able to find quite a few interesting images of gravitational

lensing on distant nebulae and clusters, but calculating any information for that was beyond our ability and unfeasible within the timeframe of the class. So we have switched to a more reasonable project of creating an HR diagram.

Initially, we started with Caldwell 14 as the object of our HR diagram. This didn't end very well because we didn't take into account its size. We ended up only having one of the 2 clusters visible in our images. This cluster is NGC 869, or h Persei. We made a reference star chart for it in astroart but we were unable to generate the HR diagram because we were unable to find a way to calibrate the B magnitudes. Thus we ended up using our backup, the Little Beehive Cluster as well as the images from our astrophotography project of the Eagle Nebula.

The images for the Eagle nebula were giving us a type error that involved the mixing of big and little endian data types. After some research this was solved by the following code:

```
image_v=image_v.byteswap().newbyteorder()  
image_b=image_b.byteswap().newbyteorder()
```

These lines switched the image endian so the astroalign function was then able to work. Unfortunately, we only realized recently that the SDSS filtered images aren't a good choice to use for the HR diagram. At this point, it was too late to try and fix the issue so it went unresolved. The SDSS images would have a different color correction index compared to what we actually used. Due to this, all of the color indices are inaccurate. There is a way to calculate the SDSS color indices, but we found out too late that there was a difference. Thus the x-axis for the HR diagram is off.

Conclusion and Future Work

We were able to generate HR diagrams using images taken with LGOGT and reference stars we had found. However, they could still use more refinement. It is possible to stack multiple images in the same filter using astropy and that could lead to more accurate results. We could also improve our star finding algorithm to reduce some errors in the HR diagrams as well. Another way the HR diagram could be improved is by calibrating the magnitudes with multiple reference stars and finding an average calibration coefficient. Since we now know how to make HR diagrams, generating another one would be much simpler.

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