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Parameter Determination for Old Open Cluster NGC 188

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ABSTRACT

NGC 188, one of the oldest open clusters in the Milky Way, provides a unique insight into the history of the universe. NGC 188 has been historically used as a reliable test subject for various methods of determining data about star clusters. Because of its importance in the field of astronomical study and due to its unique age, this paper serves to independently verify the data found by previous research and to determine the age, metallicity, distance, and mass of open cluster NGC 188. Methods involved color magnitude diagram creation, isochrone fitting, and mass determination using the virial theorem. This research verifies that NGC 188 has an age of 6 billion years, a metallicity of 0.2 [Fe/H], a distance of 1348 parsecs, and a mass of 1392 solar masses.

Introduction

When looking at the sky, there appear to be areas in which there are a higher concentration of stars. These groups of stars are called star clusters. Star clusters are physically associated groups of stars that are bound together by their mutual gravitational attraction [1]. One subsection of star clusters is called an open cluster, which contains dozens to hundreds of stars all formed from the same nebula. NGC 188 is one such open cluster.

NGC 188 was discovered in 1825 by John Hershel and is in the constellation Cepheus. This cluster has a center with a right ascension of 12.11° and declination of 85.25°. Historically believed to be the oldest open cluster, NGC 188 stars represent the old stellar population of the galactic disk. As one of the oldest star clusters in the Milky Way, NGC 188 was selected for this research as it provides an opportunity to view the later stages of stellar evolution and the formation of the galactic disk [2].

For data collection, Gaia and The Sloan Digital Sky Survey (SDSS) databases were used. Gaia is a widely used database in astronomy research that is reliable for the portion of the sky in which NGC 188 is located [3]. SDSS data was also available for the portion of the sky in which NGC 188 is located and was therefore used to supplement Gaia data [4]. From these sources, data on color magnitudes, parallax, proper motion, and radial velocity were retrieved. Dartmouth generated isochrones were used with integer ages between 0 and 15 and metallicities between -2.4 and 0.4 with an interval of 0.2. To find the distance, age and metallicity of NGC 188, a color magnitude diagram was created, then fitted to an isochrone to verify the distance to the cluster. The radial velocity standard deviation in the virial theorem was used to find the mass.

Methods

Isolating Stars in the cluster

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Journal of Student Research
Volume 10 Issue 4 (2021)

To determine parameters of a star cluster, it is first necessary to identify the stars that belong to that star cluster. It is impossible to know the proximity between stars by appearance alone; stars close together in the sky may be millions of parsecs (pc) apart. Therefore, the first step in parameter determination is isolating stars within the cluster.

