
Comparative Analysis of M 3 and NGC 2420 using SDSS Data

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Abstract

The Sloan Digital Sky Survey (SDSS) is an ambitious astrophysical survey that has obtained photometric and spectroscopic data for millions of objects in the universe. In this article we explain the use of SDSS to obtain astrophysical data. We also introduce an indispensable tool for astronomers – H-R Diagrams, in particular, Colour-Magnitude Diagrams (CMDs). Using SDSS data, we plot three CMDs each for star clusters Messier 3 and NGC 2420 and qualitatively analyse their properties. The entire process of our analysis is explained in this article. We hope it will interest undergraduate students particularly the ones interested in astronomy and astrophysics.

1. Introduction

The Sloan Digital Sky Survey (SDSS) is one of the largest astronomical surveys ever undertaken. Photometric and spectroscopic observations were made over a period of eight years using a 2.5 metre wide-angle telescope along with an array of CCDs and a pair of spectrographs, at the Apache Point Observatory in New Mexico, United States. The CCDs captured high resolution images in 5 different colours, while the spectrographs allowed the spectra of 640 objects to be studied simultaneously.

Though the survey obtained individual astrophysical data on millions of objects including stars, galaxies and quasars, the ultimate task of the survey was to connect this data and create a 3D map of a part of the universe. An advanced image processing software was used to analyse the properties of hundreds of millions of objects to provide insights into the large scale structure of

the universe. This is necessary to understand the evolution of the universe over billions of years since the big bang.

SDSS has made all collected astrophysical data public via the internet and data from their newer projects is being released till date. It is free to use for non-commercial purposes by anyone from school students to scientists and is accessible through a variety of tools including an internal SQL server. SDSS has also provided a variety of suggested research projects for interested students. As a demonstration, in this paper we use SDSS data to plot CMDs for two well-known star clusters - Messier 3 and NGC 2420. The entire process of acquisition of data from the SDSS database is explained. A brief qualitative analysis of the CMDs is also included.

2. Hertzsprung-Russell Diagrams

Astronomers have speculated about the life cycle of a star since centuries. Despite having access to

large amounts of meticulously recorded data, the first real progress in our understanding of the nature of the life processes of a star came only in the early parts of the 20th century when *Ejnar Hertzsprung* and *Henry Norris Russell* independently devised what are today known as Hertzsprung-Russell Diagrams (H-R Diagrams). These diagrams are powerful tools and remain to be one of the most widely employed devices in modern astronomy for understanding stellar evolution.

An H-R Diagram, in essence, is a 2-dimensional plot of temperature and luminosity for a group of stars. An individual star is represented as a point in the diagram. However, every star is a dynamic object and undergoes significant changes in its lifetime. As it does so, the point moves around in the diagram. By observing these changes, there is a lot that can be understood about the internal mechanisms of a star. Such processes, however, happen over billions of years and hence, instead of plotting a single star and studying its evolution, several hundreds of stars at different stages in their life cycles are plotted on the same diagram and analysed.

To plot the position of a star on an H-R Diagram, its temperature and luminosity need to be measured. However, the temperature cannot be measured directly. Instead, the spectrum of the star is first obtained by measuring the flux at each particular wavelength. Then by approximating the star to be a blackbody, its effective temperature can be determined. For measuring the luminosity, the combined flux received by us on the earth for all the wavelengths is measured to determine the star's apparent brightness. This is combined with the distance measured to the star, through parallax measurements, to get its true luminosity.

In practice, it is easier to obtain the flux for only a few wavelengths rather than for the entire spectrum. The SDSS, for instance, employs only 5 filters: two in visible; g(4770Å) and r(6231Å), two in infrared; i(7625 Å) and z(9134 Å) and one in

ultraviolet; u(3543 Å). The data obtained can be used to prepare a variant of an H-R Diagram. On the luminosity axis, the Magnitude¹(represented by capital letters; for example G for filter g) associated with an individual filter is taken and on the temperature axis, the Colour Index². The diagram obtained, though not exactly the same, is equivalent to an H-R Diagram and is called a Colour-Magnitude Diagram (CMD). Similarly, other variants of H-R Diagrams exist too and are widely employed.

H-R Diagrams find their greatest utility when used for studying star clusters. Several factors contribute to this. Firstly, all the stars in a cluster are assumed to be formed from the same interstellar gas cloud and thus are assumed to have the same chemical composition. Further, they are all formed within a few million years (an insignificant period at the time scales involved) of each other and hence can be assumed to be of the same age. Thus, stars in a cluster differ significantly in only one aspect: their mass. Thus, an H-R Diagram for a cluster can help astronomers understand how the mass of a star affects its life processes. Another factor that makes H-R Diagrams of star clusters so important is the fact that all the clusters in the galaxy seem to have the same relative distribution of stellar masses described by the stellar Initial Mass Function (IMF). Thus, by studying one star cluster, we gain insight about others as well. This can be used to determine important information about a given cluster such as its age, its distance, etc. Finally, from a practical viewpoint, star clusters are useful because all the stars in a cluster are roughly at the same distance from us. This eliminates the need to determine the absolute magnitude of brightness for the stars. Instead, the apparent magnitudes may directly be used. Thus, there is no need to measure the distance to a particular star which often proves to be the most difficult quantity to obtain. In this paper, we shall be studying two star clusters: Messier 3 and NGC 2420.

Having seen why star clusters are so important, we briefly digress from our discussion about H-R Diagrams to discuss certain important points about such clusters. From observations, it is found that there are broadly two categories of star clusters - globular clusters and open clusters. The members of each category are held together through their mutual gravitational attractions. However, significant differences exist. Messier 3 represents

a typical globular cluster and NGC 2420 belongs to the class of open clusters. Given below are inverted colour images³ obtained from the SDSS Navigation Tool of the two clusters for comparison.

