Tales of an Open Cluster: Analysis of NGC 6791

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Abstract: In this project we analysed the properties of the Open Cluster NGC 6791 in order to determine its age. We used Gaia and BaSTI data to determine the isochrone model that fitted best with the cluster and compared different ages. We determined the age of the cluster is between 7 and 8 Gyr.

Introduction

The story of a star begins and ends in equally dramatic ways. They are formed from the gas and dust present in the interstellar medium and ultimately return to that, enriching the medium with heavier elements that were produced as a consequence of the various nuclear reactions and the change in chemical abundances a star goes through throughout its life. This results in newer generations of stars being more concentrated in metals until they ultimately expel that material leading to a cyclical process of star formation, death, enrichment, and rebirth leading to a vast variety of stars observed in the night sky [1].

We can categorize the different populations of stars according to their metalicities in three separate categories. These categories are heavily dependent on the age of the stars.

Population	**Z**
Population I	≈ 0.02
Population II	≈ 0.001
Population III	≈ 0

Table 1: Categories of stars and their approximate metallicity content [2].

The collapse of a Giant Molecular Cloud (GMC) results in the formation of stellar clusters. All members of a stellar cluster are formed from the same GMC so they have similar chemical compositions and formed at around the same time. The differences in the different evolutionary states between the stars of a cluster have to do with the initial mass of the protostars.

On the Color Magntitude Diagram (CMD) for a stellar cluster, we observe that stars on the Zero Age Main Sequence are burning Hydrogen, as the Hydrogen fuel in the star begins to deplete and the Helium abundance starts increasing, the stars begin to contract and become brighter and they start to evolve off the Main Sequence, known as the Main Sequence Turn Off (MSTO), where the stars leave the Main Sequence and become redder and cooler with time. Thus, we can use the brightest point of the Main Sequence to determine the age of a cluster. The older the cluster, the brighter is the highest point of the Main Sequence. The star starts to climb the Red Giant Branch and evolves along the Hayashi Track. However, there is an important relationship between the Initial Mass Function of the star and its evolution off the Main Sequence. Stars with higher masses exhaust their Hydrogen fuel faster so they evolve off the Main Sequence quicker than stars on the lower main sequence [1, 2].

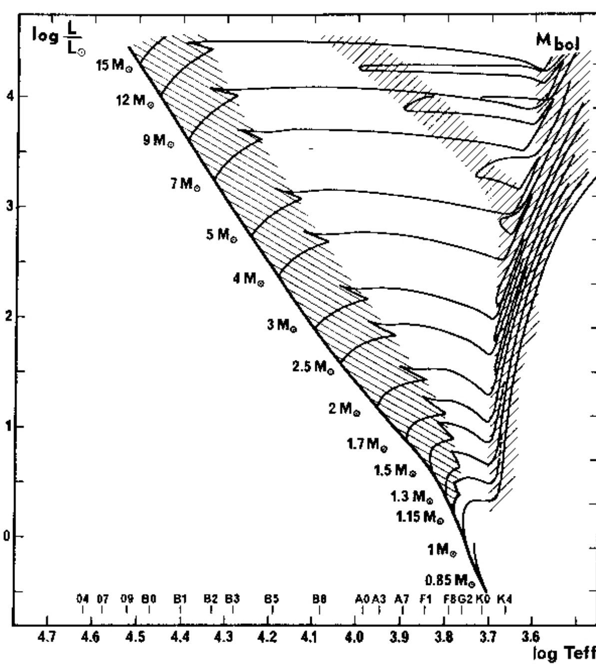

Figure 1: Main Sequence Turn Off and initial mass of stars [3].

Since members of a star cluster have approximately the same birth date [4], we can compute the evolutionary tracks for different initial mass stars, and plot their evolutionary timeline to determine the age of the cluster. The curve connecting all these points of different initial stellar masses is known as the isochrone [5]. The number of stars on a CMD is directly proportional to the evolutionary time scales. So stars in a slower evolutionary stage will be more common on a CMD.