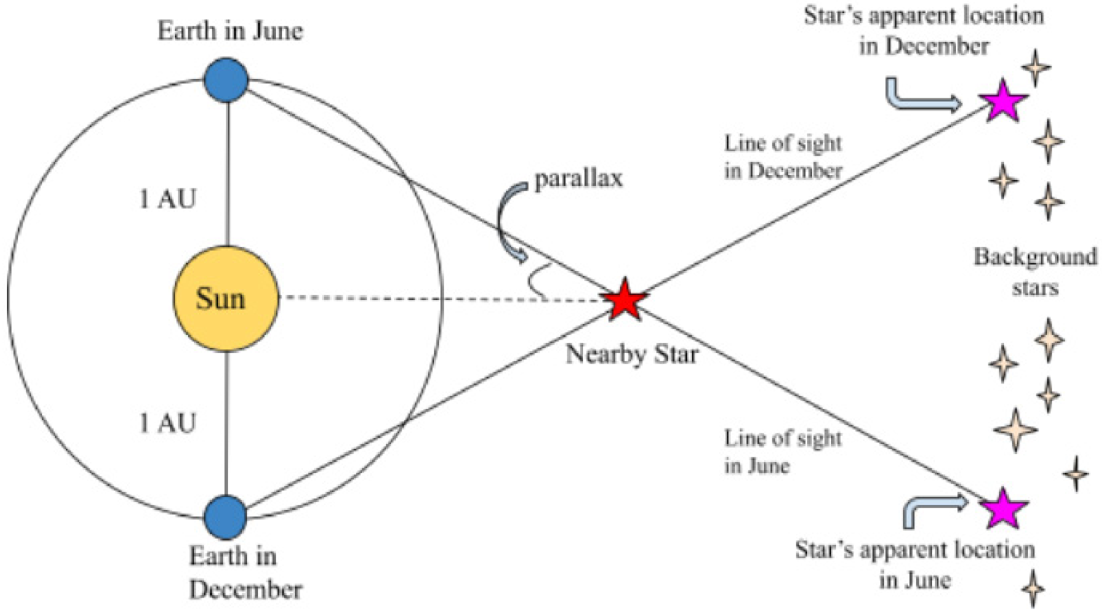

Figure 1. Diagram of parallax in relation to background stars. The red star is a foreground star that appears to move in relationship to background stars as the Earth orbits the Sun. As the line of sight to the star changes, so does the star's apparent position among background stars. The apparent motion is called parallax.

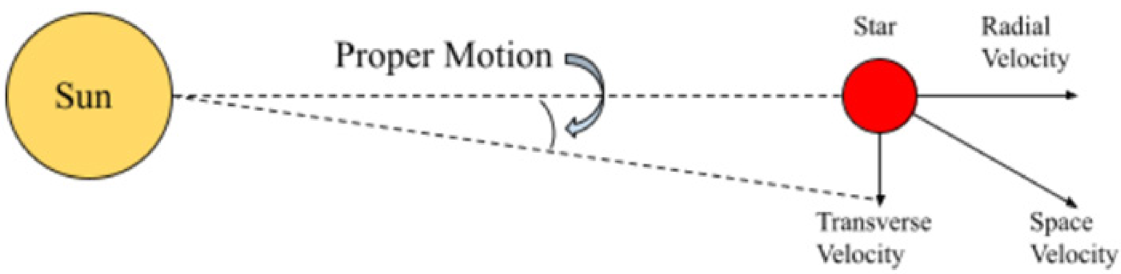

Figure 2. Diagram of proper motion in relationship to vector quantities of the total velocity of a celestial body. The velocity of the star in space can be broken into various components based on their relationship to the line of sight from the sun. The proper motion is the angle created by how a celestial body appears to move from Earth.

Stars in the same cluster will have similar parallax and proper motion values. Figure 1 shows how a celestial object appears to move against the background stars as Earth orbits around the sun, which is called parallax. Parallax is the apparent movement of a star when viewed from two different parts of the Earth's orbit. The stars in a cluster are near each other, so they will appear to move a similar amount as the Earth orbits the Sun. Because stars in a cluster are gravitationally bound, they will move together and share a common proper motion. Figure 2 shows how the velocity of a celestial object appears as an angular vector quantity, which is called proper motion, to an observer.

To isolate stars with similar parallax and proper motion values, stars that have either a parallax or proper motion outside of 1.5 standard deviations from their respective average value were excluded. The average parallax value was recalculated and stars that were outside 1.5 standard deviations from the new average were also excluded. Stars that were likely a part of the NGC 188 cluster were isolated through these methods of star exclusion.

Age of Stars in Clusters

All the stars in a star cluster formed at approximately the same time, as any slight difference in age is insignificant compared to the time frame of a star's life. Therefore, all the stars in a star cluster can be considered approximately the same age. [5]

Metallicity in Clusters

Metallicity is defined as the abundance of elements heavier than hydrogen and helium and is expressed by an iron to hydrogen ratio. The stars in an open cluster were all likely formed from the same cloud of dust and will therefore have the same metallicity.

Utilizing Color in Star Clusters

In astronomy, color is defined as the difference in magnitude between two color filters. The Gaia database analyzes light in a variety of ways. A broad pass band, G, collects as much light as possible. This light is then analyzed to isolate various colors, including blue (bp) and red (rp). Therefore, Gaia would express color as the difference between two of these filters; for example, one color could be expressed as bp-rp. A star with a high bp-rp output is redder than a star with a low bp-rp output, as magnitude decreases with luminosity [3].

A color magnitude diagram is where the color and magnitude of starlight are isolated for each star in a cluster and then plotted against each other. The band of stars that is generated through this technique is called a main sequence line. The shape of the main sequence line is impacted by the age and metallicity of the star cluster; the evolution of a star's color and brightness over time is impacted by its metal content. Therefore, star clusters with the same age and metallicity will create the same main sequence lines [1].