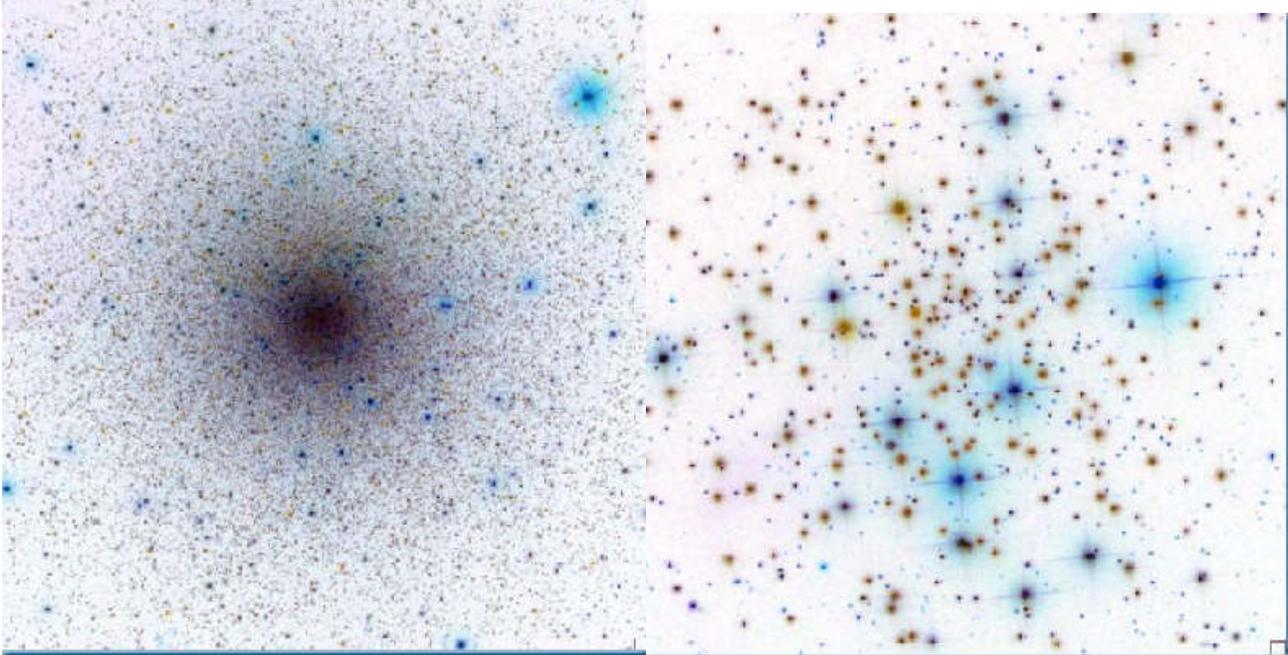


Figure 1: Inverted Colour Images of Messier 3 (left) and NGC 2420 (right) obtained using SDSS Navigation Tool

A typical globular cluster is massive, containing hundreds of thousands of stars tightly bound together forming a relatively dense spherical distribution as can be seen in the image for Messier 3 in Figure 1. An important feature of globular clusters is their age. From spectroscopic analysis it is observed that the members of a globular cluster have a low abundance of heavy elements. In its early stages the universe was mostly made up of Hydrogen and Helium (it still is dominated by them) and so the earliest stars were mainly composed of only these elements; the heavy elements were only formed later through fusion reactions in the cores of stars. Therefore, the low abundance of metals in stars in globular clusters

suggests that these stars were formed when the universe was relatively young. In fact, globular clusters are believed to be amongst the oldest observable structures of the universe. For a typical globular cluster, an age of at least 10 billion years is estimated.

Open clusters differ in several important ways. Typically they only contain a few thousand stars and do not possess any definite shape. They are only loosely held together and hence as they get older, the members tend to drift apart and the cluster “dissolves”. Thus, an open cluster is not expected to be too old. This is confirmed by spectroscopic studies which show that the

members of these clusters are vastly richer in heavier element abundances. These stars could not have been formed along with the earliest generations of stars. Typically, an open cluster is estimated to be only a few hundred million years old, though some have been shown to be a few billion years old.

These differences between the two clusters lead to interesting characteristic features in the H-R

Diagrams for each. We shall see this clearly once we have plotted our diagrams.

We now return to our general discussion about H-R Diagrams. In Figures 2(a) and 2(b), we represent broadly the important features of a typical H-R Diagram. Figure 2(a) labels the most important regions and Figure 2(b) depicts how the H-R Diagram of a given cluster evolves with time.