There are two kinds of stellar clusters found in the universe: Open Clusters and Globular Clusters. Open clusters have younger, bluer, metal-rich stars, and have active star formation regions, consisting of mainly Population I stars. They are mostly found in the galactic disk and are most common in Spiral and Irregular galaxies [6]. Meanwhile, Globular Clusters have older, redder Population II stars found in the galactic halo or bulge. These clusters are some of the oldest objects found in the galaxy from when the galaxy was very young.

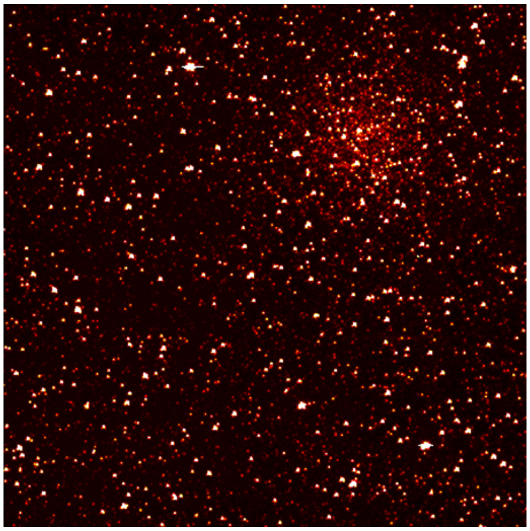

Figure 2: Open cluster NGC 6791 [7].

The Gaia mission is a space observatory launched by ESA to generate a three-dimensional map of the entire night sky. It has been observing millions of stars throughout the Milky Way and will continue to provide data on stellar motions, luminosities, magnitudes, compositions and temperatures [8]. In our project, we used the data provided by the Gaia archive to study the open cluster NGC 6791 found in the constellation of Lyra.

Methodology

Data Extraction

Stellar data for the open cluster NGC 6791 was obtained from GAIA DR3[1]. Using the 'GAIA Only Query' Form, a dataset containing NGC 6791 was requested for a circle of radius $25r_{\text{half}}$ centered around the target[9]. This contains both foreground and background stars in the Milky Way in addition to the stars in the cluster. To extract the dataset of the cluster, a visual selection was performed using TOPCAT [10]. Since the stars within a cluster are formed during the same time and from the same GMC, they have similar proper motions. This property was used to differentiate the stars of NGC 6791 from the background and foreground stars. Figure 3 shows the final selection of NGC 6791 stars from TOPCAT, and Figure 4 illustrates these same stars in a CMD.

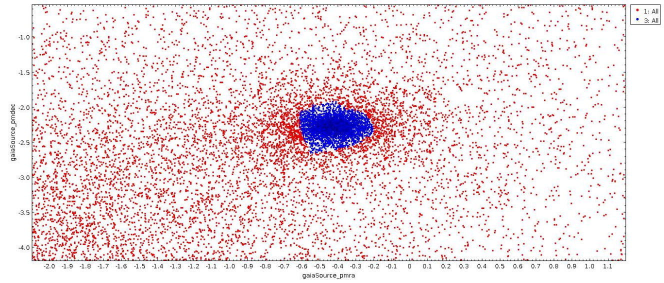

Figure 3: Data Selection on TOPCAT.

Data on the physical properties of NGC 6791 are listed below in Table 2.

R$_\odot$ [kpc] [11]	4.5308
text**E(B-V) [mag] [12]**	0.15
text**[Fe/H] [13]**	0.42
text**Age [Gyr] [13]**	5-9

