Analysis of stellar clusters in SDSS catalog

Ana Prpić

Supervisor: dr.sc. Dejan Vinković

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Department of Physics
Faculty of Natural Sciences and Mathematics
University of Split

Abstract

Photometry of globular star clusters M2 and M3 observed with the Sloan Digital Sky Survey (SDSS) is presented in this work. In order to extract stars belonging to these clusters out of over 100 million stellar objects observed by SDSS, we had to first understand how to access the SDSS database and how SDSS observed stars in its system of ugriz filters. We successfully reconstructed color diagrams of stars in M2 and M3, which would enable determination of the cluster's age and distance. However, the central region of the clusters is too crowed and SDSS photometric pipeline is not capable of resolving properties of individual stars in such a region. We also tried to perform a simple photometry by hand using software Makali'i. This attempt was successful for M3 data, but not so much for M2 cluster.

Contents

Chapter 1

Background

1.1 Globular clusters

One of the most powerful tools available in astrophysics for exploring and testing theories of star formation, stellar and galactic evolution and the chemical history of the Galaxy is the study of globular clusters. Because of this, globular clusters have been the subject of intense studies for the past several decades. Globular clusters are gravitationally bound concentrations of approximately ten thousand to several million stars packed into regions of from 10 to 30 light years across. Work in the past few decades has shown that the stars in globular clusters are among the oldest stars in our galaxy, with ages over 10 billion years. They represent snapshots of the process of stellar evolution frozen in time from a human perspective.

Since all the stars in a star-forming region begin their protostellar phase within a few million years of one another, the stars in a cluster much older than a few tens of millions of years can be considered to be all the same age. Thus the color magnitude diagram of a star cluster represents the properties of stars differing in mass, but all of the same age and chemical composition. A critical test of the validity of stellar evolution models is to be able to predict the observed properties of cluster stars, as seen in the color magnitude diagram.

Almost 160 of these clusters are now known in our Milky Way galaxy [URL-Clusters]. The brightness and distinctive appearance of globular clusters make them relatively easy to detect at large distances, so it is likely that most that exist in our galaxy have been discovered. Furthermore, globular clusters are found in the galactic halo, well above and below the thin disk of the galaxy that contains most stars and the younger open clusters. While globular clusters are strongly concentrated toward the center of the galaxy, some are found at very large distances from the galactic center. These characteristics are major reasons why globular clusters are key objects for the study of distant parts of the galaxy. Not surprisingly, globular clusters are also seen in and around other galaxies.

The stars in globular clusters have been found to differ in chemical composition from most stars in the galactic disk. They are depleted in heavy elements (metal poor) by factors ranging from at least 2 up to 200. In most clusters all stars have very similar chemical compositions, but the composition differs from cluster to cluster. Because the spatial distribution and chemical composition of the globular clusters are distinctly different from those of most stars, these clusters reveal a different aspect of galactic structure than ordinary stars. The clusters are the oldest identifiable objects so these differences contain information regarding the formation and early evolution of the galaxy. Globular clusters thus provide most of the basic observational data which any understanding of the early age of our galaxy is based on. We seek to learn more about these early stages in our galaxy's history in order to understand how the galaxy came to have its current structure and other characteristics, and we expect that much of what we learn about our galaxy's history will also be applicable to other galaxies as well.

Clusters are also a crucial step in determining the distance scale of the universe; Hertzsprung - Russell diagram (HR diagram) can be plotted for these clusters that has absolute values on the luminosity axis. Then, when similar diagram is plotted for a cluster whose distance is not known, the position of the main sequence can be compared to that of the first cluster and the distance estimated. This process is known as main - sequence fitting.

1.2 The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (http://www.sdss.org; SDSS) [Abazajian et al. (2009)] is one of the most ambitious and influential surveys in the history of astronomy. During over eight years of operations it obtained deep, multi-color images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. The SDSS uses a dedicated 2.5-meter telescope at Apache Point Observatory, New Mexico, equipped with two powerful special-purpose instruments. The 120-megapixel camera imaged 1.5 square degrees of sky at a time, about eight times the area of the full moon. A pair of spectrographs fed by optical fibers measure spectra of (and distances) more than 600 galaxies and quasars in a single observation. A custom-designed set of software pipelines keep pace with the enormous data flow from the telescope. The two key technologies that enable the SDSS, optical fibers and the digital imaging detectors known as CCDs, are the discoveries awarded the 2009 Nobel Prize in Physics.

The SDSS final data set is fully calibrated and reduced, carefully checked for quality and accessible through efficient databases and have been publicly released in a series of annual data releases, culminating in SDSS DR7. SDSS data have supported an enormous range of scientific investigations by astronomers around the world. Here is a list of some highlights among the many discoveries made by the SDSS, listed roughly in chronological order of the first investigations. Since the final SDSS datasets are only now being analyzed for the first time, the list of scientific highlights continues to grow. For more detail on SDSS see its web-pages at http://www.sdss.org.

- The discovery of the most distant quasars, powered by supermassive black holes in the early Universe
- Mapping extended mass distributions around galaxies with weak gravitational lensing
- Systematic characterization of the galaxy population
- The demonstration of ubiquitous substructure in the outer Milky Way
- Precision measurements of large scale clustering and cosmological constraints
- Detailed characterization of small and intermediate scale clustering of galaxies
- Discovery of many new companions of the Milky Way and Andromeda
- Discovery of stars escaping the Galaxy

Half of these achievements were among the original 'design goals' of the SDSS, but the other half were either entirely unanticipated or not expected to be nearly as exciting or powerful as they turned out to be.

In this work we will try to reproduce results on globular clusters from [An et al. (2008)]. Here we present some basic information on SDSS observations of galactic clusters, as described in [An et al. (2008)]. Among previous and ongoing optical surveys, SDSS is the largest and most homogeneous database of stellar magnitudes currently available. SDSS measures the magnitude of stars in five broadband filters u, g, r, i, and z, with average wavelengths of 3551, 4686, 6165, 7481, and 8931 Å, respectively. During the course of SDSS-I from 2000 to 2005, about 15 globular clusters and several open clusters were observed. Several more clusters were imaged in SDSS-II during 2005 to 2008. These clusters together provide accurate calibration samples for stellar colors and magnitudes in the SDSS filters. The SDSS images are processed using the standard SDSS photometric pipelines, which we will call Photo. Photo preprocesses the raw images, detects objects and measures their properties. Stellar clusters present a challenge to Photo because it slows down dramatically in the high-density cluster cores, which are too crowded for Photo to process, so it does not provide photometry for the most crowded regions of these scans.

