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Age of Stellar Clusters
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ABSTRACT

Open and Globular Clusters have long been objects of study, recently being understood to have significant information to tell us about galactic formation and evolution. Here, we use data of two such clusters, M44 and M14, from the Gaia Spacecraft to find the ages of these clusters and explore the implications of those determinations. We produce color magnitude diagrams of each cluster and then use theoretical isochrone models to attempt to match the ages of the clusters. First, we explore why this method of dating clusters would be significant and maybe even intuitive, then we trace through our method of isolating the cluster's stars, correcting it for extinction, and then fitting our isochrones. We determine the ages of M44 and M14 to be 9.0 Gyr and 10.0 Gyr, respectively, which are pretty significantly different than the contemporary accepted values. We hypothesize the reasons for this disparity, consider the implications of such a correction to the general model. We also take a detour to explore the correlation between cluster age and its distance from the Galactic Center, which leads to the conclusion that the Milky Way's bulge and halo, as epitomized by the Globular Clusters, are significantly older and, in the case of the halo, potentially of a different origin than its disk, for which we take the Open Clusters as a reasonable representative. This gives us a pretty detailed model of galactic evolution using only the most basic of stellar astronomy principles.

1. INTRODUCTION

Astronomers have been taking notice of star clusters for centuries, with exactly half of Charles Messier's original 110 catalogue objects being split between Open and Globular Clusters. As we discovered more about these objects, we learned that not only were these stars closely grouped from the perspective of Earth, but they were actually physically close to each other as well, relative to the size of, say, a galaxy. This lead to as many questions as it did answers though, because for what reason would so many stars in the vastness of space be grouped? Very quickly, we were able to divide star clusters into two major types: Open Clusters and Globular Clusters, and more research only made these types more distinct.

1.1. *Globular Cluster Formation*

Globular Clusters are perhaps the easier of the two to understand. These are massive amounts of usually older stars that have come together to the point where they are all gravitationally bound, orbiting the center of mass of the system. They are found almost exclusively in a two major places within a galaxy: the halo and the bulge. In both cases, they are notable for having spectra often both older and lower metallicity than the average stellar object in the galaxy. Recent works (Muratov & Gnedin (2010); Choksi et al. (2018)) have pointed to a merger-based model of Globular Cluster formation, where galaxies have a brief period at the beginning of their existences, when density of the gas clouds can still be very high and Globular Clusters can form. This is when the Globular Clusters in the bulge are theorized to have developed. Beyond this initial burst though, most Globular Clusters in large galaxies are hypothesized to have been gained from the consumption of Dwarf Galaxies, much like how the Sagittarius Dwarf Galaxy appears to be donating its Globular Clusters to the Milky Way (Dinescu et al. (2000)). These are often the clusters we find in the halo. Thus, between the two types, Globular Clusters are often the oldest objects in their associated galaxies, and the study of them can provide key insight to both the formation and development of the Milky Way and galaxies at large.

1.2. *Open Cluster Formation*

Open Clusters, on the other hand, are a more transient form of grouping. These clusters are found in active star forming regions like the Milky Way's disk, and they are comprised of the entire range of masses for stars including the most massive. Open Clusters, like Globular Clusters, are mutually gravitationally bound, but to a much looser extent. Unlike the Globular counterparts, however, we have actually been able to observe Open Clusters in the process of formation including the Rosette Nebula, NGC 2244 (Wang et al. (2008)). We know that they the stars all form out of the same Giant Molecular Cloud, usually when the cloud gets upset by some passing massive system or it collides with another cloud, triggering the collapse of the gas and the formation of stars. All of these stars form pretty simultaneously in a sort of chain reaction, and when about 10% of the mass of the cloud has been converted into stars, the radiation pressure is strong enough to begin dispersing the rest of the less-dense gas (Krumholz et al. (2019)). Many of the stars now have escape velocity for the cluster with 90% of the mass blown away, and thus it is inherently unstable. The rest of the system, still gravitationally bound, will inevitably get disturbed by a passing cloud or cluster whose tidal forces are enough to strip away members. This has been noted to happen about ever half-billion years, with cluster half lives usually being in the range of 150-800 million years (de la Fuente Marcos (1998)). In this way, we consider Open Clusters to be the building blocks of galaxies, and we can use them to determine a lot about the continuous formation of stars in active galaxies.

