The Distance and Age of the M67 and M36 Star Clusters

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Abstract

Our goal was to use photometric observations of the M67 and M36 star clusters to determine the age and distance to each respective cluster. We obtained B and V band images of the star clusters and used absolute and relative photometry to determine their magnitudes in each filter. Using this information, we constructed an HR diagram for each cluster using IDL. The HR diagram's main sequence turnoff point enabled us to determine the ages of each cluster, while the offset from the Zero Age Main Sequence (ZAMS) enabled us to determine the distances to the cluster. From our analysis, we determined that M36 is about 0.4 billion years old and is at a distance of 910 pc. Meanhile, M67 is roughly 9 billion years old and located 630 pc from the Earth.

Introduction

Finding the ages of and distances to various objects in the universe is an important and sometimes daunting task for any astronomer. Open clusters, at least, are willing to reveal a lot about themselves with just a little coaxing.

Open clusters are star clusters that orbit within or close to the disk of the galaxy. Unlike globular clusters, which exist in the halo of the galaxy and are often quite old and dim, open clusters are bright and easily observed from small telescope. Both the Pleiades and Hyades are well known examples of open clusters. For this project, however, we observed the lesser known open clusters M36 and M67. M36 is known to be a very young and bright open cluster, and is comparable to the Pleiades in luminosity. M67, meanwhile, is one of the oldest known open clusters and is nowhere near as bright.

The absolute magnitude of an open cluster is closely related to the cluster's age. The reason for this is that the brightest and most luminous stars far outshine their dimmer cousins, but also have a much shorter lifetime. The brightest stars have a lifetime numbered in the millions, not billions, of years before they exhaust their Hydrogen and become giants or supergiants, while the small, red M-type stars have lifetimes that are longer than the current age of the universe.

The stars in open clusters are generally thought to have been all formed at the same time, so therefore they should all be around the same age. The brighter stars, however, will run out of fuel and leave the main sequence sooner, and so the age of the cluster is easily determinable by looking at what main sequence stars remain. For instance, if a cluster no longer contains any A-type stars but still has F-type stars, we know that the cluster is older than the lifetime of an A-type star but younger than the lifetime of an F-type star. Generally, the age of the cluster is estimated to be around the main sequence lifetime of the brightest type of star that remains.

To find the age of an open cluster, one must simply create an HR diagram, a diagram of the star in the cluster with the V-magnitude on the y-axis and the color, determined by subtracting the V-magnitude from the B-magnitude, on the x-axis. Most clusters will be fairly linear up to a point, and then have a distinct point where they turn off to the side. This point, called the main sequence turnoff point, is where the higher luminosity stars have left the main sequence and become giants or supergiants. Comparing this diagram with an HR diagram that contains every type of main sequence star, called a Zero Age Main Sequence, we can see what type of main sequence stars remain in the cluster and from there constrain the age.

We can also use the H-R diagram to determine the distance to a cluster. The zero age main sequence diagram utilizes absolute, not apparent, magnitudes. Since the analysis of the star cluster depends on observed relative magnitudes, it will be offset from the ZAMS diagram by several magnitudes. The amount that it is offset can be used to determine the distance.

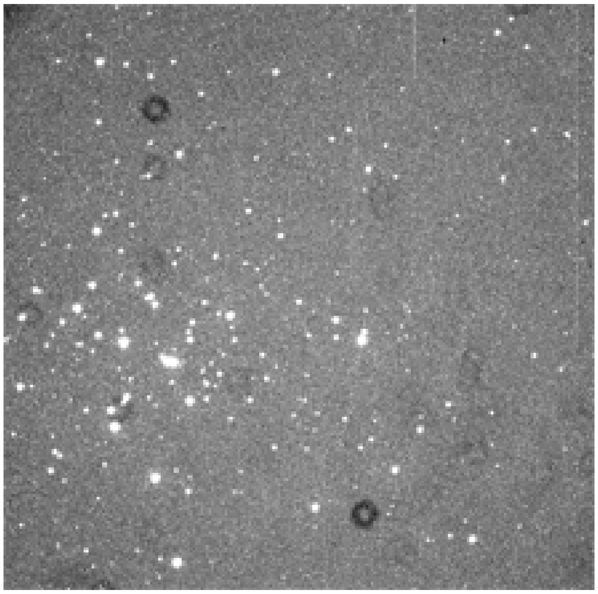
For this project, we took images of the M36 and M67 star clusters, and used absolute and relative photometry to determine their B and V magnitudes. From this we were able to construct an HR Diagram for the cluster, and, comparing it to the Zero Age Main Sequence, we determined the age of and distances to the clusters.

Methods

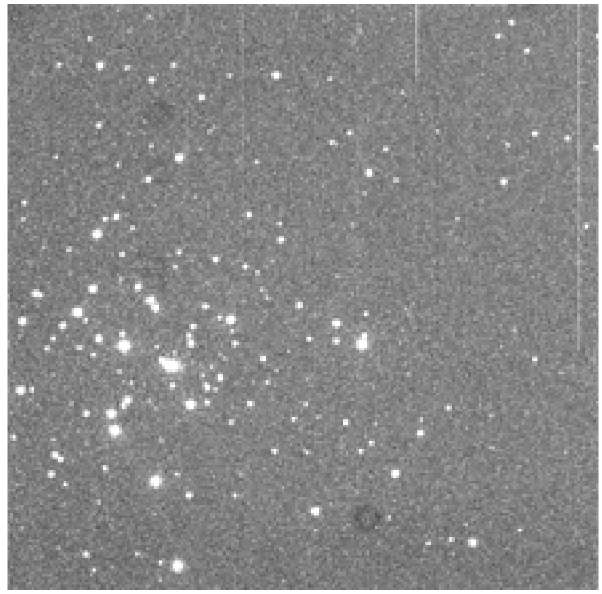
The first and most important step to any photometric analysis is taking images of the star clusters. For this project, we took B and V band images of the M36 and M67 star clusters.