In order to determine the age and metallicity, a color magnitude diagram was created from the stars remaining after exclusion. The color bp-rp was used on the x-axis and the rp magnitude was used on the y-axis. Stars that were not at a position with a high enough point density were then excluded to isolate the main sequence line. This line was compared with theoretical color magnitude diagrams called isochrones for a range of ages and metallicities. A similar effect can be observed with a change in metallicity. Different isochrones were compared to the color magnitude diagram with various combinations of different metallicities and ages. The metallicity and age of the isochrone that best matched the color magnitude diagram was recorded.

Determining Distance

Color magnitude diagrams can be used to determine the cosmic distance scale. Stars in a star cluster are approximately the same distance away from earth, as any variation in distance between stars is insignificant compared to the distance to earth. Stars that are bright but distant may appear dimmer than nearby low magnitude stars. In star clusters, the distance to the stars from earth is approximately the same, so one can assume that stars that appear brighter are intrinsically brighter.

Color magnitude diagrams with the same age and metallicity have a generally similar shape regardless of which cluster they describe but will be shifted on the y-axis based on their distance from earth. This shift is because the distance to the star cluster will affect how bright it appears. To determine the distance modulus, one can find the average distance between the color magnitude diagram and the isochrone [1].

Determining Mass

The mass of clusters can be determined by using the Virial theorem.

$$M = \frac{v^2 R}{G}$$

Equation 1: The Virial Theorem

The virial theorem is a method of relating the total kinetic energy of a stable, self-gravitating, spherical distribution of objects to the gravitational potential energy of the objects. The theorem states that the total kinetic energy of the objects is equal to -1/2 times the total gravitational potential energy [6]. By substituting in values where v is the standard deviation of the radial velocity of stars in a cluster, G is Newton's gravitational constant and R is the radius of the cluster in parsecs, one can determine the mass of the cluster M.

Data Set Characteristics for NGC 188 in Gaia and SDSS Databases

Data was drawn from the Gaia and SDSS databases to verify the parameters of NGC 188. The quantity of star data points in the portion of the sky before cluster exclusion were assessed, and then recounted after membership exclusion. The minimum and maximum values for bp, bp-rp, parallax, proper motion, and radial velocity were identified in order to have an idea of the range of data values. The standard deviations and average values of the proper motion and the parallax were calculated as a part of the cluster membership exclusion process. The standard deviation of radial velocities was calculated to be used in mass determination.

Table 1: Characteristics of Gaia and SDSS Data Describing NGC 188

	Gaia	SDSS
Data Set Size:		
Number of datapoints before exclusion:	1859	784
Number of datapoints after exclusion:	1661	692
Minimum:		
bp value	9.61	8.72
bp-rp value	-0.267	-0.20
Parallax in milliseconds	-2.85	-0.02
Proper motion in arcsec/year	0.15	0.33
Radial velocity in m/s	-94.24	-104.66
Maximum:		
bp value	20.53	14.30
bp-rp value	2.80	1.98
Parallax in milliseconds	10.83	5.06
Proper motion in arcsec/year	75.84	63.09
Radial velocity in m/s	36.73	12.92
Standard deviation:		

Parallax in milliseconds Proper motion in arcsec/year Radial Velocity in m/s	6.93 0.76 28.77	10.4 1.03 24.93
Average: Parallax in milliseconds Proper motion in arcsec/year	 4.92 0.64	 8.99 1.26

Results

Comparing Data Set Characteristics for NGC 188 in Gaia and SDSS Databases

The magnitude values are relatively similar between databases, but the rest of the data contains some discrepancies. For example, Table 1 shows that Gaia has more available data about the stars in this cluster as compared to SDSS. There are also relatively large differences between the radial velocity, proper motion, and parallax values in the two databases. These differences between data sets may cause subsequent differences between calculations using the data.