1.3. *Stellar Life Cycle*

An understanding of the standard stellar life cycle is crucial to seeing what we can learn from looking at these clusters. To start, each star is just a cloud of gas in space, slightly more dense than the gas a parsec or two away. Something disturbs the cloud, and the cloud begins to collapse on the center of mass, releasing energy from the previous potential energy, and we call it a protostar. Eventually the gas gets dense and hot enough that it begins Hydrogen fusion in the core. At this point, we consider the ball of gas a star, and it will continue nuclear fusion from there. The mass of the star is of particular interest to us for a couple reasons: First, the mass of the star directly changes the pressure and temperature in the core, which leads to greater rates of nuclear fusion, so the more massive a star is, the more energy is being released, and thus the brighter the star is. Another less obvious effect is that the more massive a star, the hotter the temperature of the outer layers will be due to this increased radiation, so the star will also release more photons of higher frequencies. This has the dual effect that more massive stars will be both more luminous and more blue. We can, and very often do, plot this relationship between luminosity and color, and we find that all the stars undergoing Hydrogen fusion form a continuous relationship we call the "main sequence."

Stars spend the majority of their lives in this main sequence, but what we're interested in here is what happens as they leave it. When stars exhaust all of the Hydrogen that exists in their cores, they start to rely on other sources of radiative energy to counteract the gravitational pressure of the outer layers of the star. Namely, as they begin to collapse, the layers of Hydrogen just outside the core begin to feel more pressure and get hotter until the point where those atoms too start to fuse, a process called Hydrogen-Shell Burning. This process happens relatively quickly, millions of years as opposed to the billions that a star can spend on the main sequence, and, for that brief period, the star will be both brighter because the increased rate in consumption and redder because the increased radiation pressure pushes the outer layers of the star further out, cooling them down. So on the plot of luminosity vs. color, we can trace the path of these stars up and to the right as they go through this shell burning process. Stars will continue this trajectory until they too exhaust this Hydrogen, at which point the more massive ones might begin fusing Helium, but that is beyond the scope of what we're interested in here.

The last thing that we want to note is that the time taken to reach this point, where all of the Hydrogen in the core is exhausted, is very mass dependent. Higher mass stars burn fuel so much faster that the lifetimes of higher mass stars is on the order of millions to tens of millions, while stars similar to our sun will be in the range of billions, and even more lower masses will be in the realm of tens to hundreds of billions and possibly longer.

1.4. *Tying It All Together*

The two key observations here are that

1. For both types of clusters, stars of all masses are born at approximately the same time

2. Stars of the same age and different masses will be in different stages of their evolutionary life cycle

Crucially, we can see what mass of stars are currently in the process of leaving the main sequence. We find that all stars of higher mass, since all the stars were born at the same time, have already left the main sequence, and all stars of lower mass will still be on it. This creates what's called a "turn-off point," and we can use it to age the cluster, as we explore in Section 3. The idea that we can model all these stars of various masses at the same point in time in their evolution is called an "isochrone," and while star clusters obviously don't match the theoretical models perfectly, the scales are close enough to where it makes for some very useful analysis.

1.5. *Motivation for Analysis*

Recall from Sections 1.1 and 1.2 that star clusters are able to give us deep insight into the formation and development of galaxies. By determining the ages of the Globular Clusters in the Milky Way, we can help potentially better determine both the age of the Milky Way and study the dwarf galaxies that the Milky Way has consumed in the past or is currently consuming, a topic of great interest in the last couple of years (see again Choksi et al. (2018)). The study of Open Clusters also gives us a better understanding of stellar formation in galaxies, especially in terms of local-scale dynamics (Krumholz et al. (2019)), where we can look at how the formation of stars in clusters can give rise to the variety of structures both on the small scale like relic filaments and larger picture like spiral arms of galaxies. This is a very active region of study due to the implications it has for both our understanding of the Milky Way and the universe at large.

2. DATA

We got all of the stellar data that we used for this project from the Gaia space observatory. We obtained the data for this project from the Gaia space observatory, which was launched by the European Space Agency in 2013 in order to collect high quality astrometric data on and to catalog massive amounts of stars with the goal of creating a 3D map of the nearby universe.

Specifically, we chose to use the data from Gaia's Data Release 2 (Lindegren et al. (2018)). We grabbed the data for all of the Open and Globular Clusters of interest, and then we were able to restrict our data to only be the one of each that we were targeting in this study.

