Indian Institute of Technology Bombay

Investigation of Star Clusters to find out their Mass Function using the HR Diagram

Project Report

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Abstract

Open clusters are groups of young stars that were formed from the same cloud of gas and are gravitationally bound to each other. Found in spiral and irregular galaxies, they contain stars of roughly the same age and similar composition, and hence, they are very important in studying stellar evolution parameters. This study aimed to analyze the stellar properties of selected open clusters **Berkeley 59** and **King 12** and to determine their mass function through photometric classification, zero point calibration and then analyze them further by plotting the HR diagrams and fitting theoretical isochrones obtained from the **MIST** and **PARSEC** datasets to estimate the age of the cluster. All the observational data for the analysis were obtained using the Growth India Telescope (Hanle, Ladakh, India) with help from STAR Lab, IIT Bombay.

Figure 1: Example of an Open Cluster: Krittika (Pleaides), Source: Krittika, IIT Bombay

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1 Theoretical Background

1.1 Star Clusters

A star cluster is a gravitationally bound group of stars that appear as a localized concentration above the stellar background. Clusters are broadly categorized into **open clusters** and **globular clusters**, along with less tightly bound systems such as stellar associations and moving groups.

Open Clusters

Open clusters are loosely bound groups of a few dozen to several thousand stars, typically found in the Galactic disk. They are relatively young, with ages ranging from a few million to a few billion years.

1. **Formation and Characteristics:** Open clusters form from giant molecular clouds and often coincide with active star-forming regions. They consist primarily of Population I stars, which are rich in metals.

2. **Density and Evolution:** These clusters possess low stellar densities and span only a few parsecs in diameter. Over time, internal dynamical interactions and external tidal forces from the Galaxy lead to their gradual dispersion.

Globular Clusters

Globular clusters are dense, spherical collections of tens of thousands to millions of stars orbiting the Galactic halo. They are much older than open clusters, with ages exceeding 10 billion years.

1. **Formation and Characteristics:** Formed during the early stages of galactic evolution, these clusters contain mainly Population II, metal-poor stars.

2. **Density and Stability:** With diameters of about 10–30 parsecs, globular clusters are gravitationally stable and persist over cosmic timescales.