The SDSS images are taken in drift-scan or time-delay-and-integrate mode, with an effective exposure time of 54.1 seconds per band. The imaging is carried out on moonless nights of good seeing (better than 1.600) under photometric conditions. A portion of the sky is imaged in each run by six columns of CCDs. Each CCD observes 13.52 arcmin of sky, forming a scanline or camcol, with a gap of 11.68 arcmin between the columns. A second scan or strip in a different run fills in the gap, overlapping the first scan by 8% on each side.

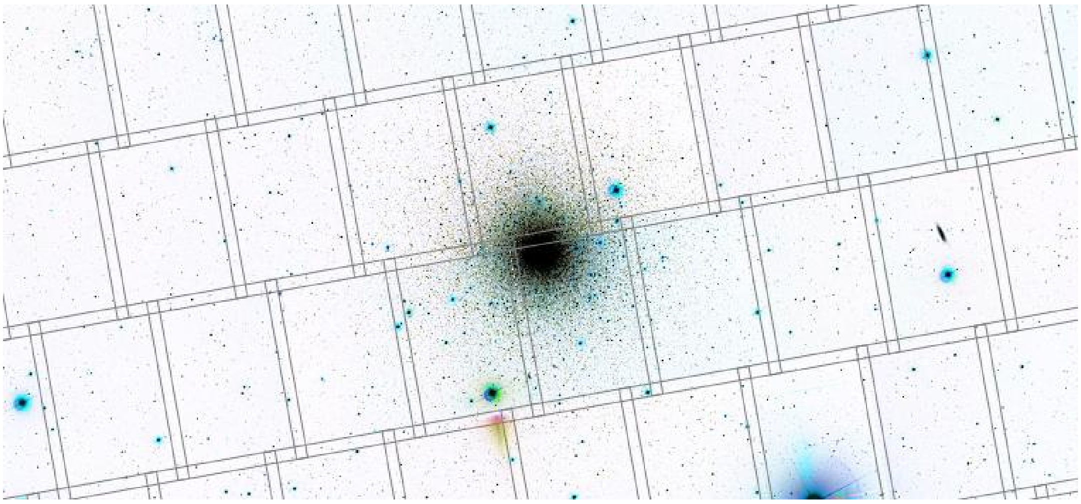

Figure 1.1: SDSS scans over the region surrounding M3, generated using the SDSS Finding Chart Tool [URL-chart]. Each of the horizontal strips represents a scanning footprint for each CCD. This strip is divided into rectangular frames with small overlapping regions.

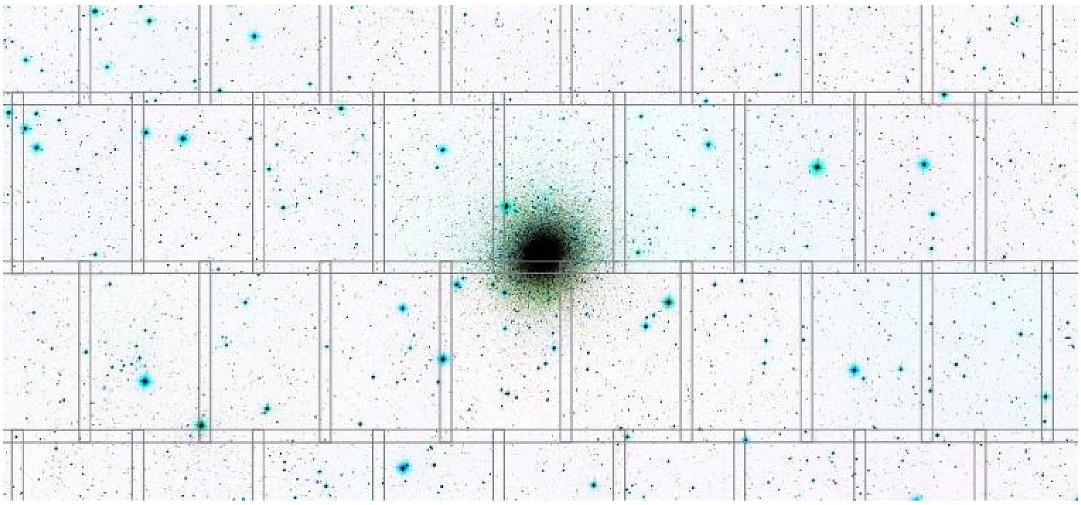

Figure 1.2: SDSS scans over the region surrounding M2, generated using the SDSS Finding Chart Tool [URL-chart].

Chapter 2

Methods

Two sets of methods for acquiring data were used. One is based on SDSS photometric pipeline, while the other is our attempt of photometry using a simple method.

2.1 Data acquisition from the SDSS catalog

The SDSS SkyServer visual tools available online were extensively used in our work. The visual exploration tools built for the SkyServer make it easy to visualize and explore detailed astronomical data in regions of the sky covered by SDSS. One can specify regions of interest by central position and size, overlay additional useful information including: boundaries of survey fields and aperture plates, outlines of individual objects and data quality masks, and locations of photometric and spectroscopic objects. The tools can also search for lists of known objects, provide links for detailed information, and formulate new database queries.