Table 2: Physical Properties of NGC 6791

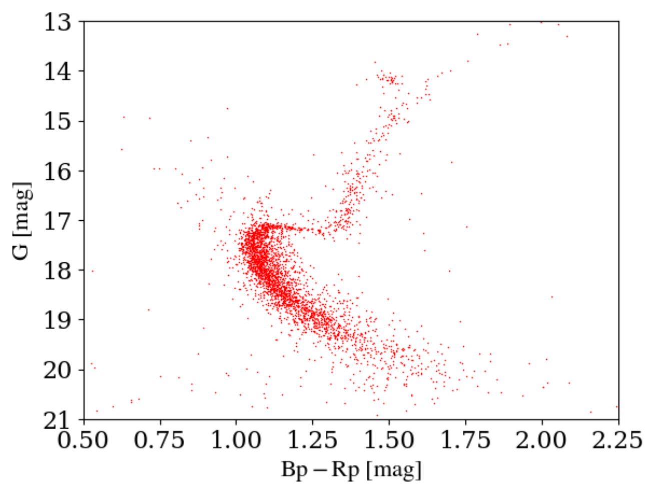

Figure 4: CMD of our selection of NGC 6791 stars.

Isochrone Models

Isochrone data was obtained from the BaSTI database[2] and is illustrated in Figure 5. From the properties of NGC 6791 given in Table 2, we notice that this is a very old open cluster and could be studied using a solar-scaled ($[\alpha/\text{Fe}] = +0.0$) or alpha-enhanced ($[\alpha/\text{Fe}] = +0.4$) models.

Due to limitations on the BaSTI database, we could not obtain an alpha-enhanced model with a metallicity comparable to that of our cluster. Thus, we chose the closest available models which were solar-scaled models with diffusion and overshooting enabled, metallicity

[1]http://gaiaportal.asdc.asi.it/DR3/GODR3/query/result
[2]http://basti-iac.oa-abruzzo.inaf.it/

[Fe/H] = 0.30, mass loss of $\eta = 0.3$ $M_\odot$ and Helium abundance of [He] = 0.247 at five different ages (5000, 6000, 7000, 8000 and 9000 Myr) in the GAIA-DR3 photometric system.

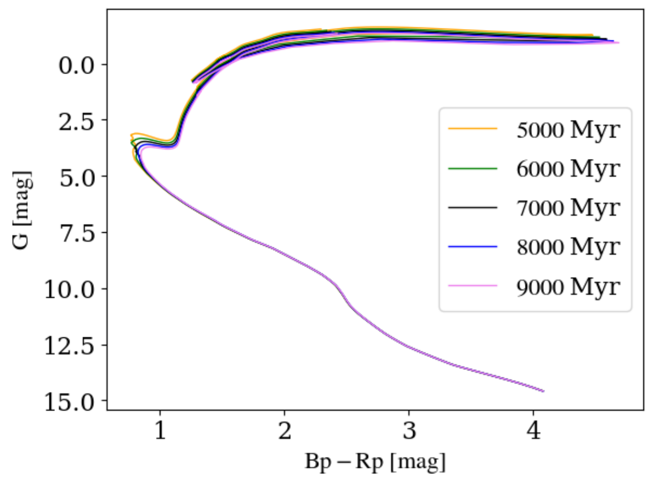

Figure 5: Isochrones at five different ages data from BaSTI.

Corrections

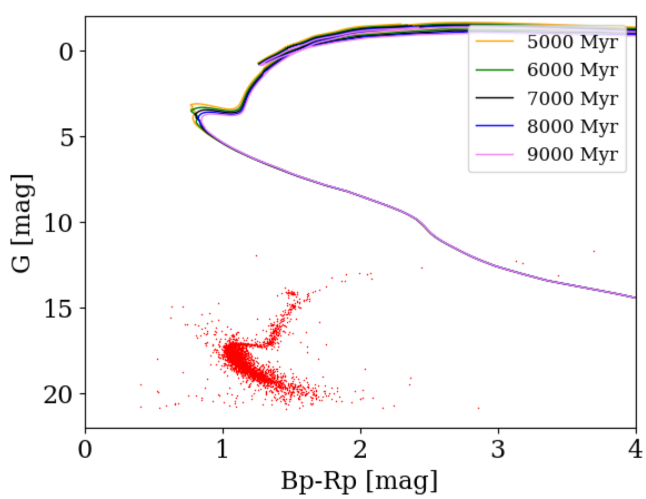

Figure 6: CMD of NGC 6791 data and uncorrected isochrones.