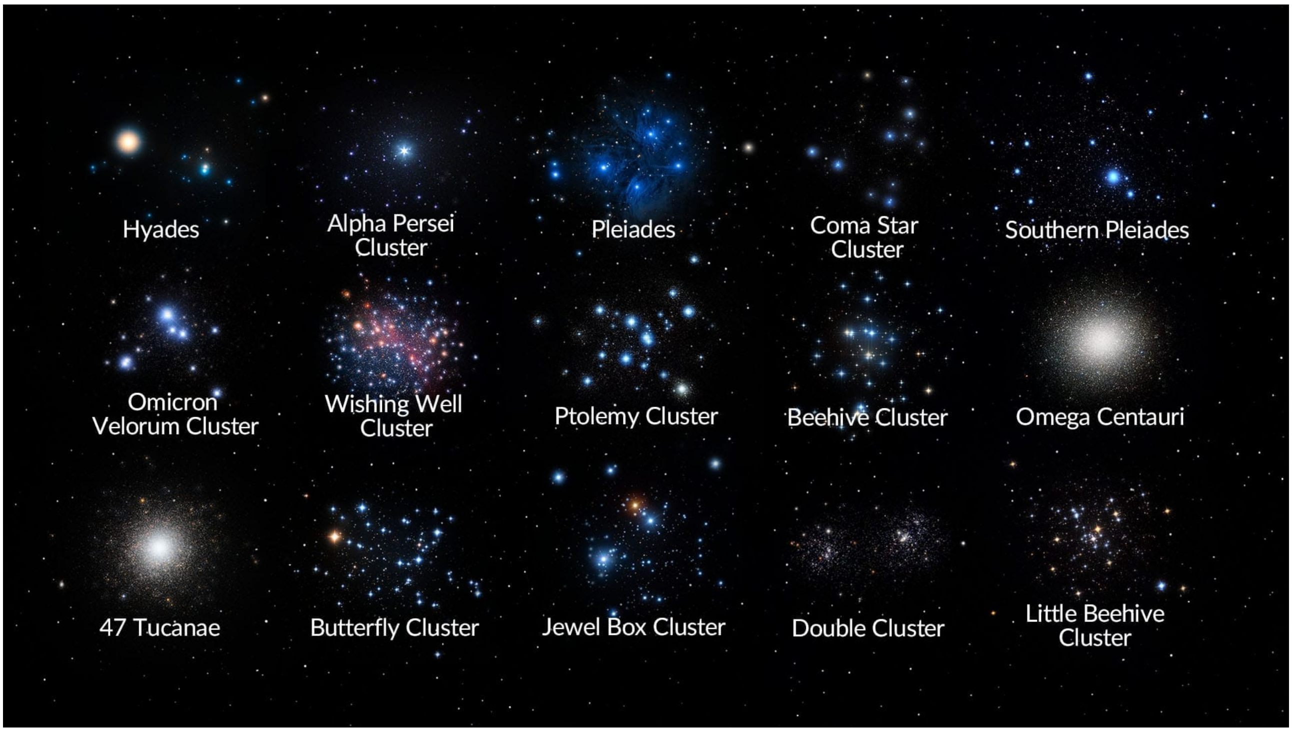

Figure 2: Examples of prominent star clusters. Source: starwalk.space

1.2 The Hertzsprung–Russell Diagram

The Hertzsprung–Russell (HR) diagram is one of the most fundamental tools in astrophysics, representing the relationship between a star's luminosity and its surface temperature (or spectral type).
Key Components:

1. **Luminosity:** Plotted along the vertical axis, often on a logarithmic scale, representing the total energy output of a star.

2. **Temperature or Color Index:** Plotted along the horizontal axis, decreasing from left (hot, blue stars) to right (cool, red stars).

3. **Main Sequence:** The prominent diagonal band where stars spend most of their lifetimes fusing hydrogen into helium.

4. **Giant and Supergiant Branches:** Represent evolved stars with expanded outer layers and high luminosities.

5. **White Dwarf Region:** Contains compact, faint remnants of low-mass stars.

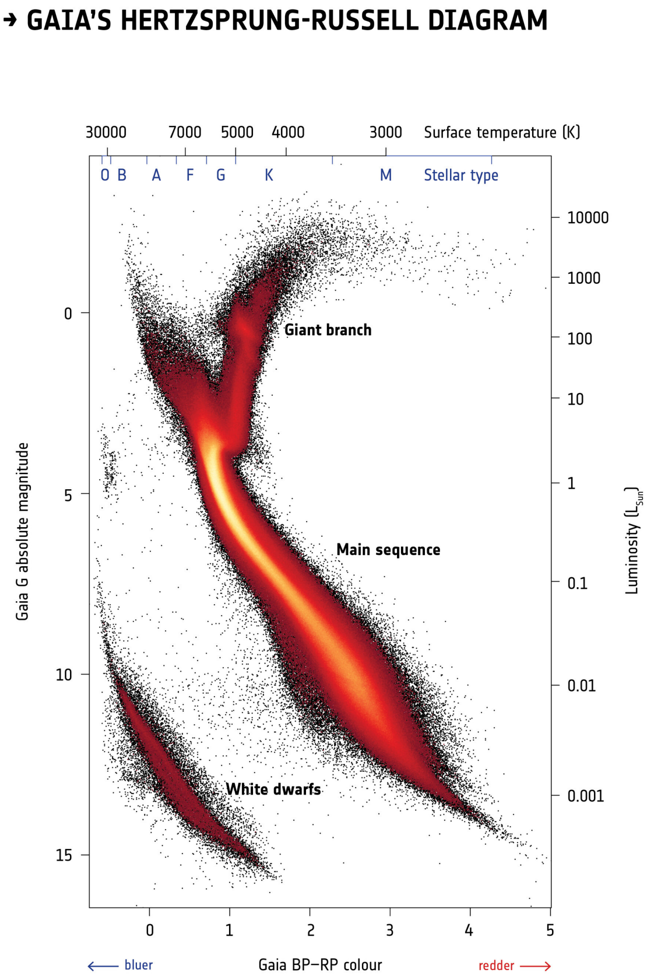

Figure 3: Standard Hertzsprung–Russell diagram, Source: European Space Agency

2 Target Selection

Two open clusters, namely Berkeley 59 and King 12, were selected for observation and were photographed in SDSS band filters u,g,r and i.

1. Berkeley 59 is quite a young cluster with many stars still not fully settled on the main sequence yet and allowed us to study the characteristics of pre main sequence stars.
2. King 12 in contrast is a more moderately aged star cluster enabling us to observe main sequence stars and also some post main sequence stars.
3. Both of these clusters were selected such that we covered a wide variety of stars and thus help us reach better and more concrete conclusions.
4. The clusters are also circumpolar from Hanle and also culminate in October nights around the time of observation, providing relatively less atmospheric seeing.
5. Member stars in the clusters in the magnitude range of 14-18 are separated enough to be resolved by the Growth India Telescope and also close enough to fit in the Field of View of the telescope.
6. Both clusters have Gaia DR3 data available which can be used to confirm our observations and cross verify our inferences.