The data points that we took greatest advantage of were the spacecraft's measured right ascension, declination, color magnitudes, and parallaxes. Right ascension and declination define the Earth based coordinate system that we can use to locate objects in the sky. Parallaxes are the observed changes of positions of nearby stars against the fixed background of more distant stars, due to the changing perspective as the Earth revolves around the sun. And finally, the color magnitudes of the stars are the amount of light that Gaia detects in each Bandpass (See Fig 1). Once we know how bright it is in both the Red Bandpass and the Blue Bandpass, we can get the color of the stars by subtracting the two magnitudes and then we can adopt one magnitude as the overall star's magnitude. In this case, we take color as B-R and then the magnitude as that in the Red Bandpass. This gives us an analogous luminosity surrogates that, along with the color, we can use to complete our analysis.

3. ANALYSIS

3.1. *Cluster Ages*

Once we specified the target clusters, we used the right ascension and declination of the stars to narrow down the angular distance from the center of the cluster that we considered to still be in the boundaries of the cluster. We empirically determined this angular distance threshold to be 15 arcminutes for M44 and 6 arcminutes for M14. This let us cut away some of the outlying stars that were close enough to the cluster to be counted but were actually not part of it.

We then observed the color magnitudes for all the stars, with the magnitude in the red band pass plotted against the color of B-R. This gave an effective color magnitude diagram.

Next, we could do a bit more trimming of outliers by using Gaia's parallax data, which essentially tells us the distance to stars.

$$d[pc] = \frac{1}{p['']} \tag{1}$$

If a star was not within a specified distance threshold from the expected distance of the cluster, we were able to cut it from consideration. These parallax thresholds were again manually determined to be 25pc and 50pc, for M44 and M14, respectively.

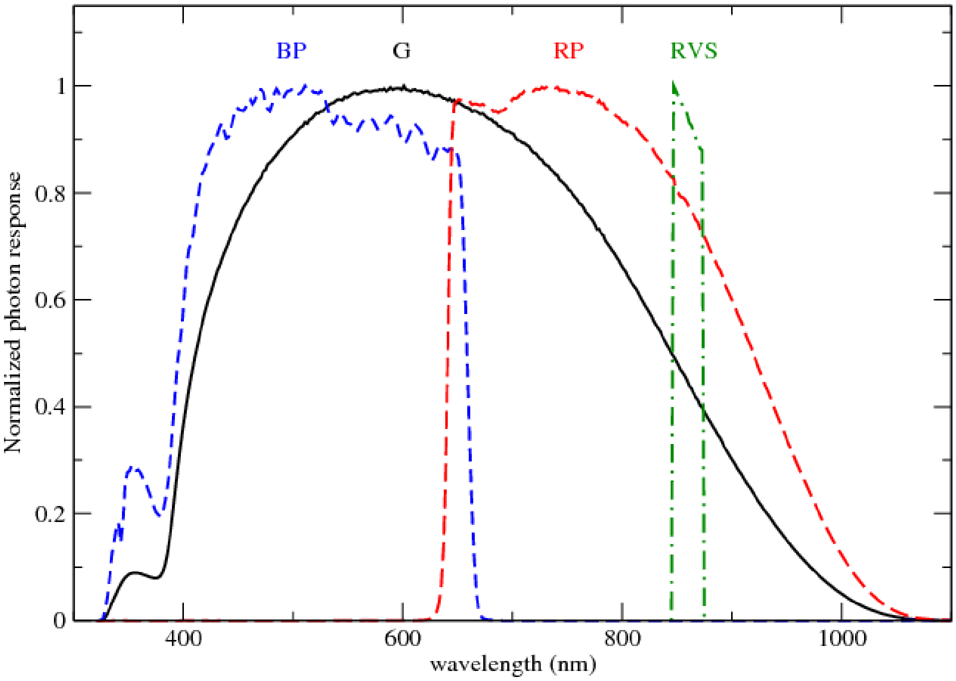


Figure 1: Four of the most prominent bands that Gaia operates in, Green: G, Blue: BP or G_{BP}, Red: RP or G_{RP}, and Gaia's Radial Velocity Spectrometer: RVS. The Bandpasses are shown with the various wavelengths of light incident upon the filters plotted on the x-axis and the value for the relative amount of that photon transmitted by the various filters on the y-axis. The BP and RP values are the ones important to us here, because our measurements in those Bandpasses collect all the photons that pass through this filter and use that to determine the magnitude. Understanding the relative transmittances of the filters, blue photons for BP and red for RP is important for our determination of a star's color.