Due to their locations in the sky, both clusters set early. Therefore, observations had to be done before about 11 pm MST. This turned out to be a more daunting task than previously expected. After many cloudy nights and failed attempts, we managed to get images in the V and B band of M36 on the night of April 14th. Unfortunately, the clouds came in later that evening, and we were unable to get standard stars that night. However, on April 19th we had better weather and were able to obtain V and B band images of M67 and our standard stars.

The observation of M36 was difficult because it set so early. By the time it even became dark enough to get any meaningful images, the cluster was already four hours west of the meridian. Although we were reluctant to observe at such an angle, we were told to do so anyway, and managed, at least, to avoid doing any damage to the telescope. However, not only was the cluster very far west, but it was tilted at such an angle that using the guide scope was difficult, even with the ladder, and centering the image in the time allotted was next to impossible. Therefore, the images of M36 are not as well centered as those taken later of M67.



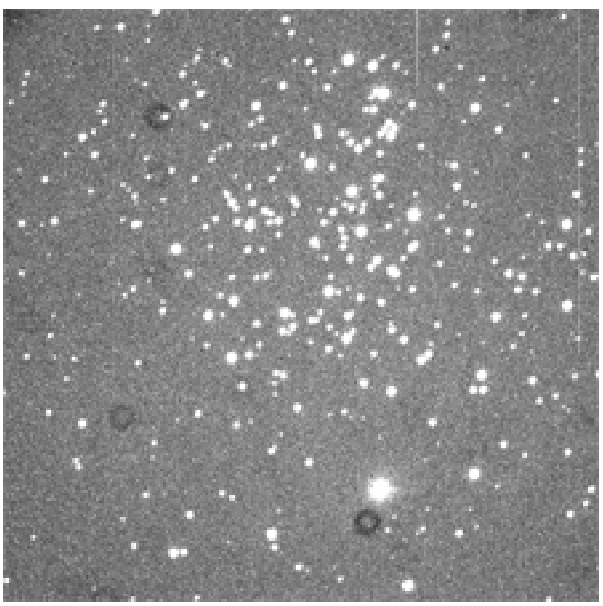
V-band Image:
Exposure time-105 sec
Airmass- 1.475



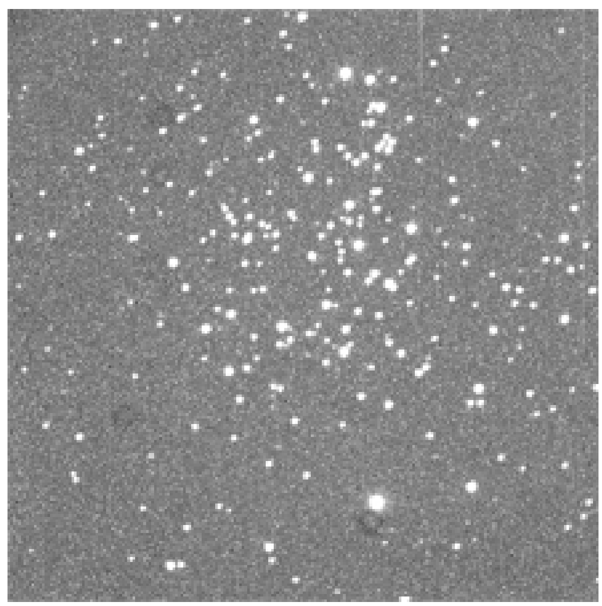
B-band M36:
Exposure time- 90 sec
Airmass- 1.531

Figure 1: Raw images in the V-band and B-band for M36.

The observations of M67 went a little more smoothly. We had better observing conditions and were able to better center the cluster.



V-band Image:
Exposure time- 90 sec
Airmass- 1.162



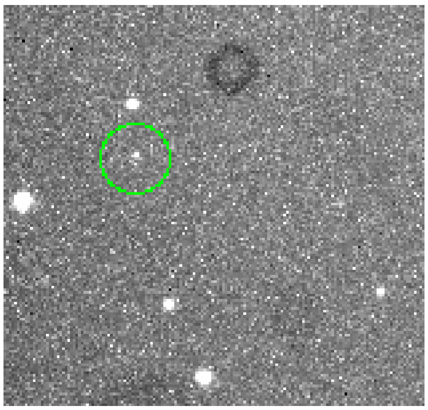
B-band Image:
Exposure time- 180 sec
Airmass- 1.192

Figure 2: Raw Images in the V-band and B-band for M67.

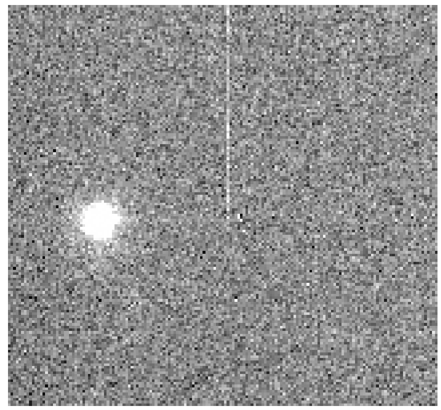
The large star near the bottom of the image is much brighter than the others and saturated easily.

Avoiding saturation meant very low exposure times and inadequate counts in the other stars. However, due to prior knowledge, we knew that it was unlikely that this star was part of the cluster. Therefore, we let the star saturate so that we could analyze the other stars, and took other, lower exposure time observations of the larger star so that we could ensure that it was not a part of the cluster.

We were also able to obtain standard star observations on that night. The v-band standard star is the one circled. The B-band standard star is the only one in the image.