3 Data Analysis

3.1 Data Inspection

We first inspect the FITS files of both the clusters in the g band for a visual check and realized that the photograph of the King 12 cluster is not centered on the correct co-ordinates and hence we decide to move forward with the analysis for the Berkeley 59 cluster.

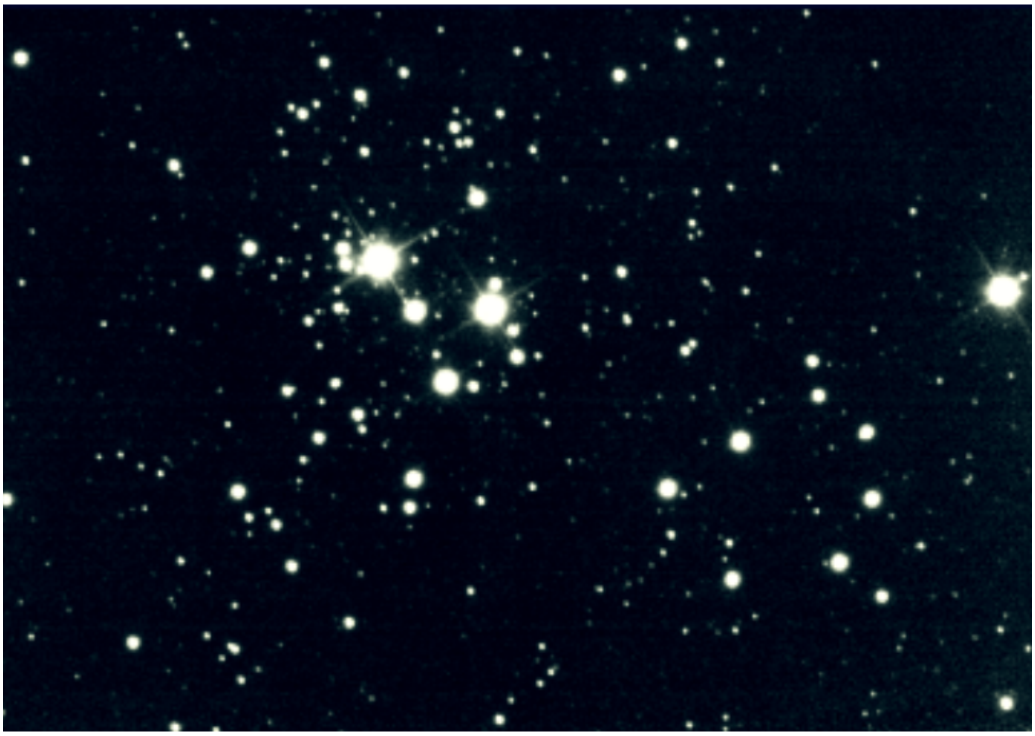

Figure 4: Berkeley 59, Source: Growth India Telescope

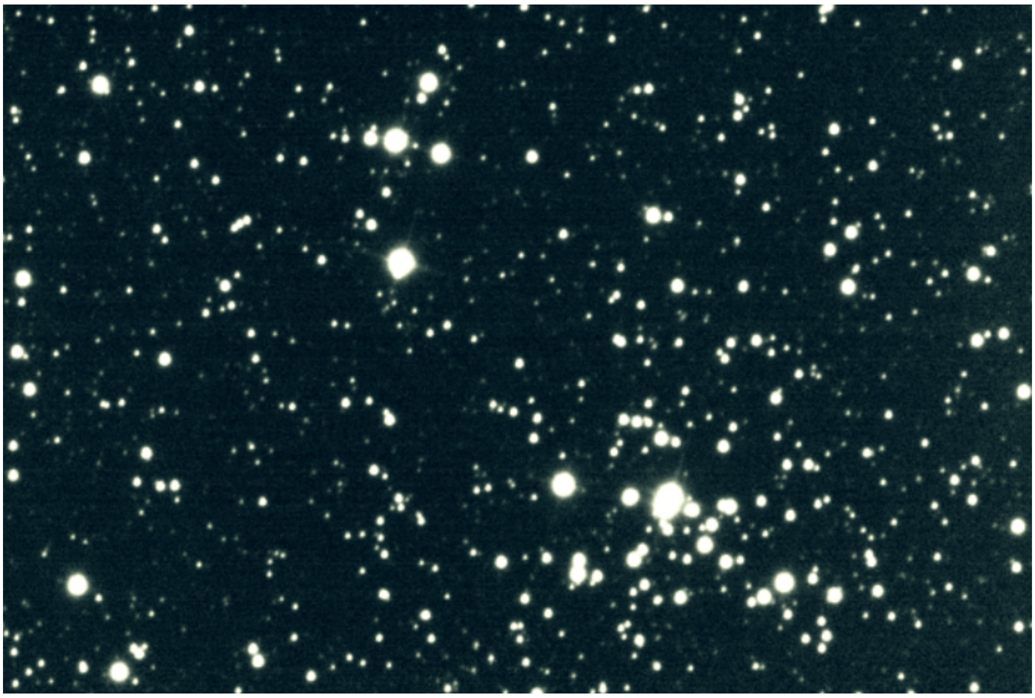

Figure 5: King 12, Source: Growth India Telescope

3.2 Cluster Member Determination

Cluster members were identified by doing proper motion analysis based on the Gaia catalog data available by an iterative process to separate the stars of the cluster which will share common proper motion within a fixed error margin of two standard deviations(chosen by convention).Out of the 2062 stars from the initial detections, only 135 stars were selected as cluster members based on the proper motion analysis.

$< pmRA >= -1.636 \pm 0.112 mas/yr < pmDec >= -1.910 \pm 0.109 mas/yr$

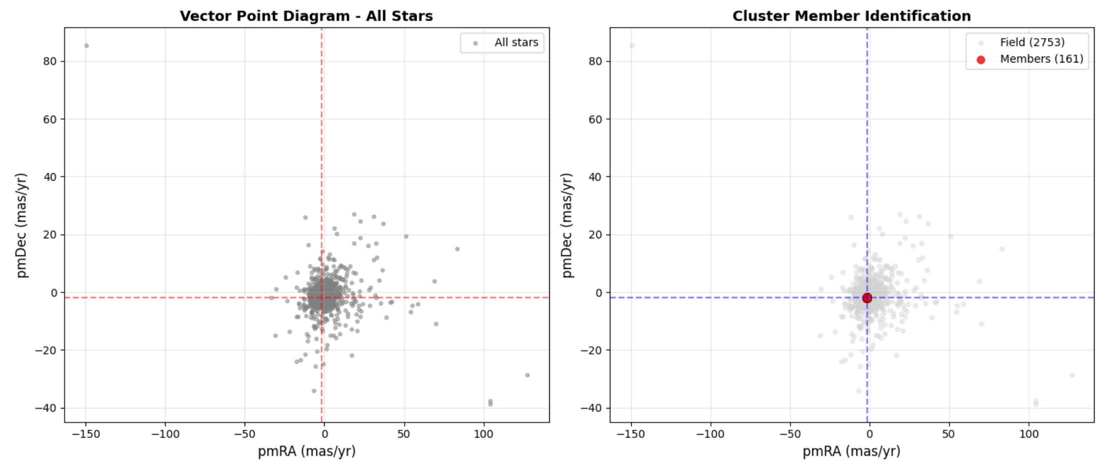