Following this, we can adjust our observed color values for interstellar reddening and extinction. This is needed because the space between us and the observed clusters is filled with gas and dust that will tend to scatter the shorter wavelength, bluer light, making the stars look redder and dimmer. We can account for this by applying a manual blueshift back to the pre-extinction value. The necessary redshifts were 0.0 for M44 and 0.4 for M14, which is pretty reasonable given that the Gaia-determined distances were 177pc and 9290pc, respectively.

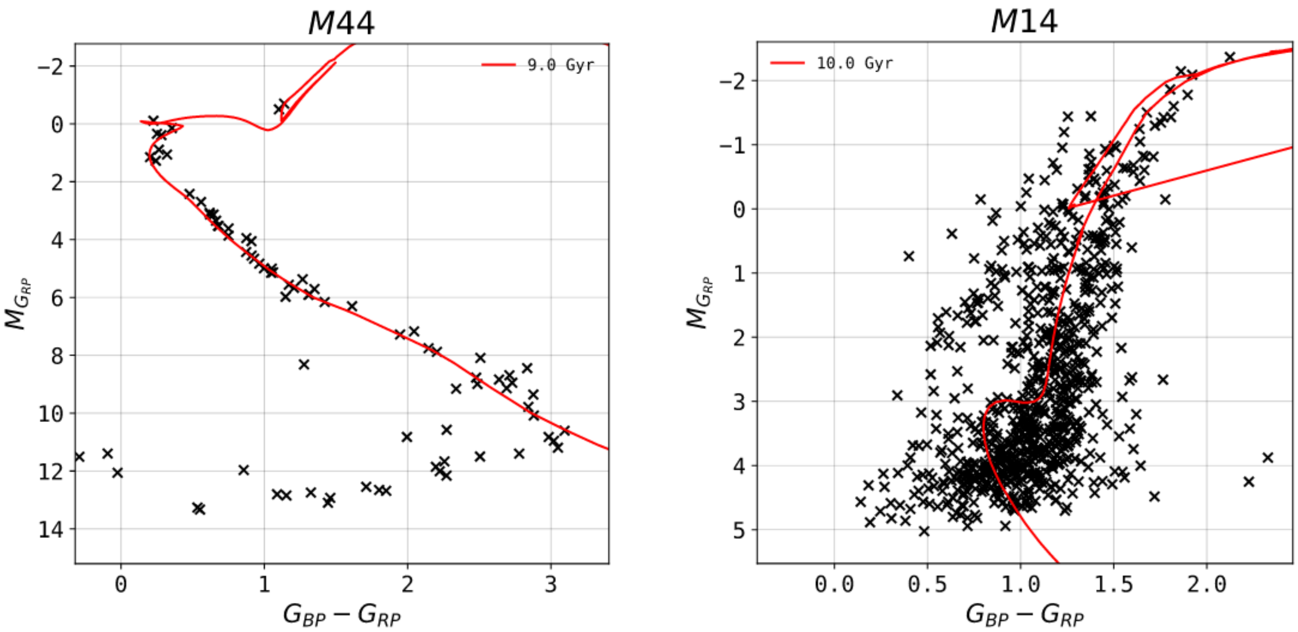
Once we understand this, we can plot our theoretical models for the various evolutionary positions of the different mass stars at the same age called an isochrone, and then we match up our observations with the nearest one. This will tell us the age of the cluster by showing us how the turn-off point (see Sec. 1.4) of the stars matches where a hypothetical one would be for the cluster of various ages.

These isochrones were taken from a website maintained by the Astronomical Observatory at Pavoda. We used the Kroupa Initial Mass Function (Kroupa (2001)) to find the locations of the stars in the diagram at their various ages. We then compared the distributions of stars to isochrones between the ages of 7.6-10.0 Gyr.

All of this analysis eventually led us to the plots Figures 2. The age of M44 was determined to be approximately 9.0 Gyr, and M14 was determined to be at least 10 Gyr. Only one other person in the class, Melissa King, analyzed M44, and she also arrived at an age of 9.0 Gyr with an almost identical plot. Andrew Marsden also analyzed M14 and arrived at the same 10 Gyr conclusion, but his write-up was not provided and thus I can only speculate that he had similar motivations.

3.2. *Distances from the Galactic Center*

Once we had the ages of all of our clusters, we wanted to put this in the context of galaxy formation and evolution, so this required that we know where the clusters are relative to the Galactic Center, Sagittarius A*. Specifically, we are interested in just the distance of the cluster from the Galactic Center. In order to move towards this, we need to know a few things.