The SDSS Finding Chart tool [URL-chart] can be used to look through millions of objects to find those you are interested in. Parameters it requires are:

- ra - center point right ascension in J2000 decimal degrees, hh mm ss.s, or hh:mm:ss.s
- dec - center point declination in J2000 decimal degrees, dd mm ss.s, or dd:mm:ss.s
- scale - arcsec/pixel (the natural scale of SDSS is 0.396127)
- height - image height in pixels, limited to [64..2048]
- width - image width in pixels, limited to [64..2048]

The Navigation tool is one of the most versatile tools on SkyServer. To use the Navigation tool [URL-navi] a right ascension and declination of the object in question need to be entered in the "ra" and "dec" boxes. To find the 'ra' and 'dec' for the M2 the following query was used: [URL-SIMBAD]. The search returns 'ra' and 'dec' of the object that now can be copied into SDSS Navigation tool. The Navigation tool then returns a JPEG image centered on (ra,dec), of size (height x width) where the image is scaled to an arbitrary scale (scale); the default scale in SDSS is 0.396127 arcsec/pix. The Zoom bar (magnifying glasses and rectangles under "Get Image") can be used to zoom in our out on the center of the chart.

Any object in the main frame of the Navigation tool can be clicked on; a close-up of the object will appear in the right-hand frame. A summary of its data will appear above the close-up. This summary shows its position (ra and dec), type (star or galaxy), and magnitudes in the SDSSs' five filters u,g,r,i,z (u,g,r,i,z are the magnitudes of the objects in the SDSS, they represent the fluxes of light measured in logarithmic units through various wavebands from ultraviolet to infrared) [URL-ugriz]. To learn more about this object (including spectral information), "Explore" can be clicked.

After retrieving 'ra' and 'dec' for M2 (323.3628, -0.8221) and M3 (205.5484, 28.3772) and getting the images from Navigation tool, the radii of the clusters need to be estimated (so that the SQL query can be limited to the stars pertaining to the cluster only). This had to be done in order to reduce the contamination from background stars. The cluster radius estimate used for the M2 cluster is 9' and for the M3 it is 21'(arc minutes). The SQL query to retrieve the data could now be executed. (An excellent SQL tutorial can be located here: [URL-sql]) The query for M2:

```
select p.objid, p.ra, p.dec, p.u, p.g, p.r, p.i, p.z,
from
photoObj p, dbo.fGetNearbyObjEq(323.365,-0.8221,9) n
where
p.objID = n.objID
and p.type = 6
and p.r BETWEEN 13 and 24
and p.g - p.r BETWEEN 0.2 and 0.9
```

and M3:

```
select p.objid, p.ra, p.dec, p.u, p.g, p.r, p.i, p.z,
from
photoObj p, dbo.fGetNearbyObjEq(205.5484,28.3772,21) n
where
p.objID = n.objID
and p.type = 6
and p.r BETWEEN 13 and 24
and p.g - p.r BETWEEN 0.2 and 0.9
```

is entered here: [URL-search] and CSV output format selected. The data can then be opened in Excel or Gnumeric (the latter was used here).

The center of the globular cluster is considerably crowded and bright, in fact, too bright to identify individual stars. Hence, this time the center of the cluster was excluded from the previous set of data. This was done by firstly estimating radius of the center of the cluster and then subtracting it from the first set of data. The point of comparison between the two was objectID and the comparison was done with Linux shell command fgrep (the command used was fgrep -v (v stands for invert-match in order to select non-matching lines)). From the remaining data the graphs for clusters without their centers were compiled.

2.2 The use of the SUBARU Image Processor: Makali'i

Another method of photometry that we used is based on obtaining images from SDSS and performing photometry by hand on these images. To acquire imaging data for the aforementioned globular clusters, SDSS images in the FITS format (Flexible Image Transport System) were used. The images for M2 were downloaded from SDSS Data Archive Server that is located on the following address: [URL-das1]; frames 135-137 contain images of the cluster (Run, Rerun and Camcol are 258-40-2). The images for M3 were downloaded from here: [URL-das2]; frames 080-082 contain image of the cluster (Run, Rerun and Camcol are 4646-40-3). We limited our color diagram to r and g magnitudes only, so the images in g - band and r - band were downloaded for both clusters and then opened with Makali'i - the program for aperture photometry (measuring the brightness of stars).

After opening a FITS image for r - band in Makali'i, a second image of the cluster is to be opened but this one in g - band. The button Photometry is to be clicked next and the Aperture photometry mode selected. First thing done here was gathering information on the background brightness of the images by doing a series od 10 clicks on arbitrary dark spots around the cluster. The program returns classification of the selected areas (sky/star/galaxy), number of pixels inside the circle and so on. After clicking on several dark spots on the both images (we used 10 dark spots), one can click Print button and save the data in CSV format. After saving, one is ready to start clicking on the stars that are visually estimated to pertain to the cluster. This process is done in such a fashion that stars are hand picked first on one image and then the same stars are selected on the other image. We used about 500 stars in this process. After this is done, the data can be also saved in CSV format.

The data obtained is then used for calculating magnitudes and plotting color diagrams. The following formulae for calculating magnitudes were used:

$$R = R_0 - 2.5log_{10}(I^*) \tag{2.1}$$

$$G = G_0 - 2.5log_{10}(I^*) \tag{2.2}$$

where R is derived from FITS in r - band, and G from FITS in g - band. R_0 and G_0 are constants that scale these magnitudes into standard r and g magnitudes in SDSS. Since we care only about relative magnitudes in the case of this exercise with globular clusters, we ignored R_0 and G_0 (set them to zero). I^* is stellar brightness measured by the camera and is calculated from the output data according to the following formula:

$$I^* = I^*_{sum} - N^* \times I^*_{sky} \tag{2.3}$$

where I^*_{sum} is Obj Count from the output table (sum of pixel values belonging to the star), N^* is Obj Pix (number of pixels belonging to the star) and I^*_{sky} is the mean value of the background pixels (brightness of the sky).

Chapter 3

Results

In this section the photometry for two clusters, M2 and M3 is presented. Figures 3.1 and 3.2 show color magnitude diagram of M2 and M3, respectively, with u - g, g - r, g - i, and g - z as color indices, and r as a luminosity index. These two graphs were compiled from all the data within a 9' and 21' radius, respectively, around the cluster center. These graphs were computed using 1990 data entries (stars) for M2 and 5013 entries for M3.