Figure 6: Motion analysis for Berkeley 59 using GAIA data

3.3 Photometric Classification

Phoutils and Astropy Libraries were used in this section to use the World Coordinate System to convert Cataloged Gaia position for the stars into pixel coordinates which were plotted onto the FITS file for visual inspection. To measure instrumental magnitudes, we first calculated the flux for each star using an 8-pixel aperture and a 12-to-14-pixel background annulus. We then created a refined dataset by filtering out all measurements with negative or undefined (nan) flux values. This cleaned flux data was used to derive instrumental magnitudes, yielding a total of 41 cluster members with reliable photometry.

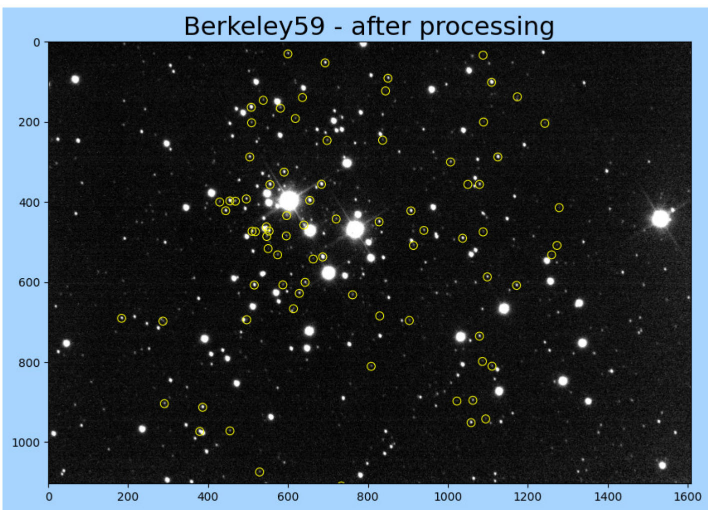

Figure 7: Photometric Classification of Berkeley 59 cluster members

3.4 Zero Point Calibration

Gaia Magnitudes were converted to SDSS ugriz band magnitudes and also corrected differential airmass extinction for different bands. Resulting Zero points were obtained as follows and corrected magnitudes are used in future for analysis.