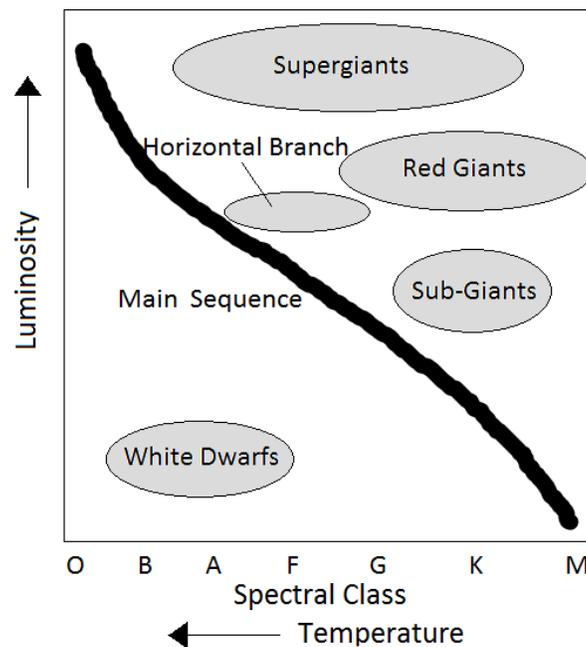


Figure 2(a): Important Regions of an H-R Diagram⁴

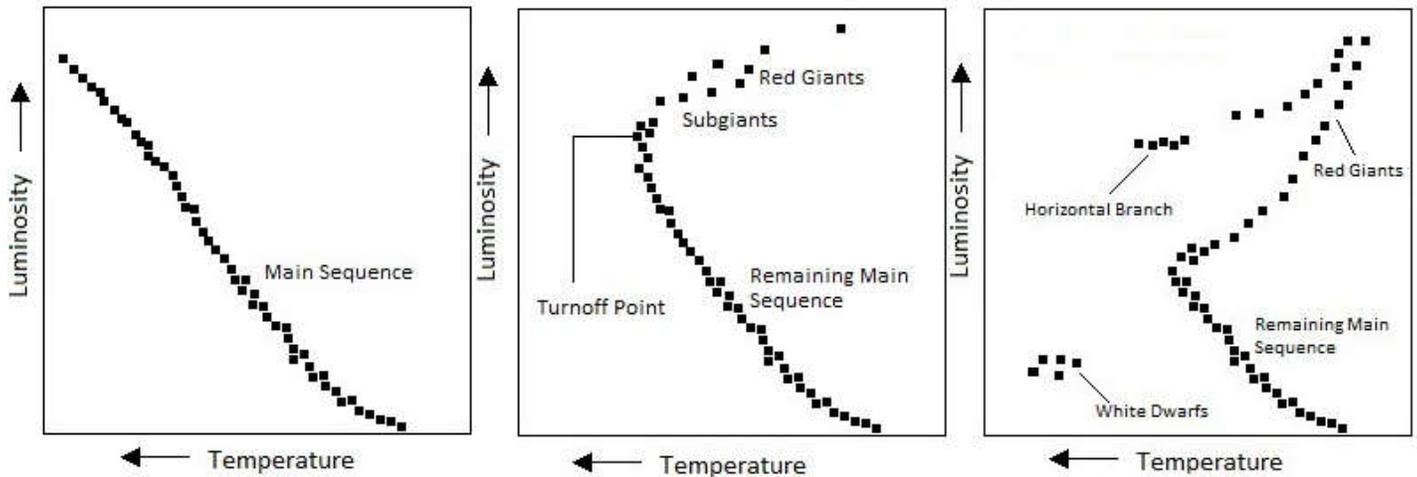


Figure 2(b): Evolution of the H-R Diagram of a cluster (time evolves as we go from left to right)

1. The most noticeable feature of any H-R Diagram is that a large number of the stars seem to be located on a diagonal curve across the graph. This region is called the main sequence. There are steady and continuous nuclear reactions in the main sequence stars and energy is produced by conversion of hydrogen into helium. The radiation pressure so generated prevents the star from collapsing under its own gravity. Along the main sequence, the position of a star depends mostly on its initial mass with the more massive ones lying higher up the diagonal. Also, the position of an individual star changes only negligibly during this stage. So, as long as a star is on the main sequence (a period that constitutes a majority of its lifetime), it remains practically stationary on the H-R Diagram. However, this cannot carry on forever - stars evolve and the details depend mainly on the initial mass M of the star. The energy stored in a star is roughly proportional to M and the rate at which it expels this energy is roughly proportional to M^4 . This means that the time a heavy star would spend on the main sequence is much less than time a light star would (the approximate variation is $t \propto M^{-3}$). The M^4 variation breaks down for extremely massive or

extremely light stars but the general rule that more massive stars evolve more rapidly still stands. Depending on the initial mass of the star, its main sequence lifetime can vary from just a few million years to hundreds of billions of years.

2. When hydrogen is depleted in the stellar core, because of the reduced nuclear fusion, the internal production of thermal energy can no longer balance the gravitational interaction and the main sequence star begins to contract. This in turn causes the core to heat up. The increased core temperature causes the outer layers of the star to expand. This leads to the star entering the “Red Giant” phase. As it expands, the temperature drops due to its larger surface area, and thus its peak wavelength shifts towards orange. Despite being cooler than main sequence stars, red giants, due to their greater size, are much more luminous than the red stars on the main sequence. They lie on the upper right corner of the diagram. Compared to the main sequence lifetime of a star, its transition period to the red giant phase is quite small. As we can see in Figure 2(b), as time evolves more and more stars begin to enter this stage and there is an abrupt turning point to the main sequence diagonal leading into the red giant region. After plotting H-

R Diagrams for Messier 3 and NGC 2420, we shall see how the age of a cluster can be estimated by noting the position of this turning point.

3. When nuclear fuel is completely depleted from a star's core, the gravitational attraction is no longer balanced by the production of thermal energy. The star contracts. Since electrons obey the Pauli Exclusion Principle, an electron degeneracy pressure builds. It balances out the gravitational attraction if the mass of the star is less than Chandrasekhar's limit. These stars are much less luminous than the blue stars in the main sequence and thus are much smaller in size. They are called White Dwarfs and lie on the bottom left of Figures 2(a) and 2(b).

We note that apart from these three main stages of stellar evolution, there are several other sub-stages that an individual star may go through. For example, Figure 2(a) shows the Horizontal Branch region and the Supergiant region. Both of these are occupied by stars that are in between the red giant and the white dwarf phases. Similarly, the Subgiant stage occurs just before the red giant phase. Other regions, not shown in Figure 2(a), such as the Planetary Nebula region, Asymptotic Giant Branch, etc. are also of interest. For details, refer to [1].

It is important to mention that our discussion above is only valid for stars with average masses. In massive stars, helium ignition causes them to expand, reducing the temperature. The red supergiant thus formed collapses in a supernova. Depending upon the initial mass of the star, a neutron star or a black hole may be formed.