V-band Standard for M67:
V = 15.67
B-V = 0.26
Exposure time = 225 s



B-band Standard for M67:
V = 4.3
B-V = -0.2
Exposure time = 1 s

Figure 3: V and B-band Standard Stars for M67

We could only use these standard stars for M67. Because we observed M36 on a different night, the lack of photometric conditions required that we use an in-field standard star for M36. The standard star is the one circled on the following image:

Standard for M36:
V = 10.61
B = 10.772
Exposure time = 105 s

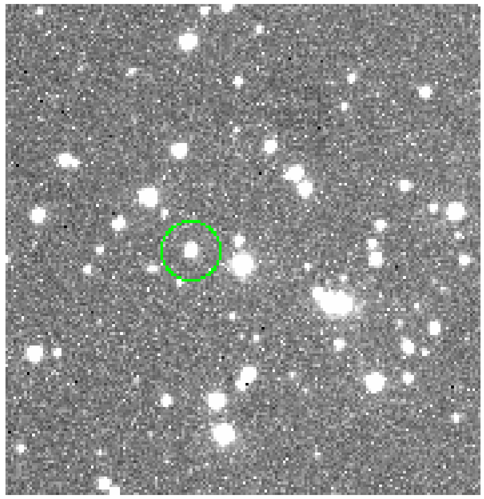
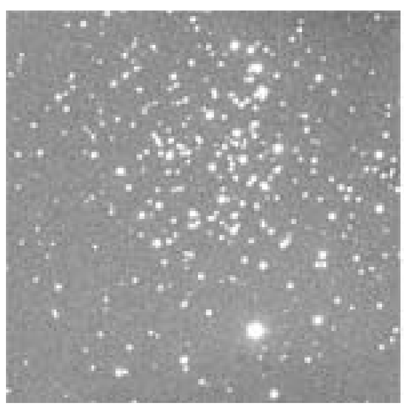


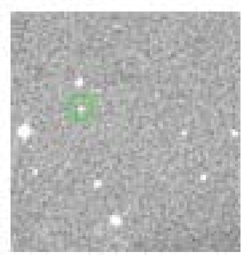
Figure 4: In-field Standard Star for M36

Once we obtained these images, we had to reduce them using the flat field and dark images we obtained on the same respective nights. We did the image reduction in IRAF using the commands imcombine and imarith. With the freshly obtained science images, we could begin our analysis of the two open clusters.

V-band M36

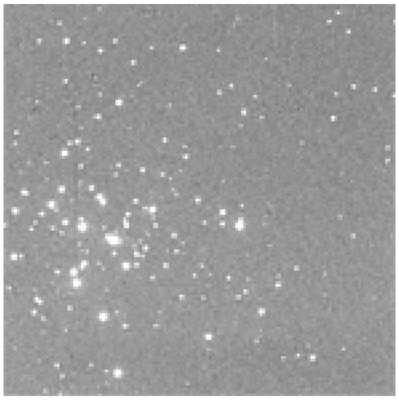


V-band M67

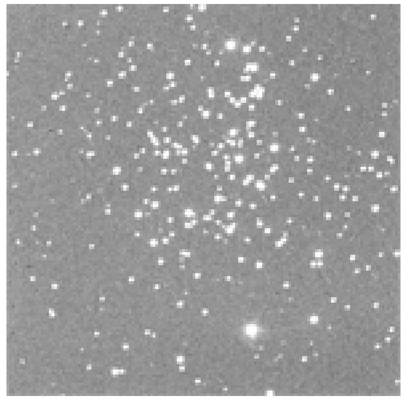


V-band Standard

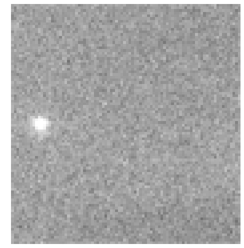
Figure 5: Reduced science images for M36, M67, and the Standard Star in the V Band



B-band M36



B-band M67



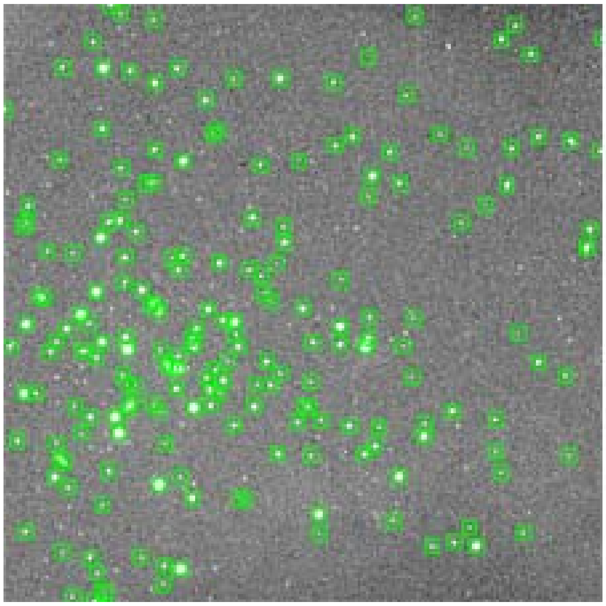
B-band Standard

Figure 6: Reduced Science Images for M36, M67, and the Standard Star in the B and V Bands.

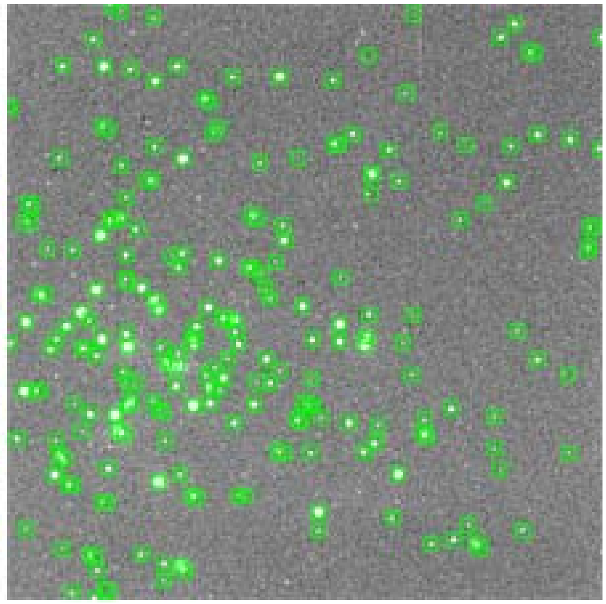
Finding the B and V magnitudes for the stars in the cluster requires aperture photometry. However, performing aperture photometry on each individual star is tedious and difficult. To help automate the process, we utilized an IRAF package called apphot. Within apphot, the two programs we utilized the most were daofind and daophot.