$g : 25.564 - 0.233 = 25.330, r : 25.175 - 0.130 = 25.046, i : 23.795 - 0.078 = 23.717$

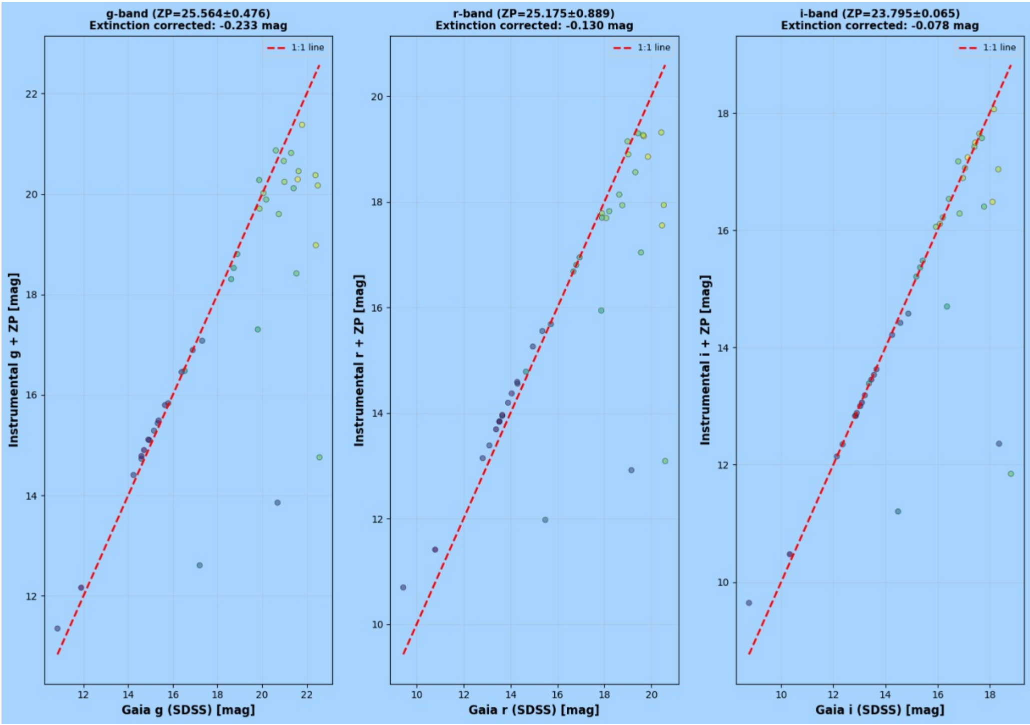

Figure 8: Zero Point Calibration for the g,r and i bands

3.5 Plotting HR Diagram

Using the magnitudes obtained in the g,r and i bands, two HR diagrams were plotted as (r-i) vs i and (g-r) vs r. Data from the u magnitude was quite unusable and hence was not analyzed along with the other bands.