Elimination using Proper Motion

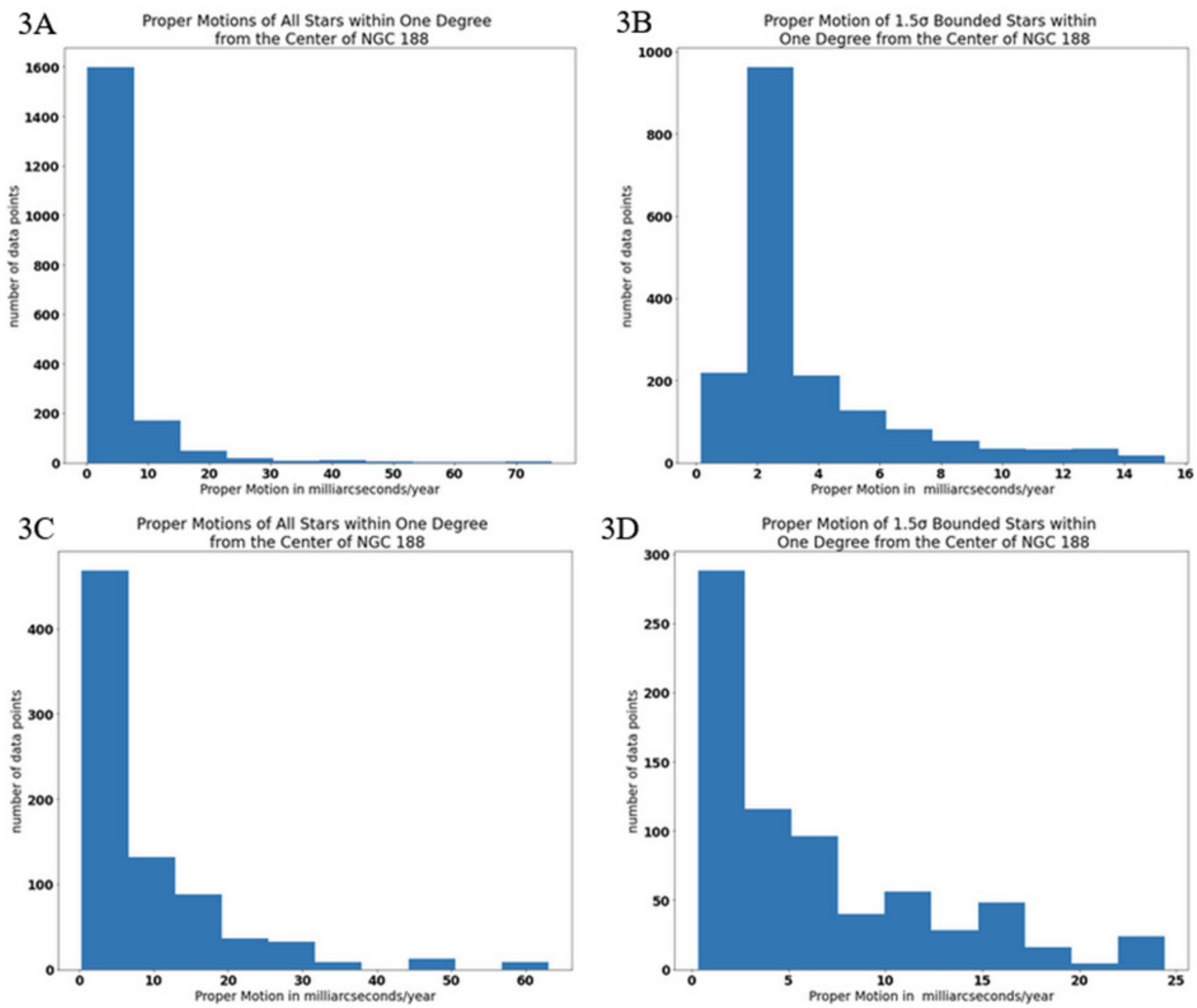

Figure 3. Histograms showing the proper motions of stars within one degree of the right ascension and declination of cluster NGC 188. Histograms 3A and 3B show proper motion from the Gaia database while 3C and 3D show data from the SDSS Database. Histograms 3A and 3C show all the values within the one-degree range, while 3B and 3C contain data of stars within 1.5 standard deviations from the mean proper motion value.

Figure 3 contains four histograms that display how the star membership was identified through exclusion using parallax data from the Gaia and SDSS databases. Histogram A in Figure 3 shows the proper motion of stars in the portion of the sky around the center of NGC 188, regardless of whether these stars belong to NGC 188 using Gaia data. Histogram 3A has most frequent values in between 0 and 10 milliarcseconds/year. Histogram 3B shows stars with frequently occurring proper motion values, as the stars outside 1.5 standard deviations from the average parallax have been eliminated. 3B therefore likely shows the parallax values of stars within the cluster. The most frequent values in histogram 3B are in between 1.5 and 3 milliarcseconds/yr. Histograms 3C and 3D show the proper motion values from the SDSS database. Like 3A, 3C shows unbounded proper motion values. 3C has most frequent values in between 0 and 7 milliarcseconds/year. Histogram 3D shows stars that have frequently occurring proper motion values from SDSS, and the most frequent values in 3D are between 0 and 3 milliarcseconds/year.