Daofind locates all the points in the image that are most likely stars based on parameters like shape and number of counts. By tweaking the parameters, we were able to get the program to find most of the stars in both clusters. The program created a coordinate file, which we could then utilize in the daophot program.

Daophot looked at the stars indicated by the daofind coordinates and performed aperture photometry, revealing useful information such as the flux, instrumental magnitude, sky background, and aperture area. This information could also be output to plain text files, which were useful for later analysis. We also were able to create region files in this way, and we loaded the region files into ds9 to make sure that the program was locating the stars properly.

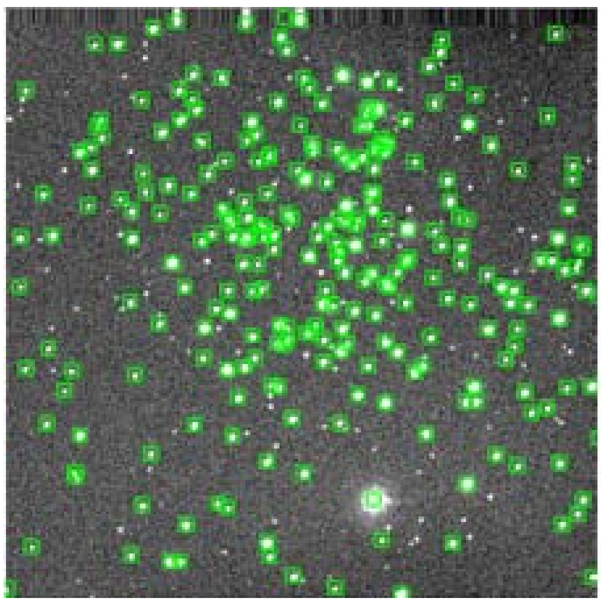


V-band M36 with overlayed region file output by daophot.

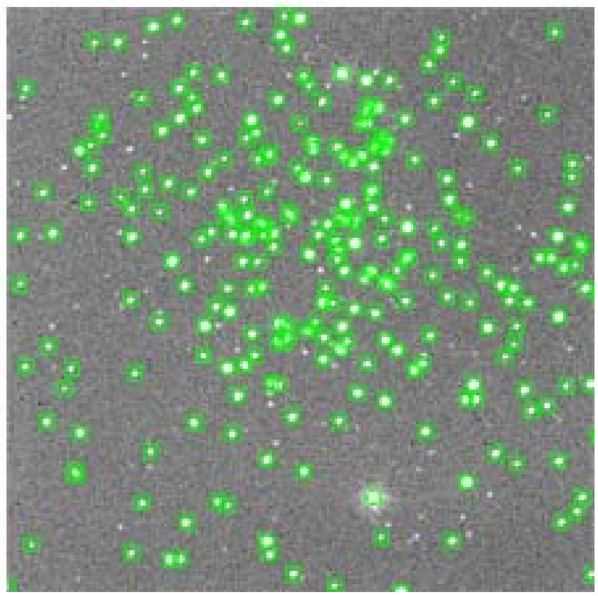


B-band M36 with overlayed region file output by daophot.

Figure 7: M36 in V-band and B-band with region file overlay



Aligned V-band M67 with overlayed region file output by daophot.



B-band M67 with overlayed region file output by daophot.

Figure 8: M67 in V-band and B-band with overlayed region files

We were then able to save much of the information, such as the coordinates and the flux, into a text file, which we could then read into IDL. We determined the instrumental magnitudes of the stars using the equation:

$$\mathbf{m_{inst} = -2.5 \log(counts/sec)}$$

We then could determine the actual B and V apparent magnitudes using the equation:

$$\mathbf{m = m_{inst} + z - Kx}$$

where K is atmospheric extinction, x is airmass, and z is the zero point magnitude. We determined the zero point magnitude using the standard stars because they had known apparent magnitudes. Z was different in each filter. For M67 in the B band, it was 19.43. In the V band, it was 19.723. For M36, it was 23.415 in the V band and 23.16 in the B band. These values for z also account for atmospheric extinction.

Uploading these values into IDL, we constructed arrays containing the B and V magnitudes, and then subtracted arrays with the B-V magnitudes. Finally, we could create H-R diagrams for both star clusters.