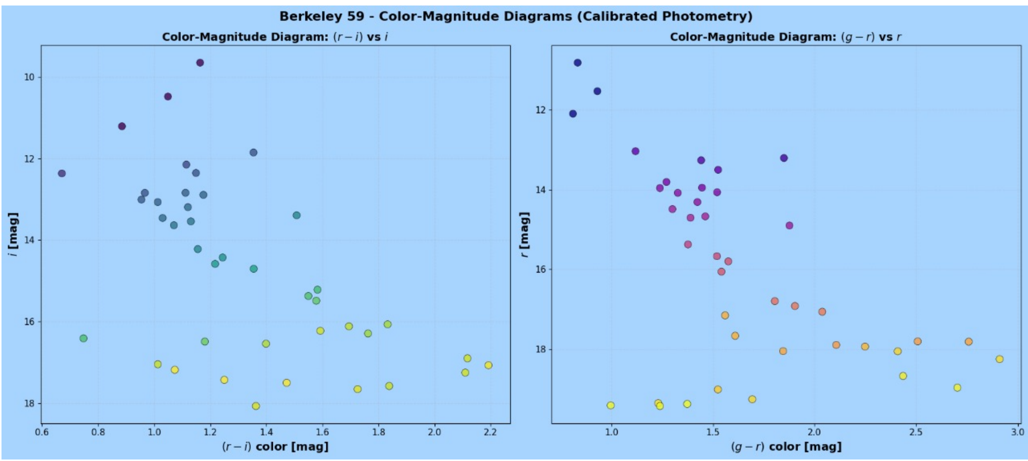

Figure 9: HR diagrams plotted for the Berkeley 59 cluster

3.6 Fitting Isochrones

Isochrone data was obtained from theoretical models like MIST and PARSEC by inputting suitable filters on the respective websites, accounting for the differential reddening in our plots and cluster distance of 1000 parsecs was assumed considering the actual GAIA catalog values.

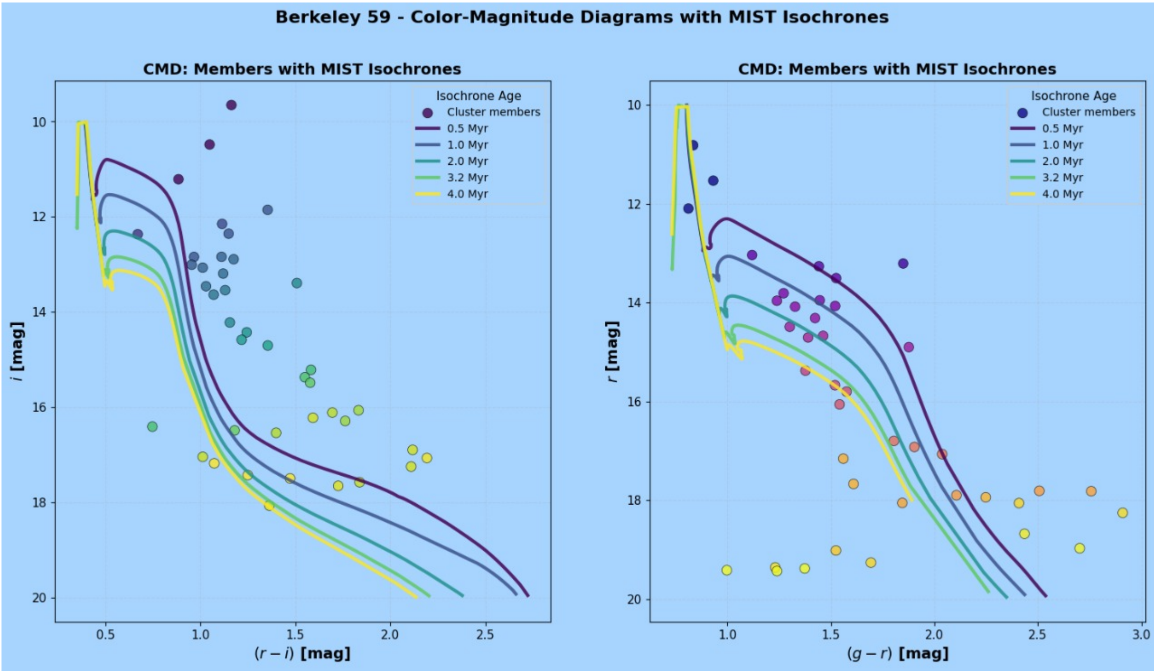

Figure 10: MIST Isochrones fitted on the HR diagrams plotted for the Berkeley 59 cluster