3. SDSS Search Tools

A variety of tools are available on the SDSS website that allow users to extract data on any of the hundreds of millions of objects that have been covered by the survey. These are:

1. Navigation Tool[10]: It allows users to navigate in the vicinity of a point in the sky by entering its coordinates (RA and Dec⁵). An image of the vicinity of that point is seen on the screen. One can obtain all the available data for any object in the frame by selecting it and clicking on 'explore'. Spectra of select objects are also available. A disadvantage of this tool is that data has to be collected individually for all objects. Figure 3 shows the SDSS Navigation Tool.

2. Radial Search Tool[11]: It allows users to search for data on all objects around a certain point, within a certain radius. A major advantage, of course, is that data for hundreds, even thousands of objects can be obtained through just a single search. Search for data is restricted by setting a particular radius and limiting values of colour magnitudes (U, G, R, I, Z). A major disadvantage of this tool is that it searches for any object in the vicinity of the given point. So, the data it provides may contain unwanted objects. For example, in a search for stars in a cluster, it may add galaxies that appear in the vicinity of the given point. Figure 4 shows the SDSS Radial Search Tool.

3. SDSS SQL Search Tool [13]: It allows the user to write SQL queries to search for the required data. It can be used to make very precise searches that only return the data the user wants without including unwanted results. This is the tool that we used to obtain the data required for the CMDs of Messier 3 and NGC 2420. The details are explained in the next section.

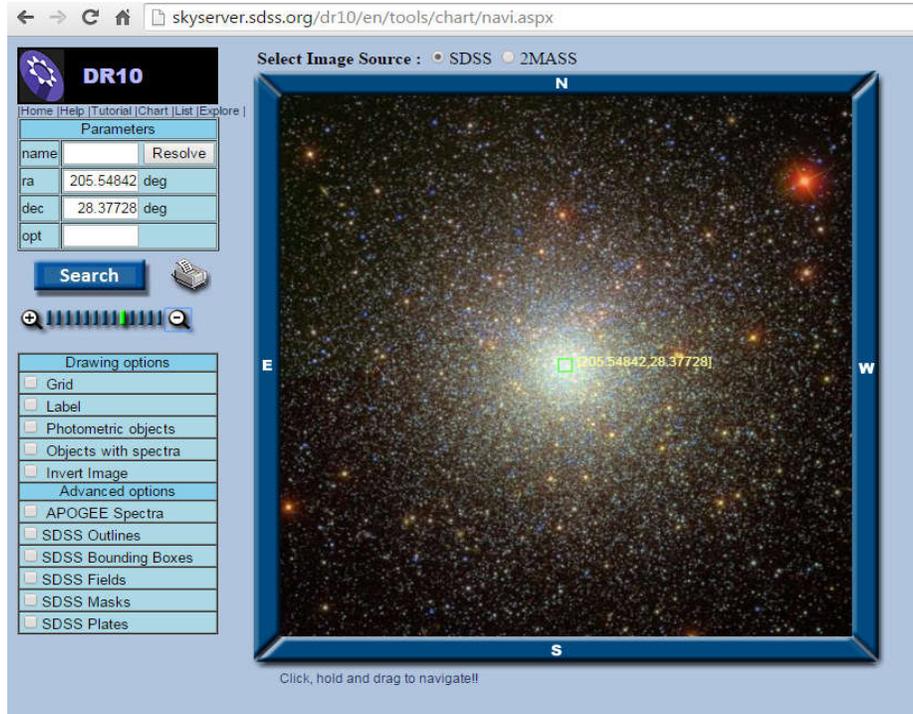


Figure 3: DR10 Navigation Tool Showing M3



Figure 4: DR10 Radial Search Tool with M3 coordinates entered

4. Data for Messier 3 and NGC 2420

For acquiring the data for the clusters, we made use of SDSS's Data Release 10. We first obtained the RA and Dec values for Messier 3 and NGC 2420 which can easily be found from any astronomy catalogue. By entering these values in the SDSS Navigation Tool, we obtained an image for both the clusters. The image was used to obtain an estimate for the apparent diameter of the cluster which is its spatial extension as seen from the earth. The values used are:

Messier 3:

Right Ascension = 205.54842°

Declination = 28.37728°

Apparent Radius = 9 arcmin

NGC 2420:

Right Ascension = 114.59958°

Declination = 21.57409°

Apparent Radius = 6 arcmin

The SDSS database contains information on millions of objects and has been organised into tables, each dedicated to data of a specific type. The data can be accessed by writing SQL queries. A complete description of the various tables and their contents can be found at[12]. Once the data required has been identified, the query may be written in the SDSS SQL Search Tool provided at[13]. We used two SQL queries, one for extracting the data for Messier 3 and the second one for extracting the data for NGC 2420.

Query for Messier 3

```
select
s.objid, s.ra, s.dec, s.u, s.g, s.r, s.i, s.z
```

```
from
star s,
dbo.fGetNearbyObjEq(205.54842, 28.37728,9) n
```

```
where
s.objid = n.objid
```

Query for NGC 2420

```
select
s.objid, s.ra, s.dec, s.u, s.g, s.r, s.i, s.z
```

```
from
star s,
dbo.fGetNearbyObjEq(114.59958,21.57409,6) n
```

```
where
s.objid = n.objid
```

The SQL queries have three parts:

1. Under 'select', we specified the data that we wanted the particular query to return. In the above queries, we instructed the system to return the following information: object ID (objid), Right Ascension (RA), Declination (Dec), and magnitudes.
2. Under 'from', we specified the tables that contain the data to be returned. In the above queries, we instructed the system to search in the table called 'star'. This ensured that only data for stars is returned and not for other objects. We also employed the function `dbo.fGetNearbyObjEq` which accepts three arguments (a, b, c). It works by creating a temporary table based on the arguments entered and can be used to return the required data for all stars within a radius of 'c' arcmin around the point with RA 'a' and Dec 'b'. For example, in the Query for Messier 3, we specified the region within a radius=9 arcmin around the point with RA=205.54842° and Dec=28.37728°. All the stars (not other objects) within this region were thus returned by the query.
3. Under 'where', we specified the constraints that we wished to impose on the returned data. For the above queries, the condition imposed ensured

that both the table ‘star’ and the one generated by the function `dbo.fGetNearbyObjEq` contained the same data.