(a) M44 plotted against a 9.0 Gyr isochrone.

(b) M14 plotted against a 10.0 Gyr isochrone.

Figure 2: The black marks in the image represent stars determined to be in the clusters based on an angular directional cutoff and a parallax distance cutoff. We then plotted the color of the star as the magnitude in the blue bandpass minus that in the red on the x-axis and a stand-in for the luminosity as the magnitude in the red bandpass on the y-axis. This gives us an effective Color Magnitude Diagram because we have plotted essentially luminosity vs. color. Then, once we have the stars all correctly plotted, we added a line representing the locations of all masses of stars at a given age called an isochrone. (a) M44's similarity to the 9.0 Gyr isochrone tells us that it is 9 billion years old. (b) M14's similarity to the 10.0 Gyr isochrone tells us that it is at least 10 billion years old.

First, we need to calculate the angular separation of the cluster from Sagittarius A*. This is pretty straight forward to do since we have the Right Ascension and Declination of the clusters from the Gaia data and the Right Ascension and Declination of the Galactic Center are widely known. With these in hand, we can simply turn to a formula developed just for this purpose:

$$cos(\theta) = cos(\alpha_1 - \alpha_2) sin(90^\circ - \delta_1) sin(90^\circ - \delta_2) + cos(90^\circ - \delta_1) cos(90^\circ - \delta_2) \tag{2}$$

This gives us the separation in degrees, and then it is an easy conversion to radians.

Then once we have the angular separation, we can use the fact that we know two sides to our distance triangle and one of the angles to get the last. We know the distance to the clusters from the Gaia data as well, and we know the distance to the Galactic Center, 7860 pc, from the extensive research that has been done on the subject. Now, we can just use the law of cosines with these values to get the distance to each cluster.

$$c^2 = a^2 + b^2 - 2 * a * b * cos(\theta)$$

$$c = \sqrt{a^2 + b^2 - 2 * a * b * cos(\theta)}$$

We plotted our results from running this computation for each cluster against the determined age of the clusters in Figure 3.

4. DISCUSSION

The results that we have arrived at are perhaps even more meaningful when put into the context of the average Open and Globular Clusters. Collecting our entire class's results together gives us the graph in Figure 3. We can see a clear split between the two types of star clusters, where the Globular Clusters are significantly older than the Open counterparts. This should not be super shocking given what we know about the types of clusters, but the specific values for the ages we arrived at are curious.

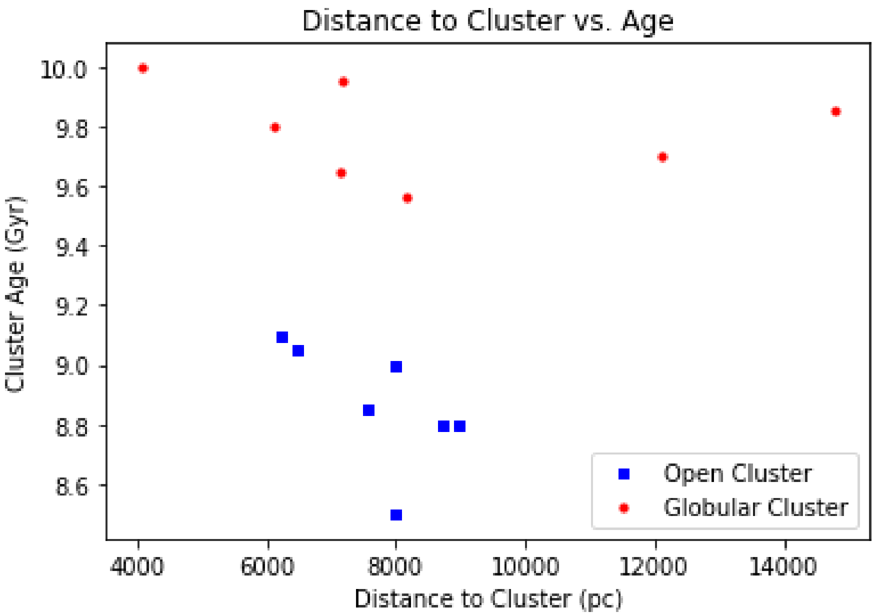


Figure 3: Open and Globular Cluster observations provided by our class. This is plotting the distance in parsecs to the center of the cluster on the x-axis and the derived age of the cluster on the y-axis in billions of years. Open Clusters are shown as blue squares and Globular Clusters as red circles. The encouraging thing to note with this plot is that the two types of star clusters form two distinct populations. The perhaps less thrilling result is that the values for Open Clusters are generally about an order of magnitude above the accepted value for ages and the Globular Clusters fall short by about a third. Another interesting thing to note is that not all globular clusters are further from the galactic center than the open clusters, which suggests that there are some in the Bulge as well as the Halo.