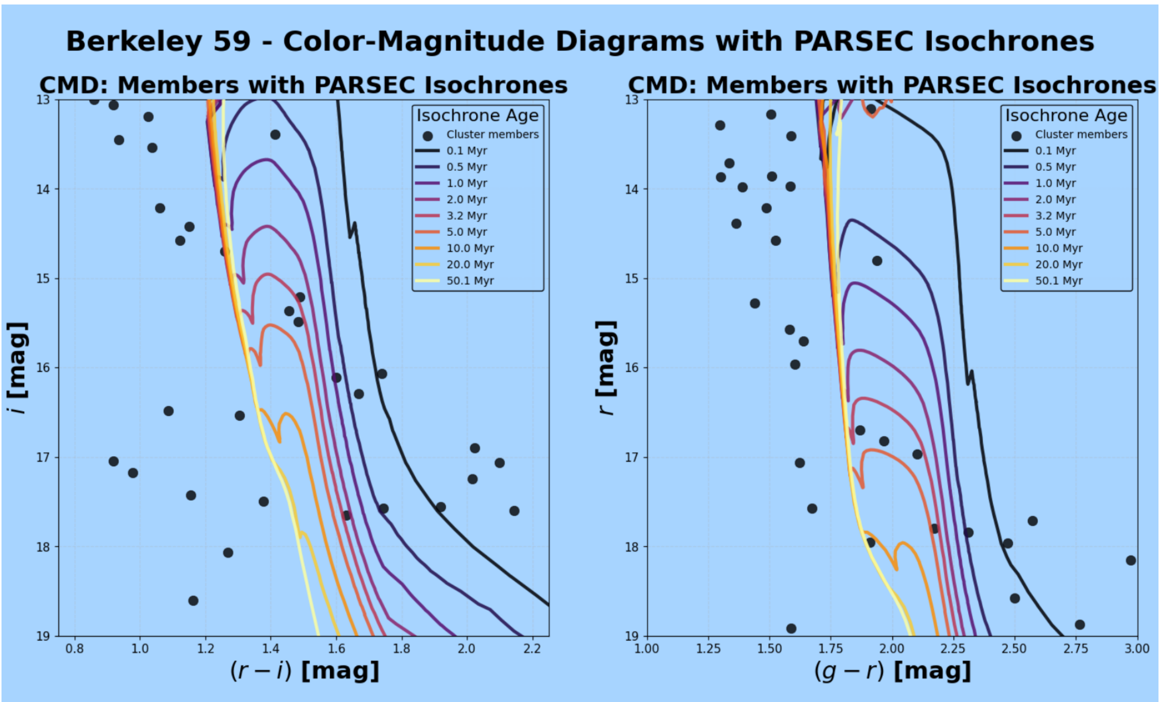

Figure 11: PARSEC Isochrones fitted on the HR diagrams plotted for the Berkeley 59 cluster

3.7 Mass Estimation

Each star was mapped to its nearest isochrone on the previously shown plots using thecKDTree method from the scipy module and from these age values, stellar masses were derived.

The resulting mass range for the cluster was found to be 0.628-11.10 Solar masses. Bootstrapping was done to derive the Initial Mass Function and the power law slope was found to be $\alpha = 1.85 \pm 0.41$.