Figures 3.3 and 3.4 were compiled from a subset of data. As mentioned before, globular clusters M2 and M3 are considerably dense and bright, so, the data from the cluster center were excluded here. With the removal of the cluster center, the amount of data was reduced to 1746 entries for M2 and 4106 entries for the M3. The resulting graphs do not differ much from those with the complete set of data. We hoped that removing unreliable photometric points from the clusters' center would decrease the scattering of data points in color diagrams in Figures 3.1 and 3.2, but that did not happen. Hence, we tried an experiment with performing photometry by hand using SDSS images. The color diagrams obtained is such a way using Makali'i software is shown in Figure 3.5. Notice that magnitude scales are shifted relative to Figures 3.1-3.4 because we use $R_0 = 0$ and $G_0 = 0$ in equations 2.1 and 2.2.

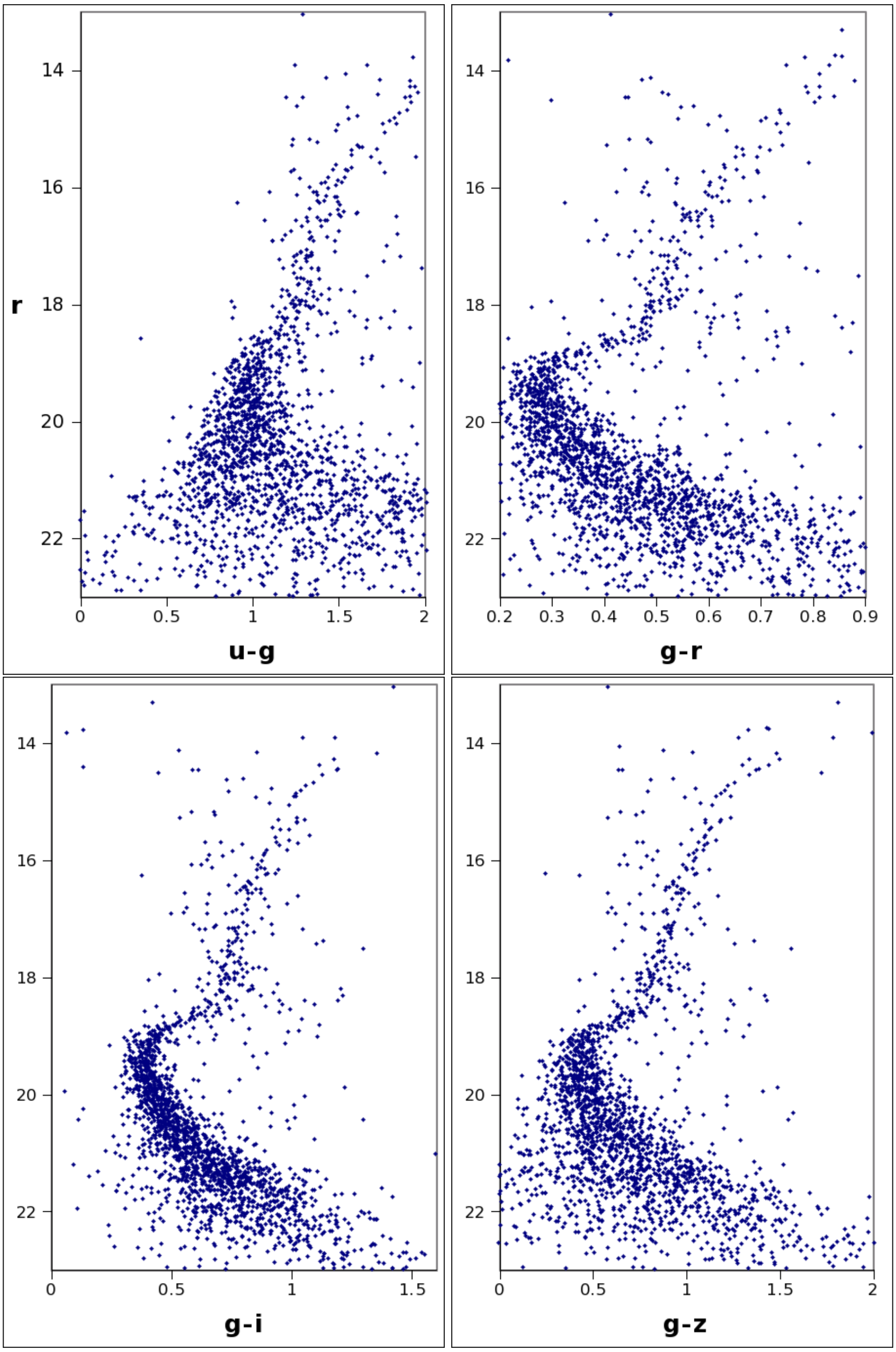

Figure 3.1: Color magnitude diagrams for M2 from the SDSS photometric pipeline (Photo)