Figure 6 shows a CMD of our selection of stars and the uncorrected isochrones from BaSTI on the same axes. The absolute magnitudes of the isochrone models require corrections accounting for the extinction due to reddening, to fit them to the stellar data. First, the distance modulus was computed as follows,

$$\mu = 5(\log(R_\odot) - 1). \tag{1}$$

The reddening was computed separately for the G & BP-RP bands as shown in Equations 2 & 3. The value for the ratio of the extinction coefficients in the BP-RP band was taken to be $R_{BP} - R_{RP} = 1.339$ following [14], and that of the G band was taken as $R_G = 1.89$ following [15]. The corrections are then given by,

$$E(BP - RP) = (R_{BP} - R_{RP}) \times E(B - V), \tag{2}$$

$$A(G) = R_G \times E(BP - RP). \tag{3}$$

Taking into account the effects of both the reddening and distance modulus, the final formula giving the corrected isochrones which are plotted in the Figures is shown for the BP-RP band in Equation 4 and for the G-band in Equation 5,

$$(BP - RP)_{cor} = (BP - RP)_{uncor} + E(BP - RP), \tag{4}$$

$$G_{cor} = G_{uncor} + \mu + A(G). \tag{5}$$

Results

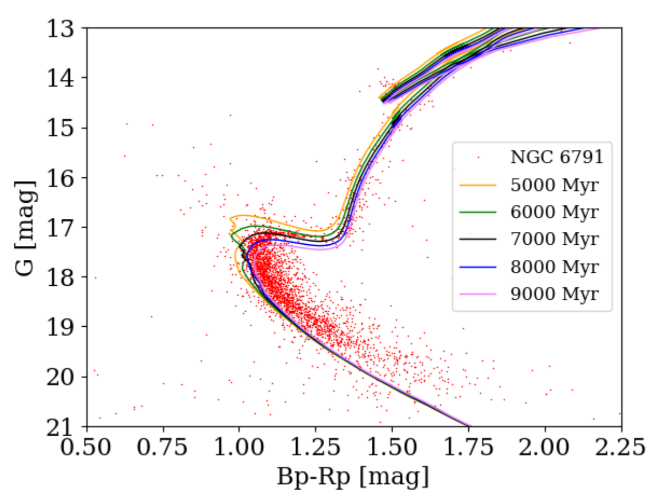

Figure 7: CMD with corrected isochrones and NGC 6791 data.

Figure 7 shows the colour-magnitude diagram compiled from the observational GAIA data with all the corrected isochrones from BaSTI on the same axes. It can be seen that the isochrones at 7000 Myr (in black) and 8000 Myr (in blue) fit the data best, which suggests that age of NGC 6791 is between 7 and 8 Gyr.

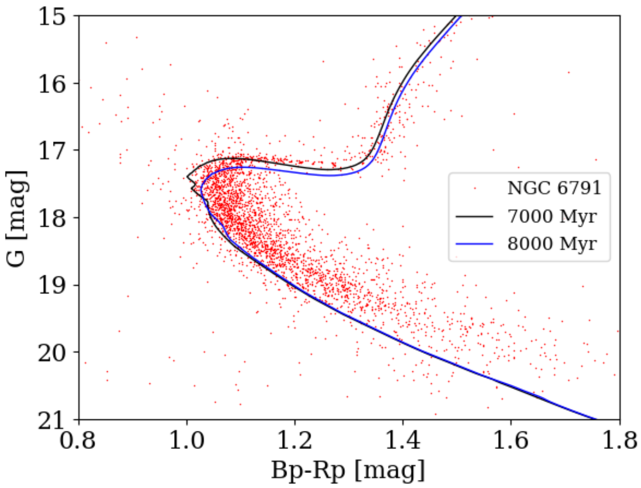

Figure 8: CMD with the two best fitting corrected isochrones and NGC 6791 data.

A closer look at the two best fitting isochrones is given in Figure 8, where we can see that the isochrone at 8000 Myr gives the best fit to the data, implying that the age of NGC 6791 is around 8 Gyr.