A comprehensive tutorial for writing SQL queries on SDSS may be found at [14].

The data for the analysis was obtained in CSV format and analysis was done in Excel®.

5. Results

Shown in the following pages are the CMDs for NGC 2420 and Messier 3 obtained using the data extracted from SDSS. We plotted three diagrams for each cluster: R vs $G-R$, G vs $R-Z$ and U vs $G-I$. These quantities simply represent the luminosity vs temperature variation with temperature decreasing along the positive direction of X-axis (increasing $G-R$, $R-Z$ and $G-I$) and luminosity increasing along the positive direction of Y-axis (decreasing R , G and U).

The screenshot shows the SkyServer DR10 SQL Search interface. The browser address bar displays `skyserver.sdss.org/dr10/en/tools/search/sql.aspx`. The page header includes the Sloan Digital Sky Survey III logo and navigation links: Home, Data, Schema, Education, Astronomy, SDSS, Contact Us, Download, Site Search, and Help. The main content area is titled "SQL Search" and contains a text input field with the following SQL query:

```
select
s.objid, s.ra, s.dec, s.u, s.g, s.r, s.i, s.z
from
star s,
dbo.fGetNearbyObjEq(205.54842, 28.37728, 9) n
where
s.objid = n.objid
```

Below the query input, there are buttons for "Submit", "Check Syntax Only?", "Output Format", and "Reset". The "Output Format" section has radio buttons for HTML, XML, CSV (selected), JSON, VOTable, and FITS. To the left of the main content, there is a sidebar titled "DR10 Tools" with a list of options: Getting Started, Famous places, Get images, Scrolling sky, Visual Tools, Search (with sub-options: Radial, Rectangular, Search Form, SQL, Imaging Query, Spectro Query, IR Spec Query), Object Crossid, and CasJobs. Below the query input, there are several informational text blocks: "This page allows you to directly submit a SQL (Structured Query Language) query to the SDSS database server...", "Please note: To be fair to other users, queries run from SkyServer search tools are restricted in how long they can run and how much output they return, by timeouts and row limits...", "To find out more about the database schema use the Schema Browser.", "For an introduction to the Structured Query Language (SQL), please see the Searching for Data How-To tutorial.", and "The inclusion of the imaging and spectro columns for SAS upload in your query (as in the default query on this page) will ensure that when you press Submit, the appropriate button(s) are displayed on the query results page to allow you to upload the necessary information to the SAS to retrieve the FITS file data corresponding to your CAS query..."

Figure 5: DR10 SQL Search with Query for M3 (Output format CSV is selected)