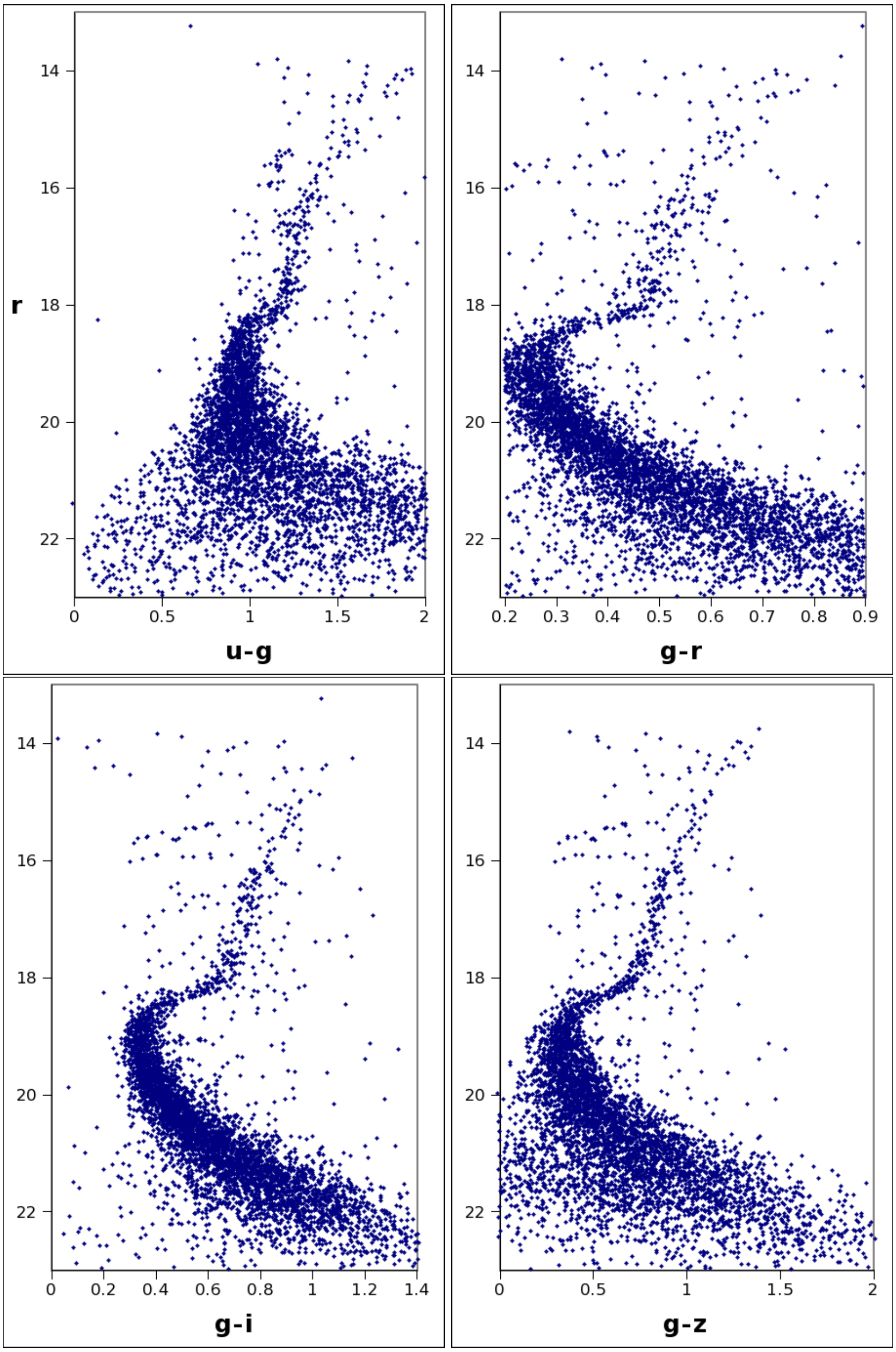

Figure 3.2: Color magnitude diagrams for M3

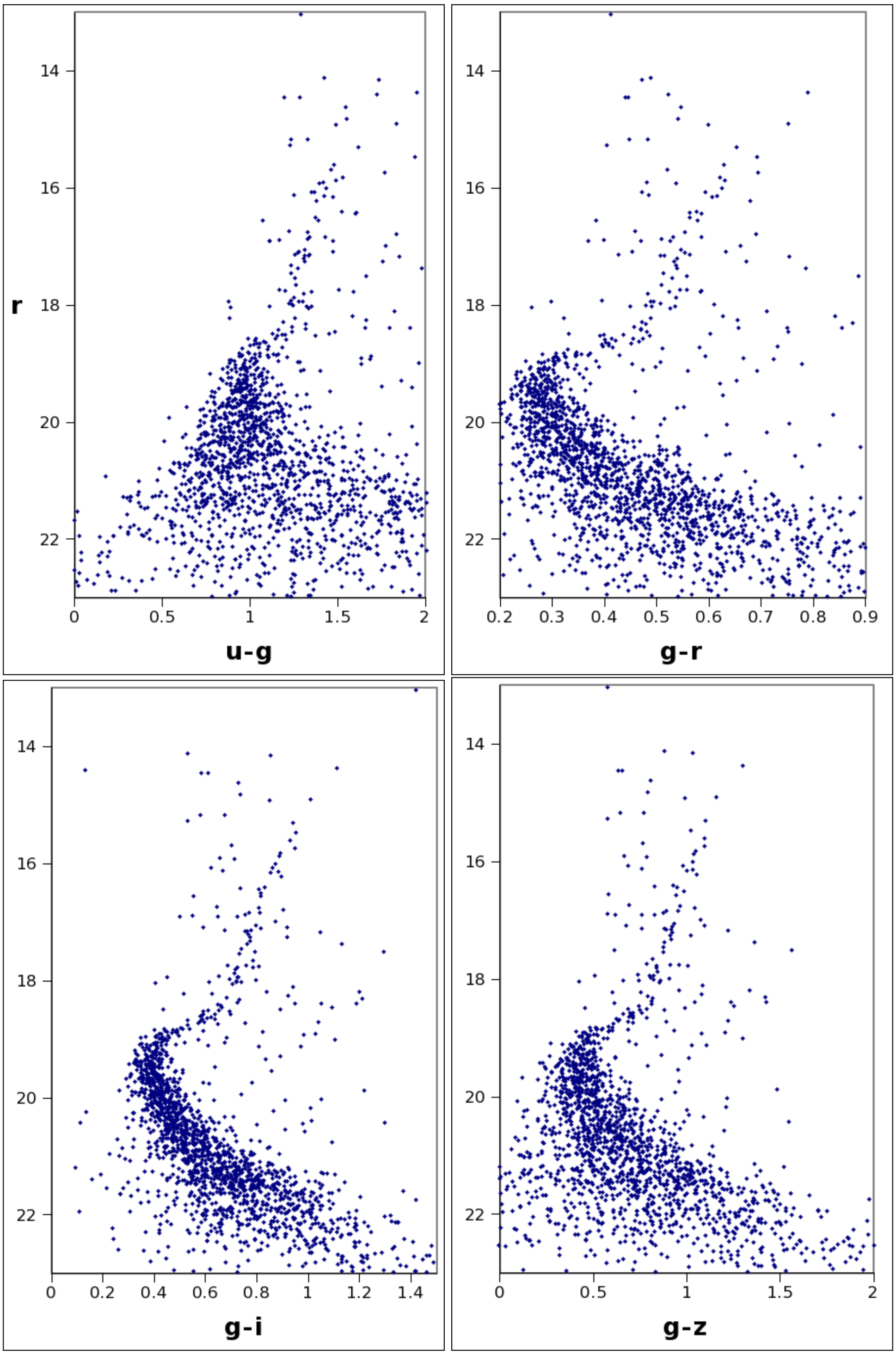

Figure 3.3: Color magnitude diagrams for M2 (the cluster center excluded)