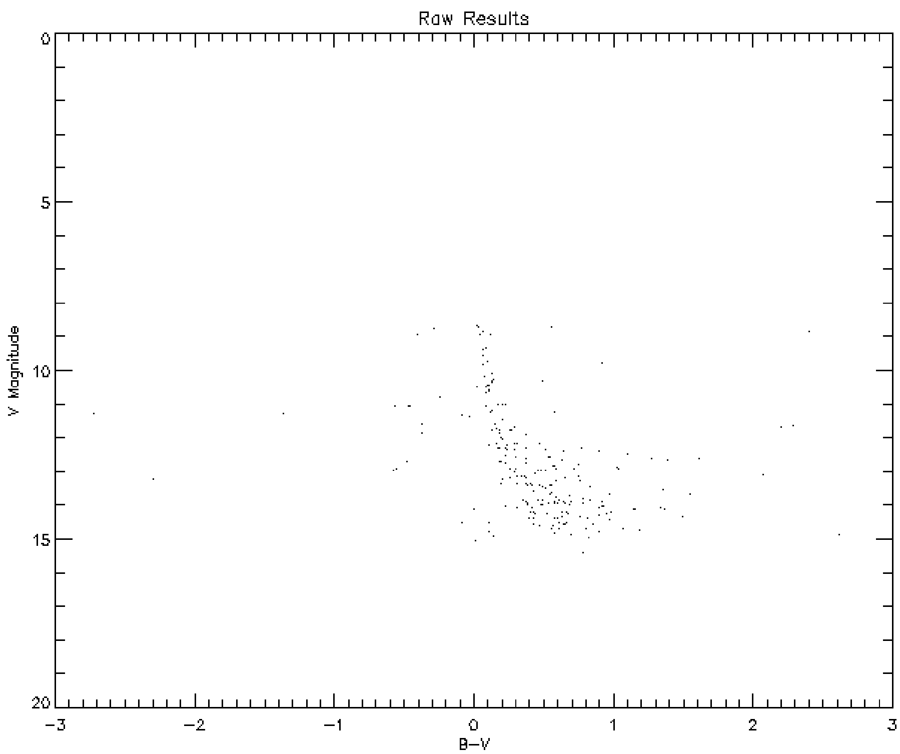


Figure 9: Raw H-R Diagram for M36

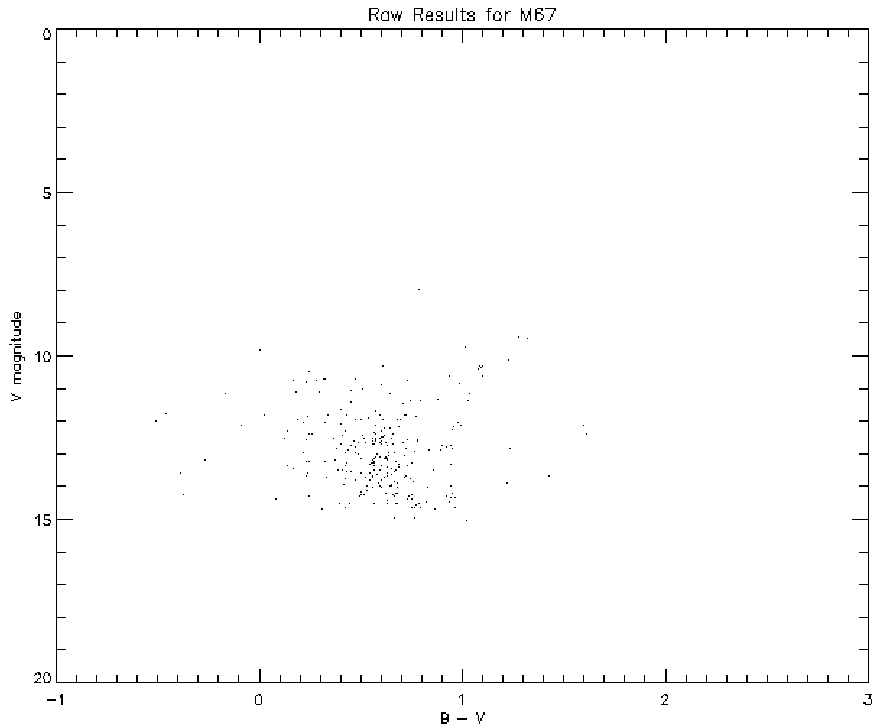


Figure 10: Raw H-R Diagram for M67

As you can see, many of the stars on the far left and right do not appear to follow a given pattern. These stars are likely not part of the cluster and will be removed later. However, many of the stars *do* fall into a pattern, and appear to be roughly linear until they turn off quickly. M67 seems to have a much rougher turn-off point than does M36. We will need to remove the excess stars in order to get a better analysis of the H-R diagram. This process is known as winnowing.

There was no easy automated process for winnowing, so we mostly just had to do it by hand. There were entire groups of stars, however, that needed to be removed outright. Anything with a B-V magnitude of less than 0 for M36 and less than about 0.3 for M67 was immediately removed. After that, the field was a lot less cluttered, so we were able to plot the ID numbers of the stars that we saved into our files on the plot itself. From this, we could go back into the original text files and pick out the ones that didn't belong. Although there is no guarantee that all stars in the winnowed plots are members of the star cluster, the new plots seem much more reasonable and easy to analyze.