First, we can compare the values that we determined with the consensus models for the two cluster types. As a class, we arrived at Globular Cluster ages in the ballpark of 9-10 billion years. This is actually pretty consistent with the generally agreed-upon age range centered at about 12.7 Gyr. Open Clusters, on the other hand, are expected to be much more short-lived systems, on the order of tens to hundreds of millions of years, and they aren't known to ever stay gravitationally bound above one billion years. This presents a pretty significant challenge to our class's range of 8-9 Gyr, and it is not obviously clear why the determinations are so off of the mark. One hypothesis could be that this isochrone matching method does not hold up for Open Clusters in the same way it does for Globular Clusters. This idea is explored by Monteiro et al. (2010), and they are able to develop a Machine Learning-based technique that achieves reasonable success. Perhaps, then, our technique just isn't robust enough. Moving beyond this though, the general observation that the halo stars are older than the disk stars is consistent with the current hypothesis that Open Clusters are signals of active star formation we discussed in in Section 1.2 while Globular Clusters are remnants of the early galaxy as we explored in Section 1.1.

Next, the distance distributions for the two types of clusters is interesting and potentially unexpected. If all Globular Clusters were to live in the halo and all Open Clusters in the disk, we would expect that Globular Clusters, on average would be further away. Instead, we see that while some are indeed much further away, there is a significant population closer or as close to the galactic center as the open cluster. So these two sets of observations combine to tell us two things. First, it supports the model of early gas clouds condensing into Globular Clusters before angular momentum could take over and spin everything up into the galactic disk, where we now see all of the active star formation. The Globular Clusters, at 9 to 10 billion years old are likely older than the Milky Way disk, and this is consistent with the observations that the thin disk was formed as recently as 8.8 billion years ago (del Peloso et al. (2005)).

The scatter in the distances of Globular Clusters is also compelling for a few reasons. The ones close to the center of the galaxy are more than likely in the Galactic Bulge, since the disk is full of gas and dust that would cause continuous star formation. This means that at the center of the Milky Way, and probably most galaxies, there must be some region akin to a small elliptical galaxy, where star formation has already used up most of the gas and dust and orbits are more random to avoid disk formation. This region must also be full of significantly older stars and have developed early in the galaxy's history. Now, the further out Globular Clusters could also lend at least some credence, as well, to the idea that Globular Clusters could be donated from smaller, less active Dwarf Galaxies that the Milky Way consumes. We find this to be consistent with what we know as well, since the wildly different angular momentum found in the Globular Clusters have a much less clear meta-pattern out here, and also with how dense these clusters are, it seems unlikely that such a large gas cloud just happened to form and stay in the halo. So even if our derived values for the cluster ages don't directly suggest such a strong parity being only 1 Gyr apart on average between the two types, the consistency of the observations do at least hint at some deeper, underlying pattern to explore.

5. CONCLUSION

We determined the ages of our clusters solely using isochrone matching, using Color Magnitude Diagrams produced from Gaia's Red and Blue Bandpasses for the clusters M44 and M14 and isochrone models from the Astronomical Observatory at Pavoda. The imprecision of our method really had an impact on the general success of the measurements. For one, while both Melissa King and I estimated the age of M44 to be 9.0 Gyr based off of this data, the widely-accepted range for the cluster's age is .60-.70 Gyr. This is obviously a pretty significant overestimate, and it could represent a serious problem with using this method, especially since the observed value so wildly overestimates the understood physical limits for Open Clusters. Next, Andrew Marsden and I determined that M14 most closely approximated the oldest isochrone in our range, the 10.0 Gyr model, although a quick look at Figure 2(b) will show that the turn-off point is lower than that which is modelled. This suggests that it is possible that the value actually determined might have been close to the agreed upon age of 13 Gyr had we had more isochrone models to work with. Overall, given the limitations of the method, the results were pretty reasonable, and it was a valuable exercise in looking into the building blocks of galaxies.

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