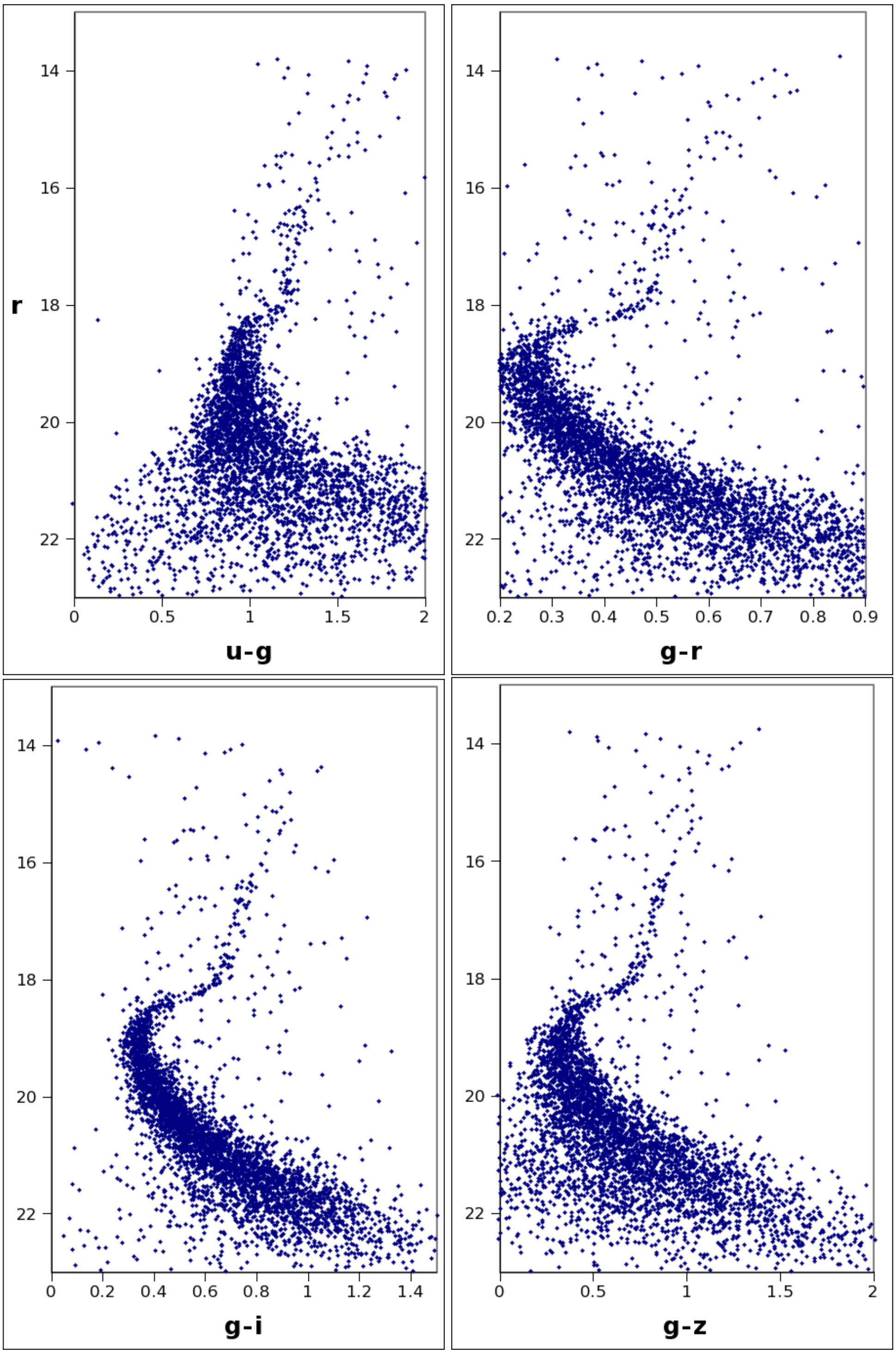

Figure 3.4: Color magnitude diagrams for M3 (the cluster center excluded)