HIGH SCHOOL EDITION
Journal of Student Research
Volume 10 Issue 4 (2021)

Elimination using Parallax

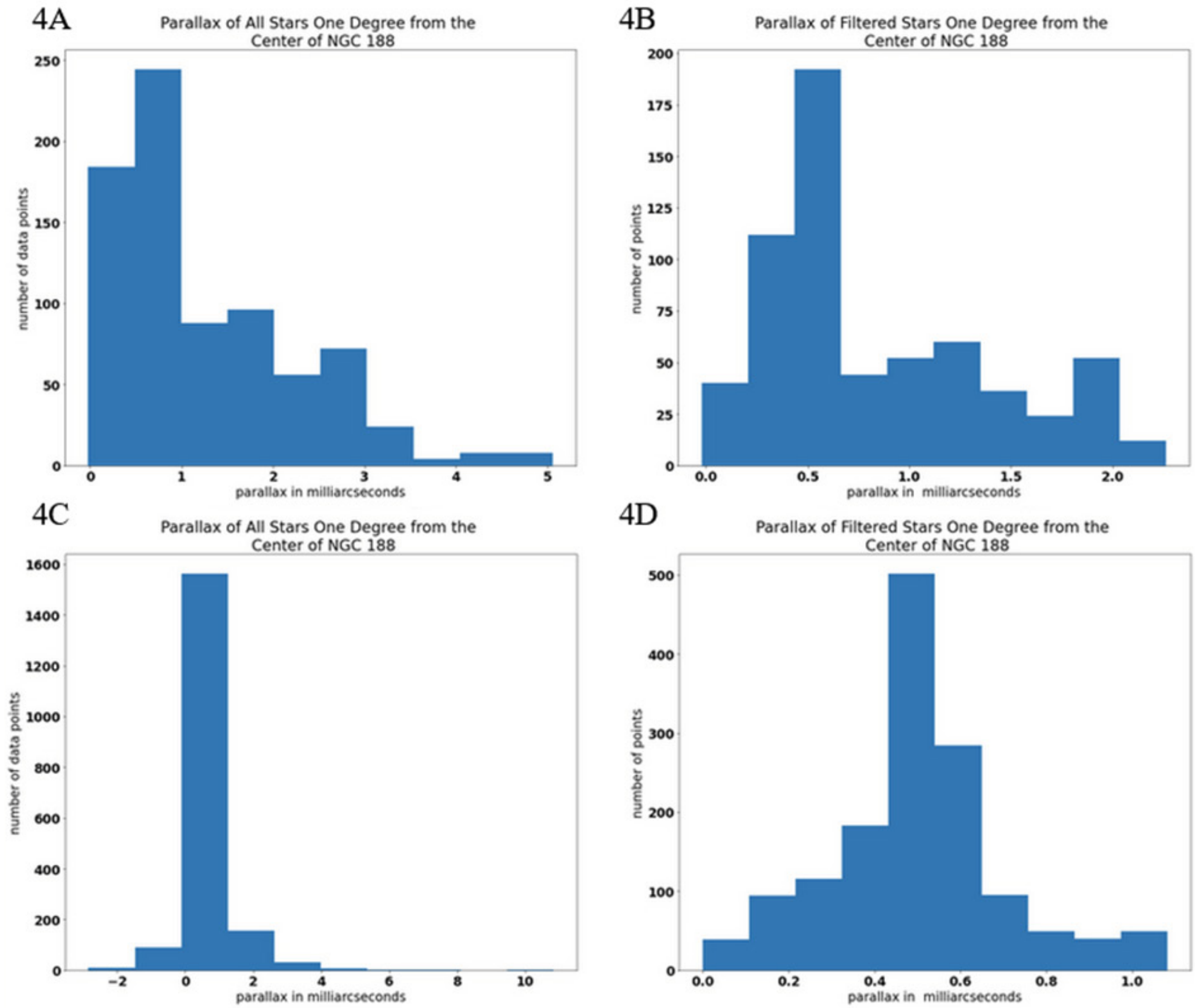

Figure 4. Histograms showing the parallax of stars within one degree of the right ascension and declination of cluster NGC 188. Histograms 4A and 4B show parallax from the Gaia database while 4C and 4D show data from the SDSS Database. Histograms 4A and 4C show all of the values within the one-degree range, while 4B and 4C contain data of stars within 1.5 standard deviations from the mean parallax value