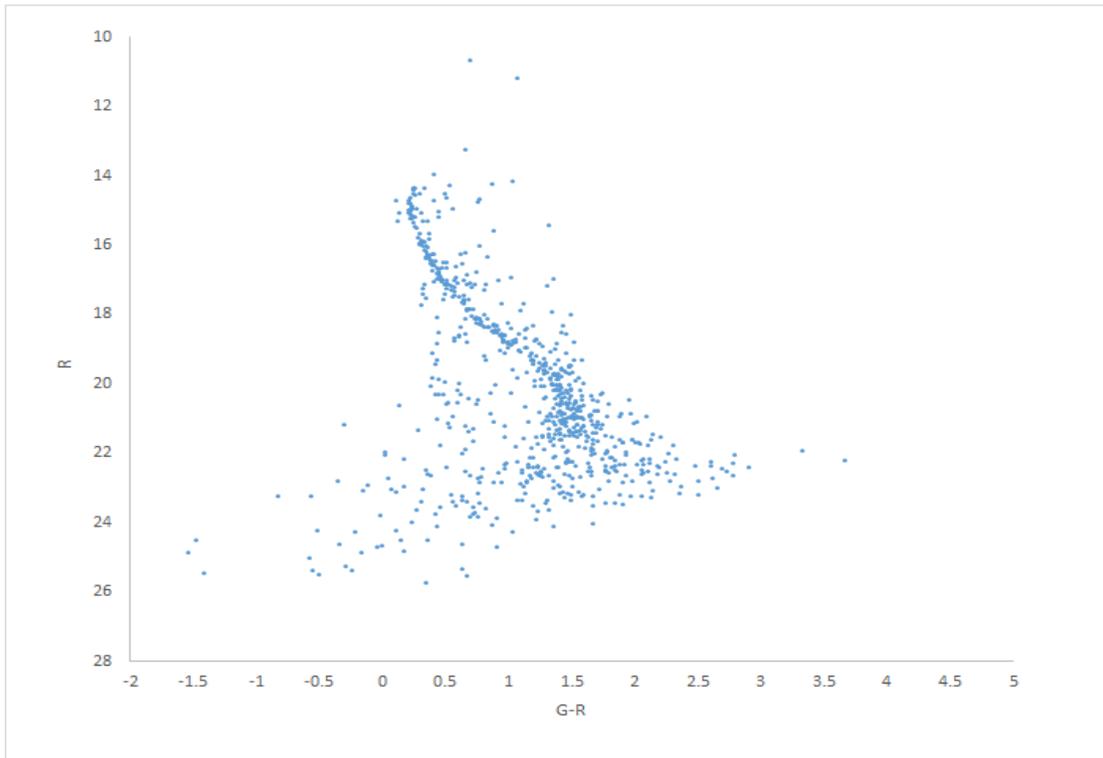


Figure 6: R vs G-R CMD for NGC 2420

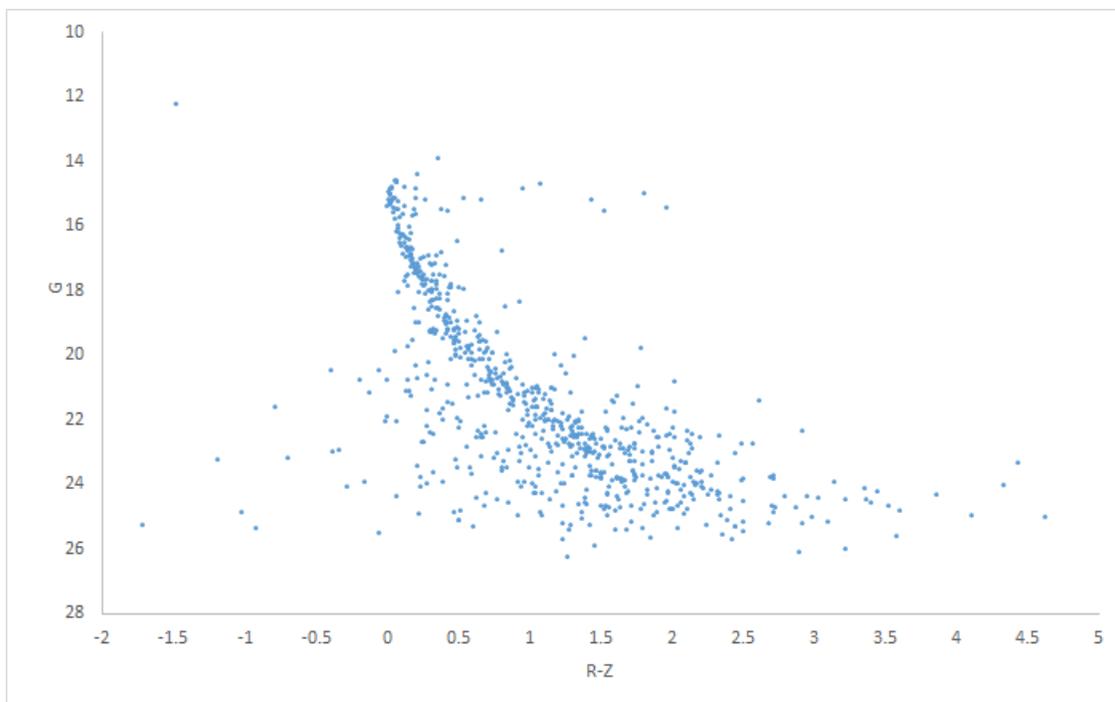


Figure 7: G vs R-Z CMD for NGC 2420

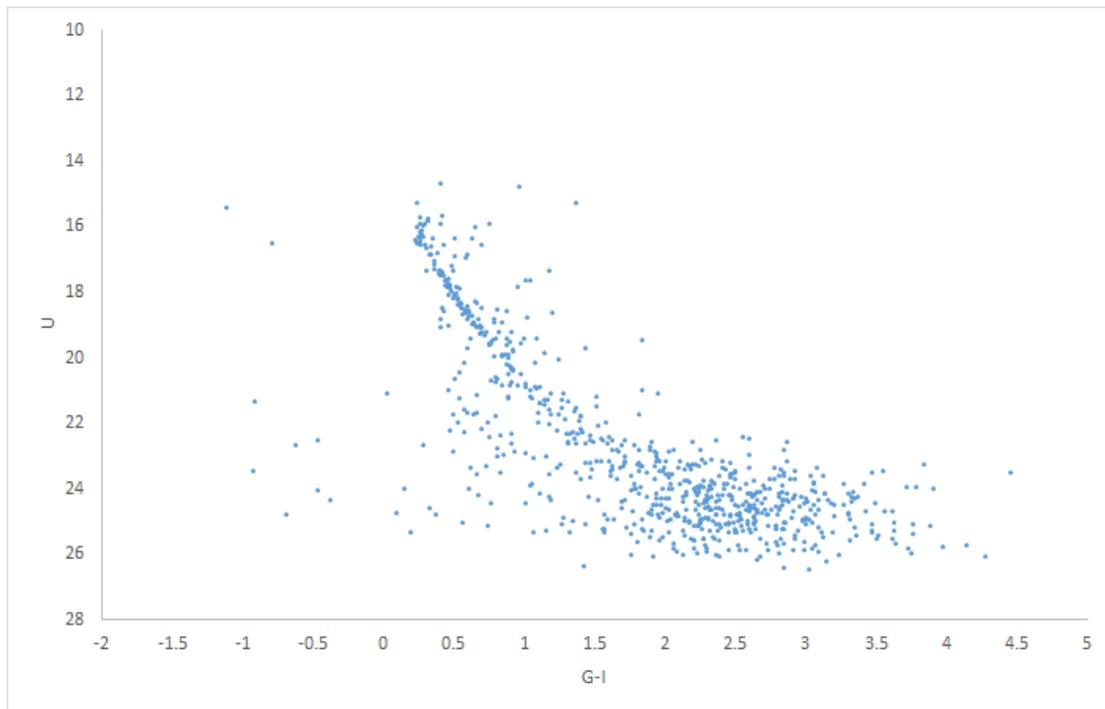


Figure 8: U vs G-I CMD for NGC 2420

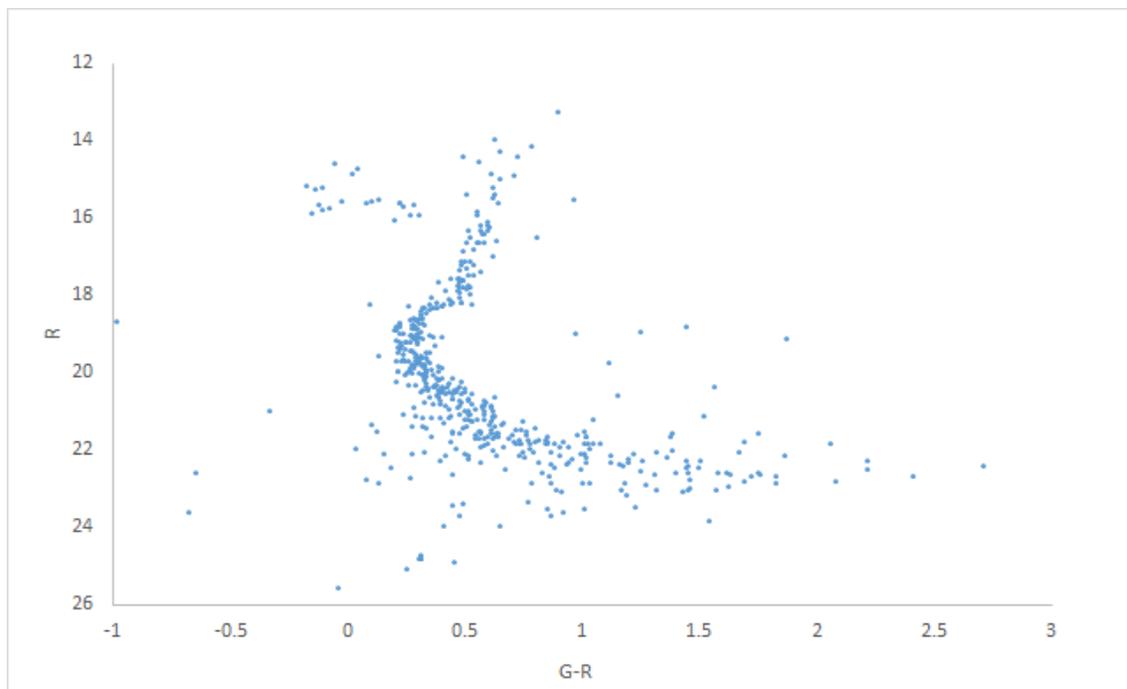


Figure 9: R vs G-R CMD for Messier 3

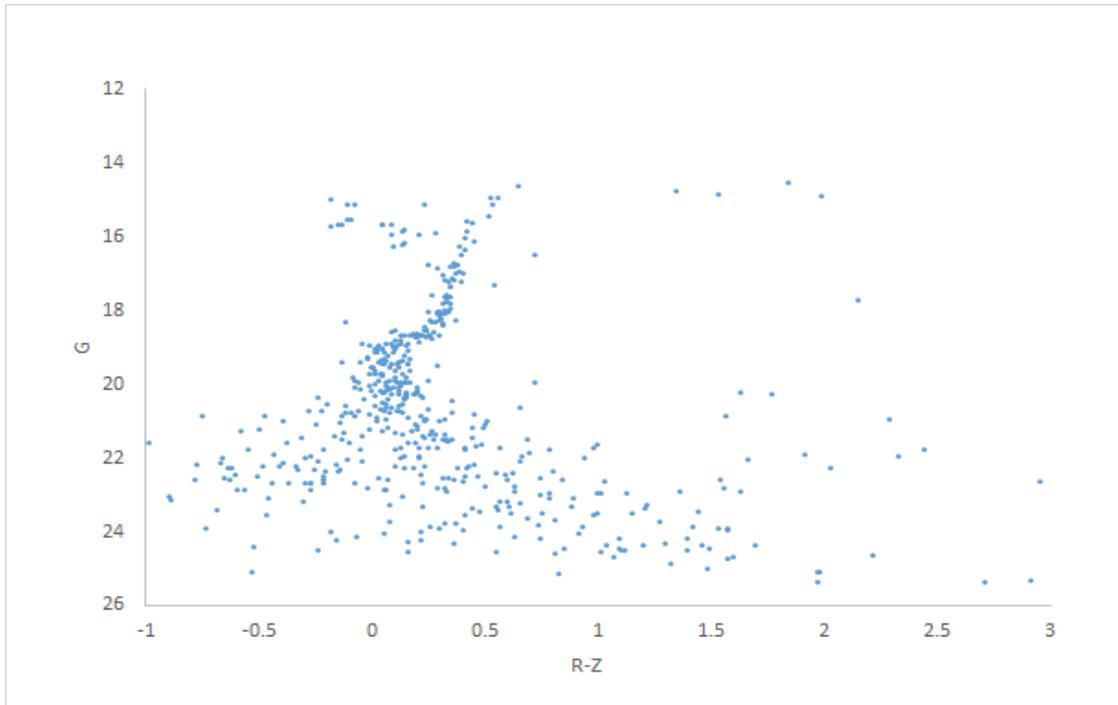


Figure 10: G vs R-Z CMD for Messier 3

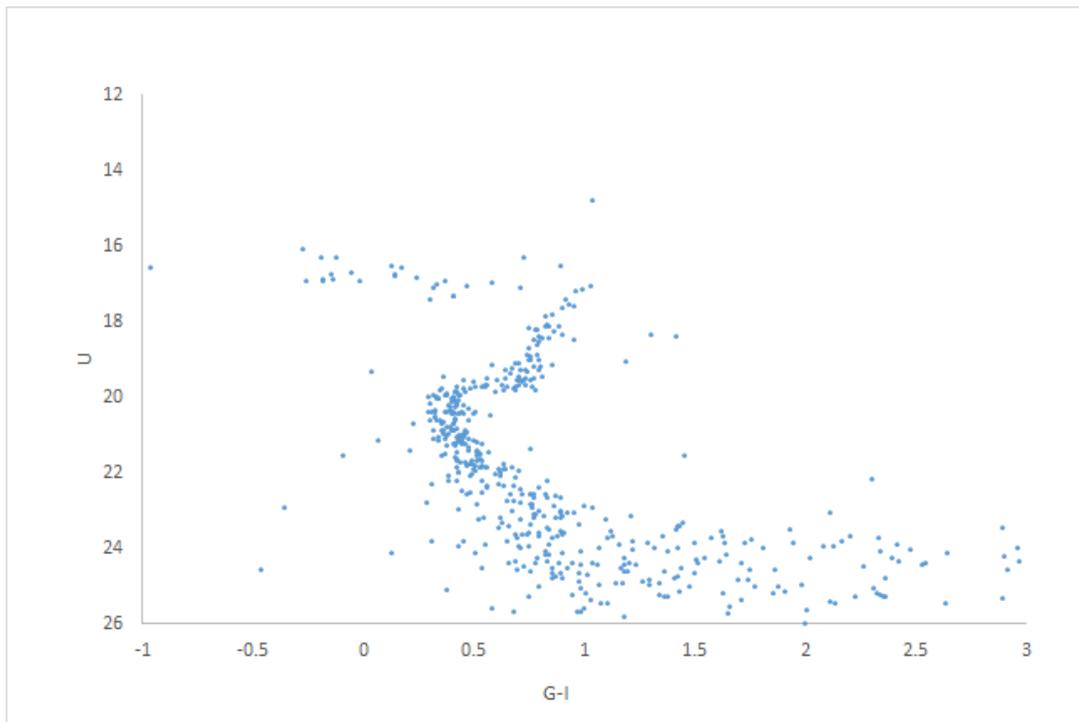


Figure 11: U vs G-I CMD for Messier 3

6. Analysis

Our diagrams clearly show the main sequence for both the clusters. For NGC 2420, it is the most prominent feature with almost the entire population occupying it, from the more massive stars to the lesser ones. For Messier 3, however, the more massive stars seem to be missing and the main sequence region only seems to extend up to the stars with lesser mass.

The diagrams represent typical features to be expected in the CMD of an open and a globular cluster respectively. To see why, we need to consider what we had discussed above. NGC 2420, and open clusters in general, are young. Most of their stars are still in their Hydrogen-burning stage in which they spend the major part of their lives. These stars are found along the main sequence band. In fact, the young age of the cluster means that some of the least massive stars of the cluster are yet to even enter the main sequence region and are called Pre-Main Sequence stars (PMS stars). It is only the most massive stars that have had enough time to evolve out of the main sequence as they have burned up all their Hydrogen (the fate that awaits these is a catastrophic one - a supernova explosion; however, for this discussion we are more interested in the evolution of the cluster as a whole, rather than that of individual stars). Now, as time progresses, the CMD for a cluster undergoes changes. The PMS stars also enter the main sequence region but more prominently, more and more stars begin to leave it and enter the red giant region. The point on the CMD at which the stars just begin to leave the main sequence is called the turn-off point. For older clusters, this point corresponds to successively lower mass stars.