Average stellar mass = 1.91 ± 0.159 Solar masses

Median stellar mass = 1.357 Solar masses

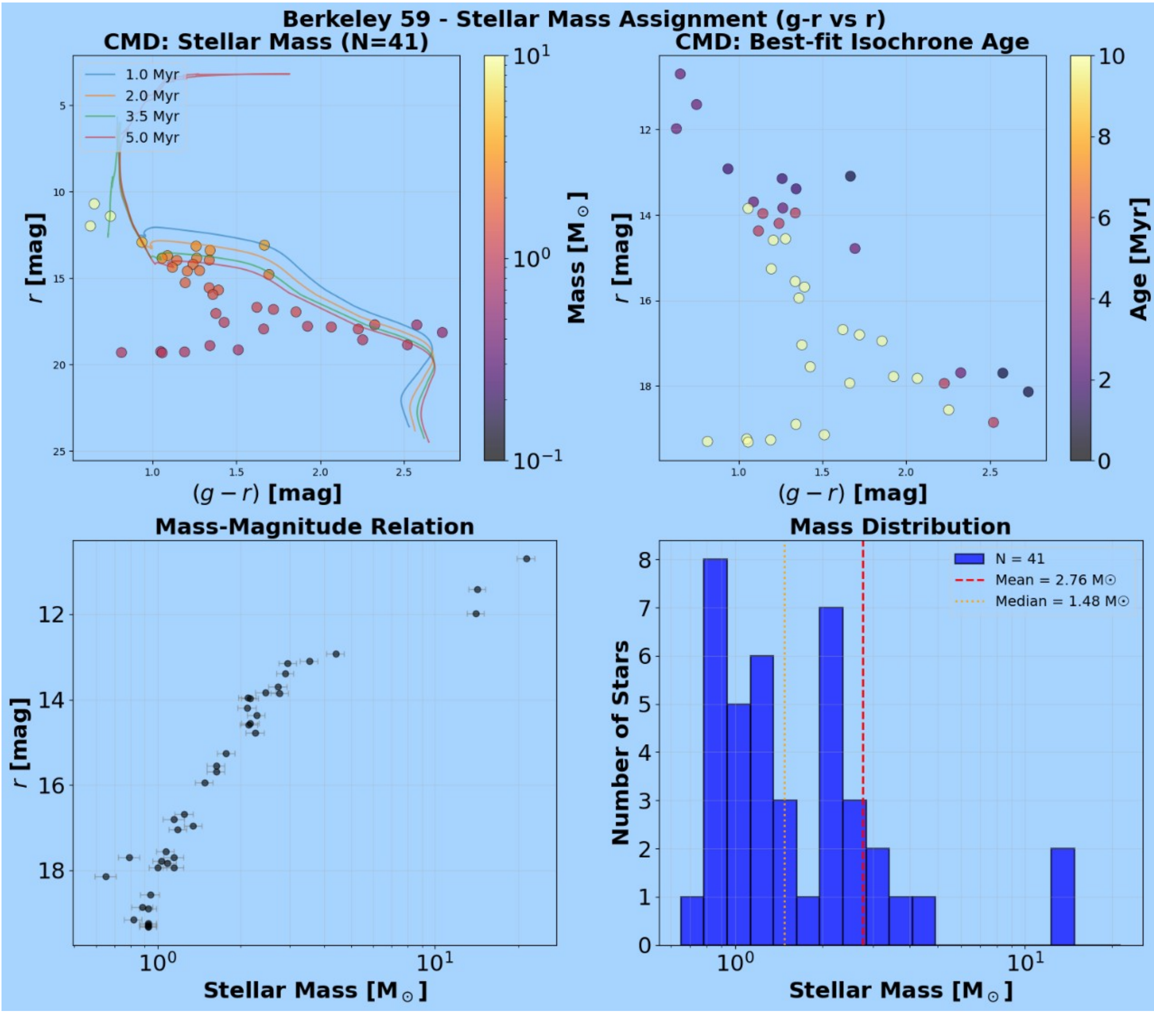

Figure 12: Mass histogram plot

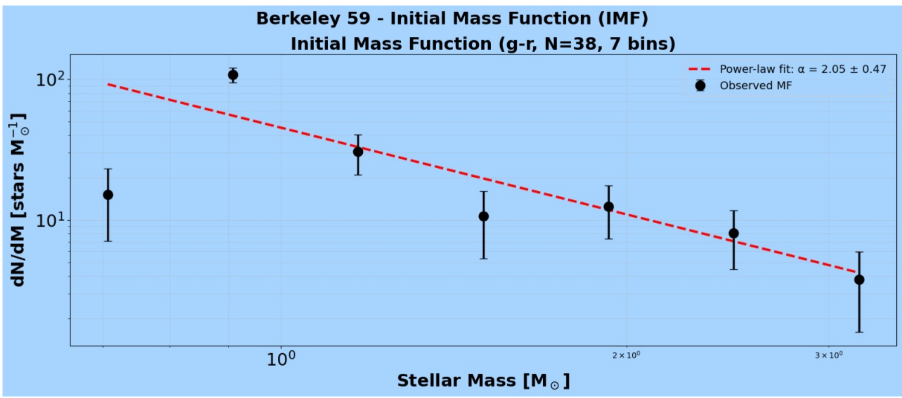

Figure 13: Initial Mass Function fit

4 Sources of Error

1. **Cluster Membership:** Identifying members based on Gaia proper motions is not entirely precise. There can be miscalculations due to field stars, errors in the astrometric data, and biases introduced by the sigma-clipping criteria used.

2. **Photometric Conversion:** Some systematic errors may arise while converting Gaia magnitudes to the SDSS system. The empirical relations used for this transformation can have small inaccuracies that vary with stellar colour.

3. **Aperture Photometry:** Photometric errors arise from issues in background estimation, dense regions contaminating the values and also the aperture radius choice.

4. **Reddening Correction:** A uniform $E(B-V)$ value was assumed for the cluster, which might not hold true if there's differential reddening across the field, potentially affecting the isochrone fitting.

5. **Model Dependence:** The derived parameters depend on the theoretical models used, along with assumptions about metallicity, rotation, and distance modulus. Any uncertainty in these inputs propagates into the results.

6. **Statistical Noise:** Bootstrap resampling used to estimate the IMF slope can introduce sampling noise, especially in bins with fewer stars.

5 Conclusion

Concluding the report, the complete pipeline for analyzing star clusters was developed in this project and then applied on the Berkeley 59 cluster. The methodology consisted of member identification using proper-motion, photometric classification and zero-point calibration, HR diagram plotting, isochrone fitting, and then obtaining the stellar mass distribution and Initial Mass Function. We observe that the Berkeley 59 cluster has significant pre main sequence stars which have not yet settled on the main sequnce yet and are moving on the HR diagram.

The same procedure was also applied to the King cluster; although since the obtained FITS file was not centered on the correct part of the sky, the results for King are not conclusive and hence have not been included in the report.

6 References

References

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