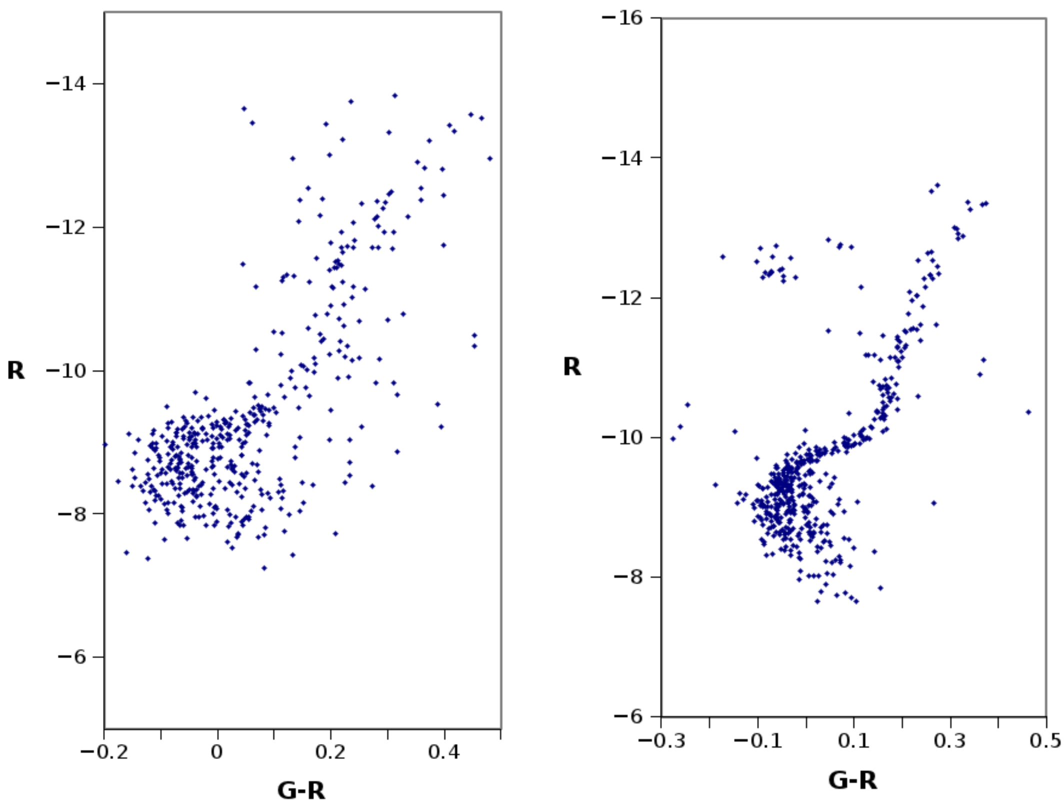

Figure 3.5: Color magnitude diagrams for M2 (left) and M3 (right) obtained with photometry by hand using Makali'i software.

Chapter 4

Discussion

The resulting graphs for M2 and M3 clusters are very similar, except for the difference in the amount of the output data. Considering M2 globular cluster contains approximately hundred thousand stars and M3 globular cluster contains approximately five hundred thousand stars, it is to be expected. The most problematic part of the obtained color diagrams is scattering of data points, which does not enable precise determination of stelar evolutionary tracks that are needed for further analysis of clusters' properties. This is the reason why [An et al. (2008)] used a better photometric software that can handle crowded regions in images. This photometric package is called DAOPHOT and their result for M3 is shown in Figure 4.1. Notice how the scattering is considerably reduced in this case. Instead of DAOPHOT, we tried to do photometry by hand. Results shown in Figure 3.5 can be considered partially successful - They are not complete and precise enough for further analysis of clusters' properties (especially results for M2), but they show how simple photometric method can yield recognizable color diagrams.

Observations of star clusters consist of performing photometry on as many individual stars that can be measured in a cluster. For a physical understanding of observed stellar populations it is essential to interpret the data via stellar evolution tracks (called isochrones). A computer model can be built that follows the changes in stars of various masses in time. Then a theoretical HR diagram can be built at each timestep. Observations of star clusters are compared to the computer generated HR diagrams to determine the magnitude of the main sequence turn-off (which spectral type of stars have recently left the main sequence) in order to get an approximate age of the cluster. Figure 4.2 shows the position of main-sequence, as well as stars that are approaching the end of their life and move away from the main sequence.

Thanks to the improved photometry shown in Figure 4.3, [An et al. (2009)] applied models of stellar evolution to fit the distribution of stars in color magnitude diagrams. Since stars remain on the main sequence during their hydrogen burning lifetime, we can determine the age of a cluster by noticing which stars are missing from the main sequence plotted from the clusters' stars (turn-off point). These missing stars move out of the main sequence, which is seen as a narrow line of stars in the upper part of the clusters' color diagram. However, the position of the main sequence in color diagram critically depends of the stellar metallicity, that is, the amount of elements heavier than helium. Therefore, [An et al. (2009)] used different estimates of clusters' metallicity and used theoretical stellar evolution models to fit the data (see Figure 4.3). They analyzed M3 cluster and determined that its age is 13.3 ± 1.4 or 11.4 ± 1.1 billion years. Two results are outcomes of two different metallically estimates. Notice that the age of the Universe is about 13.7 billion years, which means that the age of M3 is comparable to the age of the Universe.

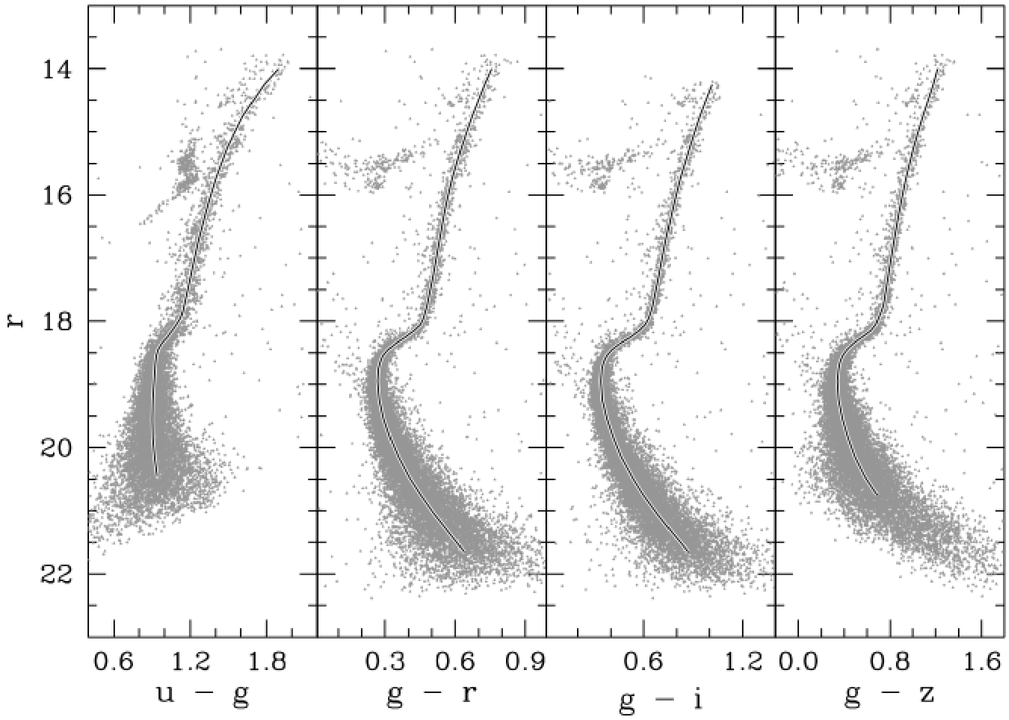

Figure 4.1: M3 from [An et al. (2008)] (DAOPHOT/ALLFRAME photometric package used)