We can clearly see the turn-off point in the CMD for Messier 3. Also, the red giant region is significantly populated. These are features that are missing from the CMD of NGC 2420. This can again be understood by considering the age of Messier 3. Because globular clusters are quite old, many of their stars have used up all their Hydrogen and moved out of the main sequence region. Indeed, the most massive ones evolved first and underwent supernovae explosions, but with time stars with lower masses too have burned through their hydrogen reserves. These stars don't possess enough mass to undergo violent explosions; rather they enter a new phase of generating energy through Helium-burning and become red giants. Eventually, these stars will end up as white dwarfs - their final evolutionary state.

There are two more important features that may be seen in the CMD of Messier 3. One is the presence of the horizontal branch region. This region is occupied by stars not having too high masses immediately after they evolve out of the red giant phase. Again, this represents aging and it is a characteristic feature of old clusters and hence, we cannot find it in the CMD for NGC 2420. Finally, there is the white dwarf region. Globular clusters such as Messier 3 contain several white dwarfs.

As we mentioned before, CMDs can be used to determine important information about a cluster. Before concluding, we briefly mention one such possible extension to this work - using a CMD to determine a cluster's age. Through the knowledge of internal stellar mechanisms of energy generation, observations of metallicity for the cluster whose age is to be found, the stellar initial mass function, etc. astrophysicists can generate theoretical CMDs corresponding to different ages using computer simulations. These are known as isochrones. By comparing these isochrones to the