Histograms 4A and 4B show the standard deviation of Gaia parallax values within one degree from the center of NGC 188. In histogram 4A, the most frequent parallax values are between -1 and 2 milliarcseconds. Histogram 4B contains stars that are likely within the cluster, as values that are outside the 1.5 standard deviations have been removed. The most frequent values are between 0.3 and 0.7 milliarcseconds. Histograms 4C and 4D show parallax values using the SDSS database. In histogram 4C, the most frequently occurring parallax values are between 0.5 and 1 milliseconds. In histogram 4D, stars have been eliminated in the same manner as in 4B, and the most frequent parallax values are between 0.2 and 0.6 milliseconds.

Age and Metallicity

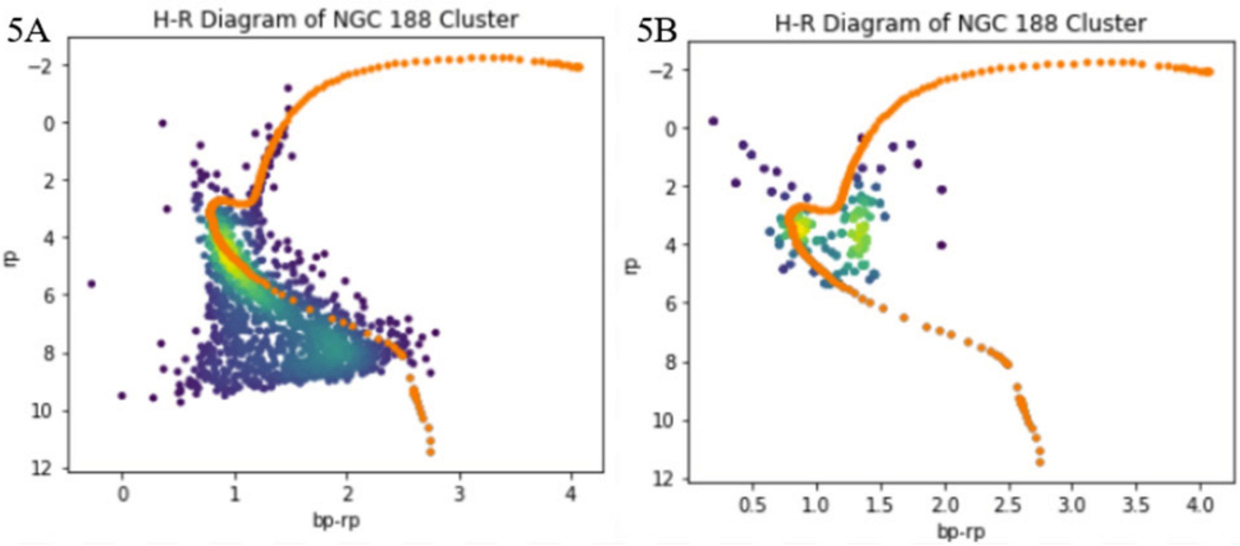

Figure 5. Shifted color magnitude diagrams of NGC 188 where the left diagram was created using Gaia data and the right using SDSS data. Lighter points represent sections with a higher point density. The orange line represents the isochrone values.

The age and metallicity of the cluster were determined through isochrone fitting. Star membership was calculated through excluding stars that had proper motion or parallax values outside the 1.5 sigma range from the average. After membership exclusion, the remaining color-magnitude points were plotted with bp-rp magnitude as the x axis and rp as the y axis. The line of points on the diagram with the highest point density was fitted with the isochrone line. The shape of the isochrone line is affected by the age and metallicity of the cluster it models, and so various sets of values were used to try to determine the closest match between the isochrone and color-magnitude lines. After testing various isochrones, it was found that the combination of values that generated an isochrone that best matched the color magnitude diagram were an age of 6 billion years and a metallicity of 0.2 [Fe/H]. Figure 5 shows two color magnitude diagrams with isochrone lines using 6 billion years and 0.2 [Fe/H] as parameters. The more yellow appearing sections in the scatter plotted color-magnitude points are sections with a higher point density, and therefore show the main sequence lines. These isochrone lines are the best fit to the color-magnitude diagrams.