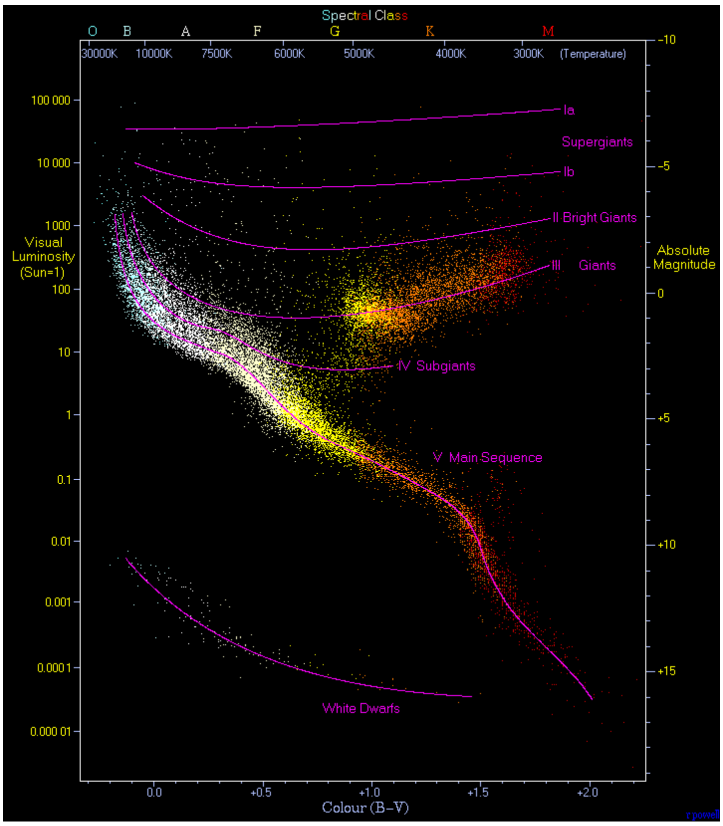

Figure 4.2: The HR diagram (plot of luminosity against the color of the stars ranging from the high-temperature blue-white stars on the left side of the diagram to the low temperature red stars on the right side) [URL-HR]

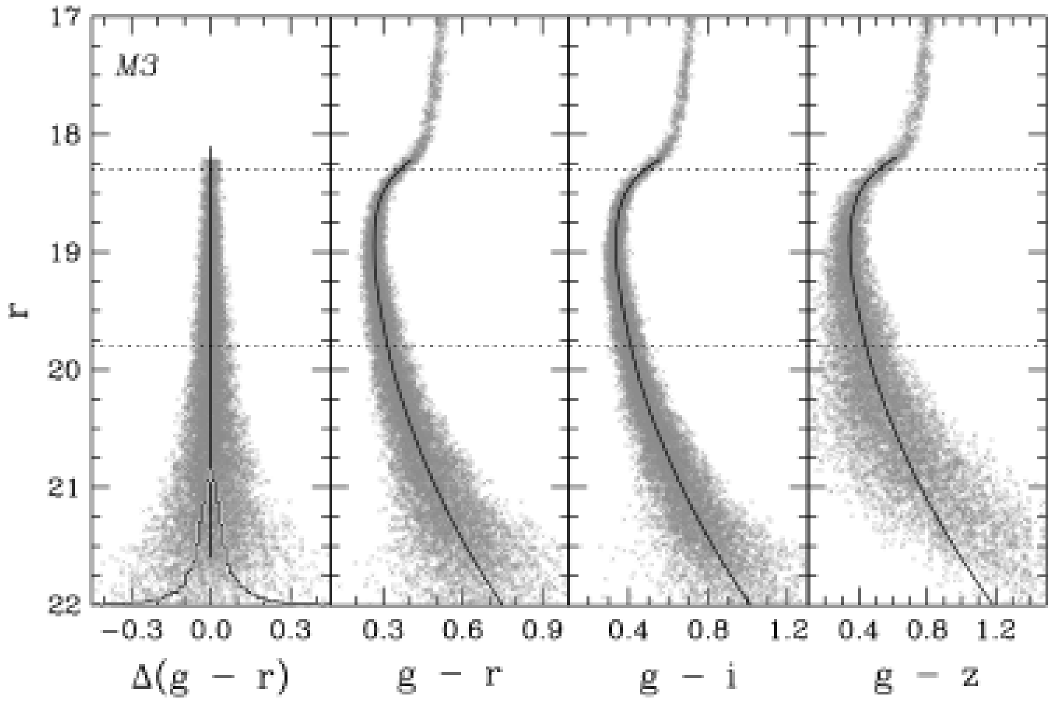

Figure 4.3: Figure from [An et al. (2009)] showing color diagrams for M3 with lines of theoretical models of stellar evolution. The leftmost panel shows the fitting residuals in (g - r, r).

Chapter 5

Conclusions

In this work we explored color magnitude diagrams of globular clusters M2 and M3. Photometry was performed on the publicly available data obtained by the SDSS survey. The photometry was based on the ugriz system of magnitudes used by SDSS. One apprach used the SDSS data on stellar magnitudes measured by the SDSS photometric pipeline. Color diagrams were successfully obtained and they agree with results by [An et al. (2008)], who performed the same approach. The color diagrams show a considerable scattering and we explored if a simple photometry by hand on the SDSS images can yield more useful results. We used the SUBARU Image Processor Makali'i software to measure the stellar brightness and derive photometry. Results in this case were not satisfactory for M2, but can be considered successful in the case of M3. Nonetheless, photometry by hand was still not good enough for further analysis requiring comparisons with theoretical models of stellar evolution. We discussed an improved photometric method used by [An et al. (2008)] and results on cluster age derived by [An et al. (2009)] who combined such an improved photometry with fits to the theoretical models. We can conclude that SDSS data can be used as a simple, but powerful tool for studying globular clusters in classroom setting, while the experience can be further enriched using a relatively simple photometry by hand on SDSS images.

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