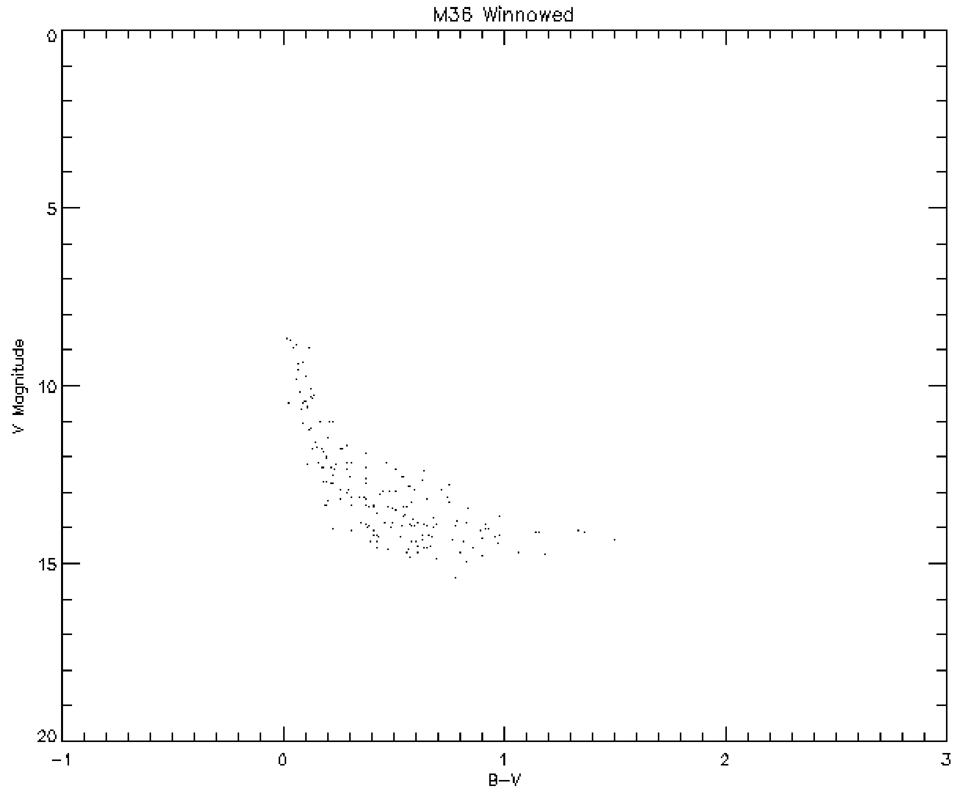


Figure 11: Winnowed plot of M36

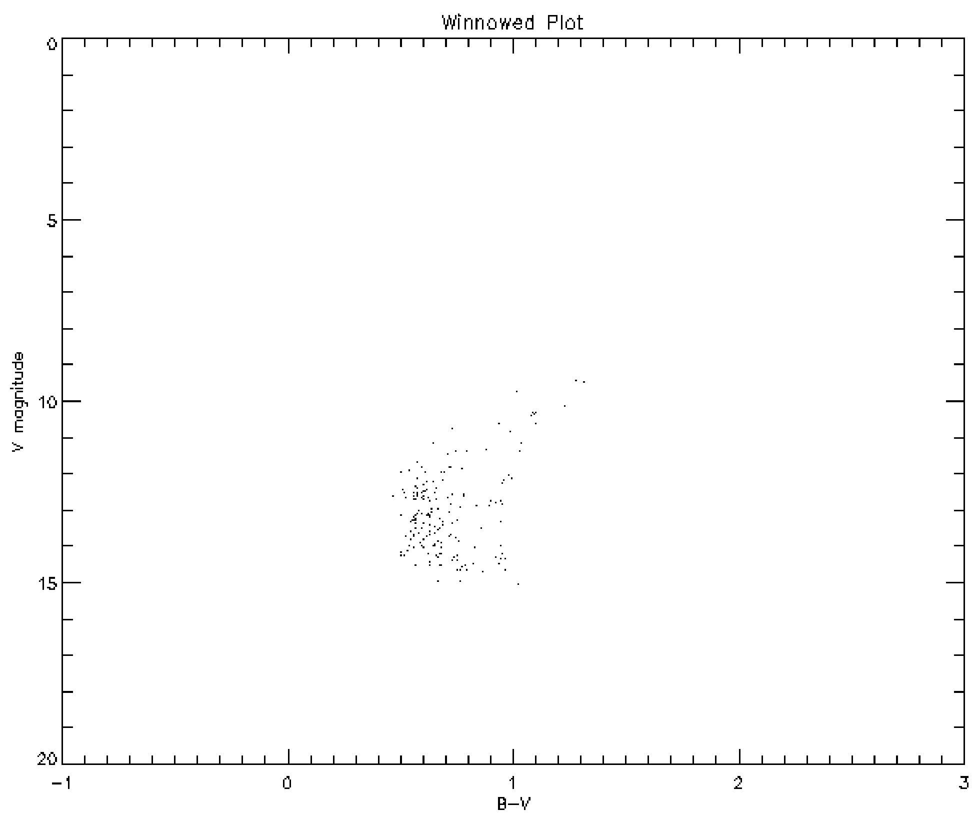


Figure 12: Winnowed plot of M67

We knew that the stars to the left and right of the clusters could be removed because, since B-V is independent of distance, a star closer to us or farther away from us would have a visible magnitude that did not correspond to its B-V in the same way that the cluster stars did. This would cause them not to be located with the main bunch of stars on the HR diagram. Thus, any stars well outside of the main pattern could be disregarded as not part of the cluster.

Next, we needed to perform the error analysis. The standard star magnitudes provided to us were quoted with no error. However, error was naturally introduced by our observations. For the error analysis of our star cluster, however, we could assume root N counting statistics.

$$\textbf{sigma}^2 \textbf{ = star counts + 2*sky counts + dark counts}$$

For the star cluster magnitudes, we found the error by adding their own magnitude errors in quadrature with the magnitude errors from the standard star. The B-V errors were then determined adding in quadrature the individual errors in the B and V band.

Results

The final H-R diagrams, complete with winnowing and error bars, are as follows:

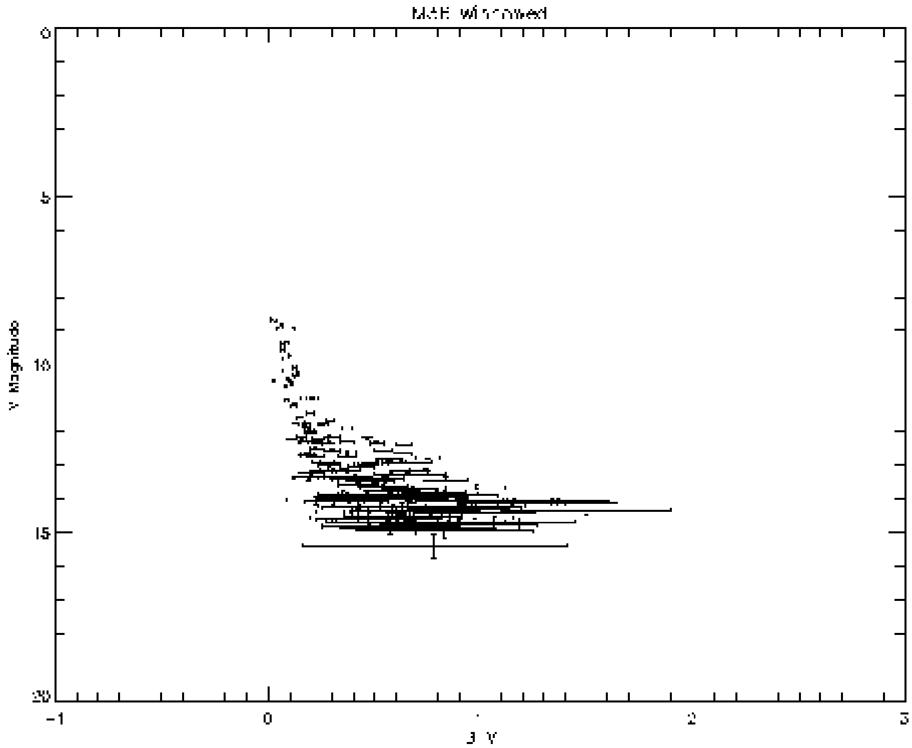


Figure 13: M36 Winnowed with Error Bars

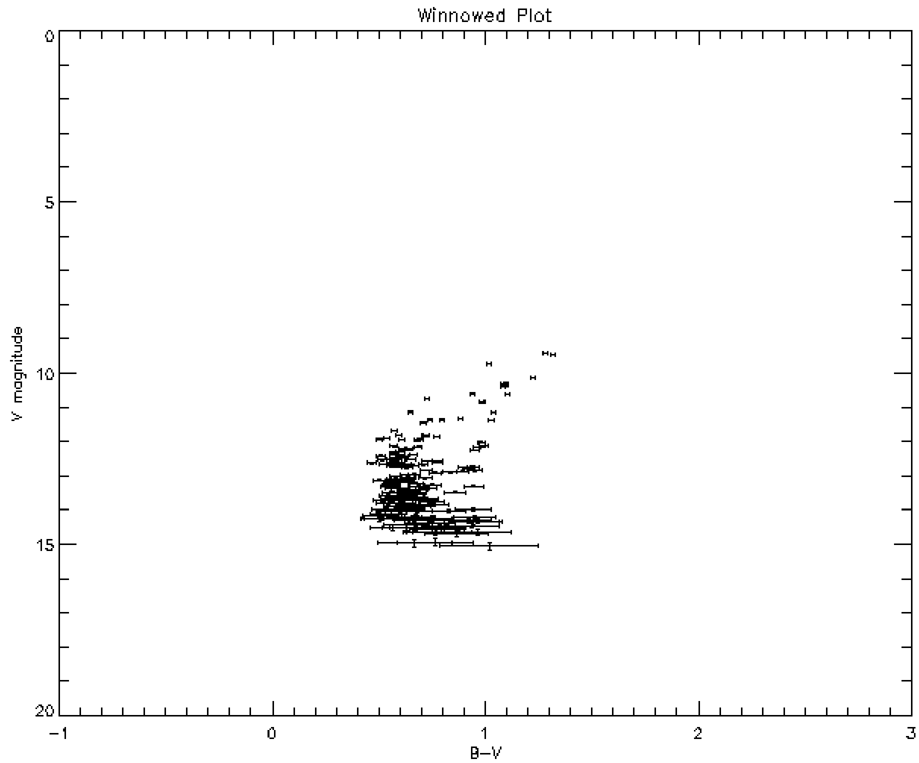


Figure 14: M67 Winnowed with Error Bars

Consistent with root-N statistics, the error bars are larger for larger magnitudes. The vertical error bars seem to be much smaller than the horizontal error bars. However, this is only a function of he axes of the graph. Because the x-axis is to a much smaller scale than the y, the error bars will naturally cover more area.

To determine the distance and the age of the cluster, we must also compare it to the Zero Age Main Sequence (ZAMS). In order to do this, we plotted the ZAMS with the numbers provided to us in the lab report. We then shifted the plot so that it matched the location of the ZAMS. From that, we could easily locate the main sequence turnoff point.