Discussion

In our project, we had to use the Solar-Scaled Isochrone data from BaSTI as according to some observational data, in NGC 6791 the stellar compositions with enhanced alpha-elements are inconclusive[16]. However, in our analysis, the Isochrone fits show an inconsistency with our open cluster NGC 6791. This is due to the metallicity of this open cluster being 0.42 whereas the maximum metallicity of the Isochrone available in BaSTI is 0.30. Due to this difference in the metallicity, the Isochrone is blue-shifted, introducing difficulties in accurately determining the age of our metal-rich, old cluster.

Even with this difficulty, using the Solar-Scaled Isochrone model for our open cluster provides a reasonable estimation to understand the cluster's characteristics. The actual age of NGC 6791 was found to be 8 billion years old [17] which agrees with our analysis.

Conclusions

In this report we analysed the open cluster NGC 6791 in order to determine its age. We used Gaia and BaSTI data to determine the isochrone model that best fits our data selection. We concluded that the cluster is around 8 Gyr.

To improve our fitting we would need a better isochrone model from BaSTI that has a bigger metalicity content.

References

[1] W. B. Carroll, and A. Dale. Ostile, *An Introduction to Modern Astrophysics*, Cambridge University Press (2017).

[2] M. Salaris, and S. Cassisi, *Evolution of Stars and Stellar Populations*, John Wiley Sons (2005).

[3] G. Schaller, D. Schaerer, et al, *New Grids of Stellar Models* ,A&AS, **96**, 269 (1992).

[4] A. Frebel, *Searching for the Oldest Stars: Ancient Relics from the Early Universe*, Princeton University Press (2015).

[5] R. Kippenhahn, A. Weigert, A. Weiss *Stars and clusters*, Springer(2012).

[6] C. Payne-Gaposchkin, *Stellar Structure and Evolution*, Harvard University Press (1979).

[7] NASA Exoplanets Exploration, *Star Cluster NGC 6791 from Kepler First Light Image*, https://exoplanets.nasa.gov/resources/74/star-cluster-ngc-6791-from-kepler-first-light-image/ (2009).

[8] European Space Agency, *GAIA Astrometry Mission*, https://www.eoportal.org/satellite-missions/gaiareferences (2013).

[9] A. G. A. Brown, A. Vallenari, T. Prusti et al, *Gaia Early Data Release 3*, Astronomy and Astrophysics, **A1**, 649 (2021).

[10] M. B. Taylor, *Astronomical Data Analysis Software and Systems XIV* **3**, 347, (2005).

[11] T. Cantat-Gaudin, C. Jordi, A. Vallenari, et al, *A Gaia DR2 view of the open cluster population in the Milky Way*, Astronomy & Astrophysics **618**, A93, (2018).

[12] E.F. Schlafly, P.D. Finkbeiner, *Measuring Reddening with Sloan Digital Sky Survey Stellar Spectra and Recalibrating SFD*, The Astrophysical Journal **737**, 2, (2011).

[13] M. Netopil, E.Paunzen, U.Heiter, et al, *On the metallicity of open clusters. III. Homogenised sample*, Astronomy & Astrophysics **585**, A150, (2016).

[14] L. Casagrande, A. Don. VandenBerg, *On the use of Gaia magnitudes and new tables of bolometric corrections*, MNRAS. Lett, **1**, 479 (2018).

[15] S. Wang, X. Chen, *The Optical to Mid-Infrared Extinction Law Based on the APOGEE, Gaia DR@, Pan-STARRS1, SDSS, APASS, 2MASS and WISE Surveys*, The Astrophysical Journal, **2**, 877 (2019).

[16] B.Chaboyer, E.M.Green, J.Liebert, *The Age, Extinction and Distance of the old, metal-rich Open Cluster NGC 6791*, arXiv:astro-ph, (1998).

[17] B. King, R. Ivan, Anderson, et al. *Reaching the End of the White Dwarf Cooling Sequence in NGC 67911*, The Astrophysical Journal **2**, 678, (2008).