Distance

Using the line of high-density points on the color magnitude diagram as seen in Figure 5, the average vertical distance was found between points on the high-density color-magnitude and isochrone lines that have similar bp-rp values. The color-magnitude diagram was then shifted using the distance modulus to create a H-R diagram. The distance modulus using Gaia data is 10.79 pc and using SDSS data is 8.44 pc. After converting the distance modulus to parsecs, it was found that the distance to the cluster NGC 188 using Gaia data is 1441 parsecs and using SDSS data is 488 parsecs.

Mass

The mass of the cluster was found using the virial theorem. The standard deviation of the radial velocity and the radius of NGC 188, which was 11.8 light years, was plugged into the virial theorem [6]. This value was then converted into solar masses. Using this method, it was found that the mass of NGC 188 using Gaia data is 2923 solar masses and using SDSS data is 2195 solar masses.

Discussion

Comparison to Previous Research

This paper aimed to verify the parameters of the cluster NGC 188. The values that were found in this research were all relatively close to what previous research had found. This research was able to further collective understanding about the star cluster NGC 188. The parameters determined mostly agree with previous research, confirming their veracity.

Age

The age that this research found agrees with the accepted age. The age of the cluster is believed to be around 7.7 ± 1.4 billion years by Hobbs et al., 6.27 ± 0.2 billion years by Meibom et al., and between 6 and 8 billion years by Bonatto et al. [8][2][9]. The value of 6 billion years that was determined using isochrone fitting in this study is consistent with these values.

If NGC 188 is 6 billion years old, then it means that NGC 188 is one of the oldest open clusters. Most open clusters do not reach this age, as they are part of the disk population of the galaxy. The location of open clusters means that they are commonly pulled apart over time by passing stars and other objects and therefore are not able to survive as long as globular clusters [7]. The old age of this cluster means that NGC 188 provides a unique opportunity to study the later stages of stellar evolution in open clusters.

Metallicity

The metallicity that was found using isochrone fitting is close to the values found by outside research. Hobbs et al found that the [Fe/H] value for NGC 188 is between -0.12 ± 0.16 [8]. The metallicity that was found in this study was 0.2 [Fe/H], which is outside the range found by Hobbs et al but is close the values they determined. This discrepancy may be since the isochrones used in this research had metallicity values in an interval of 0.2, and may therefore not include the same degree of precision as in the study by Hobbs.

Distance

The distance that was found is partially consistent with outside research. The distance found through Gaia data is 1441 parsecs, while the distance found through SDSS data is 488 parsecs. Bonatto et al. believes the distance is 1660±80 pc, Meibom et al found a distance of 1770±70 pc, and Nowakowski believes the distance is about 1656 parsecs [9][2][10]. There is difference of a few hundred parsecs between the distance found in this paper using Gaia data and the distance found by previous studies, which is a discrepancy that should not be overlooked. The value found by the SDSS data is very different from both previous studies and the distance found through Gaia data.

The two values for the distance of NGC 188 are quite different. This discrepancy is likely due to the SDSS data having fewer data points for the distance modulus algorithm to use. The distance found by the Gaia data is likely more accurate. Although this value is not within the range of the values found by previous research, a distance of 1441 parsecs is consistent with the distance of most known open clusters, as the majority of the known open clusters are within a few kiloparsecs of the Sun [1].

Mass

The mass agrees with current research. The mass found through Gaia data is 2923 while the mass found for SDSS is 2195 solar masses. The range found in previous research by Bonatto et al is 3800 ±1600 solar masses [9]. The masses found using Gaia data is within this range, and the mass found using SDSS data is slightly outside this range.

These two values are very similar to each other, which is surprising due to the difference in the amount of data between SDSS and Gaia. There are far fewer documented radial velocities than there are stars in the cluster, and it is probable that the available radial velocities do not perfectly reflect the cluster. Even so, both values for mass are within the typical range for open clusters, which is between 10 and 100,000 solar masses [1].

Reflection
In the future, I hope to continue to improve and expand upon my research. More isochrones could be compared to have a more precise metallicity. The method of isochrone fitting could be refined to find a better distance modulus. Another option for calculating distance could be found using the relationship between parallax and distance in parsecs, where the distance to a star is the inverse of its parallax. It may also be beneficial to experiment with different sigma values for my initial star exclusion to see if that could improve my calculations. I would like to use these techniques to evaluate parameters for star clusters that have less available data in the hopes of continuing to expand upon our collective knowledge about the universe. Overall, I am happy that the majority of my calculations agree with the previous research on NGC 188, and I hope to continue to learn more about open star clusters.

Acknowledgments

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