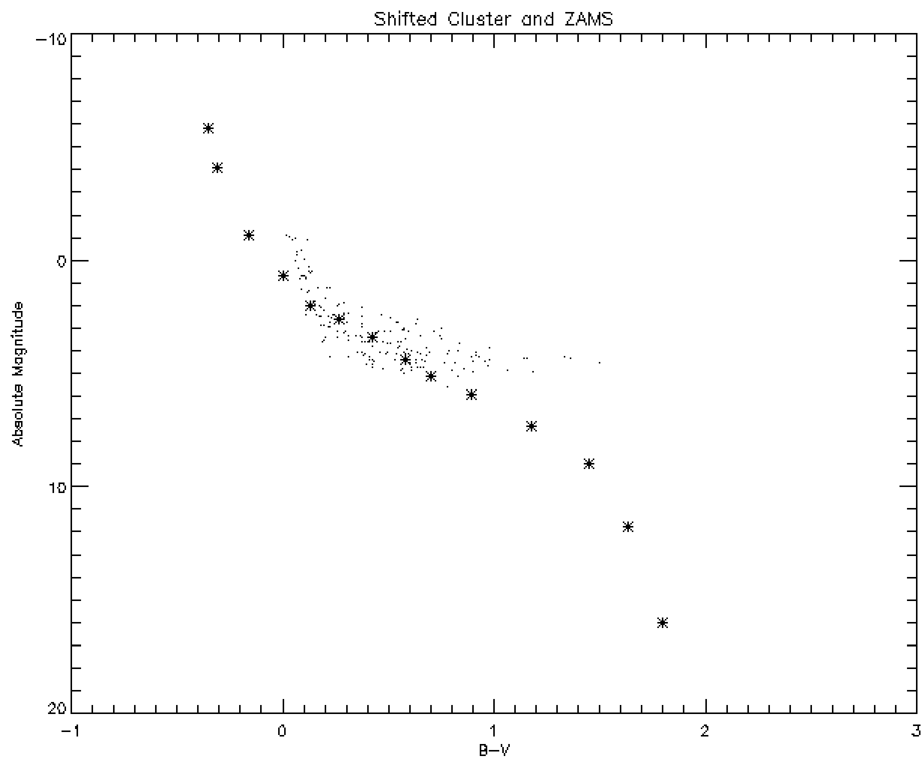


Figure 15: M36 with ZAMS Overlay

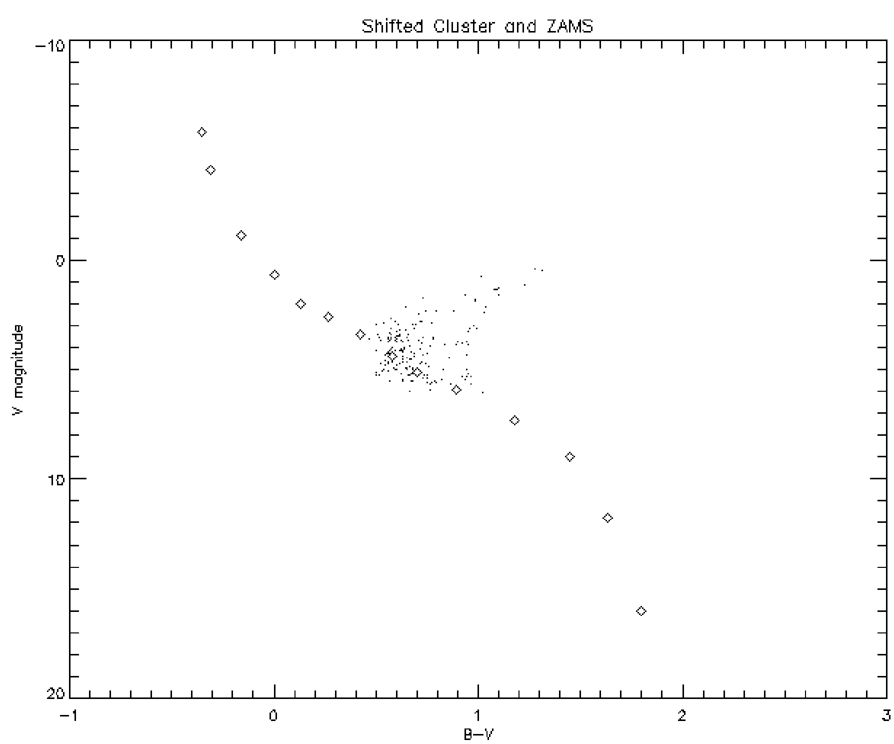


Figure 16: M67 with ZAMS overlay

From here we can see the main sequence turnoff point. For M36 the main sequence turnoff point is about B-V = 0.07 +/- 0.03. For M67, the turn off is around 0.55 +/- 0.1. These errors are so high because we had to determine the main sequence turnoff point by simply eyeballing the graph, and that comes with a lot of uncertainty. According to the tables provided by the lab, these turnoff points correspond to about an A3 type stars for M36 and G0 type stars for M67.

The lifetime of a star on the main sequence can be calculated by comparing its mass and luminosity to that of the sun using the equation:

$$\textbf{MS lifetime} = 1.1\times10^{10} \times (L_o/L)\times(M/M_o)$$

Using a table in the lab to determine L_o/L and M/M_o based on B-V values, we determined that an A0 star has a lifetime of ~4.5e8 years. Because we are using the values from a table, it is difficult to trace the error, but it will likely be substantial. We estimate that the age of the M36 star cluster is **4.5×10^8 +/- 2×10^8 years**.

Using similar methods, the M67 star cluster is roughly **9×10^9 +/- 2×10^9 years** old.

The next step was to find the distance to each cluster. B-V is independent of distance, unless the object in question is severely redshifted, which these clusters and most observable objects are not because they are relatively close to us. Therefore, combining the ZAMS graph with the cluster graph gives a way to compare apparent magnitudes to absolute magnitudes. When we plotted our H-R diagrams over the zero age main sequence, we had to offset our graphs a little bit to get them to "match up." This offset can help us determine the distance. To determine the distance also requires the distance modulus,

$$m-M = 5 \log (d/10pc)$$

To bring M36 into alignment with the ZAMS required 9.8 magnitudes. Therefore,

$$\text{Distance} = 10*10^{(9.8/5)} = \mathbf{912 \pm 30\ pc}$$

M67 required an offset of 9.0 magnitudes, so

$$\text{Distance} = 10*10^{(9.0/5)} = \mathbf{630 \pm 20\ pc}$$

The errors here are, again, quite large, because we were making a by-eye approximation of the offset. The error in the offset was estimated to be ~0.3 magnitudes.

Discussion

The ages calculated for the two clusters were considerably higher than the estimated ages we were able to find online. This was most likely because a lot of our values had to be interpolated by reading graphs and charts, and therefore lead naturally to a high degree of uncertainty.

There were also several problems with the daophot program we used to perform aperture photometry. The most pressing problem was that daophot re-centroids the stars when it runs the coordinates from daofind, meaning that, for example, star #57 in the v-band was not the same as star 57 in the b-band. Since most stars were the same in both filters, this was not enough to skew our results considerably because those stars would not appear in the correct place on the HR diagrams and would be removed in the winnowing process anyway, but it did cause a number of headaches. Another thing that the daophot program did was it sometimes "discovered" the same star several times. When found, these duplicates were checked against the region image to confirm that they were the same star and then removed from both the B and V band lists, a very long and tedious process. However, in the end it was still more convenient to do that than to run aperture photometry on each of the stars in the cluster individually.

Daophot had a feature that produced instrumental magnitudes that we could have used to determine the apparent magnitudes. However, these magnitudes were based only on the sheer amount of counts in the star and did not take into account exposure time. Therefore, we found it better to simply use the raw fluxes the program output and divide them by the exposure time, getting a consistent result in counts per second. With this, we found instrumental and apparent magnitudes using IDL.

In order to make the conclusions that we did about the age of the entire cluster, we made the assumption that all of the stars were formed at the same time. This is a fairly good assumption in terms of cosmological time scales. However, the reality is that the stars were not formed instantaneously, but rather within a few million years of each other. This adds a few million years of uncertainty to the age of the cluster. For most types of stars, a trifling number such as a few million years can generally be ignored, however keep in mind that "A few million years" represents a significant fraction of a large, luminous O or B-type star's main sequence lifetime, and so this uncertainty is especially high for newer clusters.

Uncertainty is also introduced when considering the amount of "fudge space." The stars at the main sequence turnoff point could have left the main sequence fairly recently, as early as a few million years ago. But on the other extreme, it might have happened a very long time ago, and the brightest remaining stars in the cluster might be almost ready to end their own main sequence lifetime. The method of determining main sequence turnoff points, therefore, is more of a constraint than an absolute determination of the cluster's age.