observed data, the best fit can be determined. This gives an estimate of the age. From such estimates (as well as other techniques), the age of NGC 2420 is estimated to be about 2 billion years [8], whereas that for Messier 3 is estimated to be about 11.39 billion years [9].

7. Conclusion

We have prepared and analysed Colour-Magnitude Diagrams for Messier 3 and NGC 2420 and used them to illustrate the differences between globular and open clusters. We have demonstrated how the data was obtained from SDSS; one important point to note is that our method of data acquisition cannot differentiate between stars that are actually members of a particular cluster and stars that just happen to be in the same field of view. This can lead to some non-member stars being plotted in the CMDs. Perhaps this explains why we see certain unexpected features such as the presence of some stars in the white dwarf region for NGC 2420. However, the diagrams still bring out the most important features for each cluster. We hope our work shows how SDSS can be an extremely useful resource, particularly for undergraduate students who can use the platform to pursue a number of independent research projects.

8. Acknowledgements

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Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

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[10] <http://skyserver.sdss.org/dr10/en/tools/chart/navi.aspx>

[11] <http://skyserver.sdss.org/dr10/en/tools/search/radial.aspx>

[12] <http://skyserver.sdss.org/dr1/en/help/browser/browser.asp>

[13] <http://skyserver.sdss.org/dr10/en/tools/search/sql.aspx>

[14] <http://skyserver.sdss.org/dr1/en/help/howto/search/>

10. Glossary

¹Magnitude: It is a logarithmic scale that measures the brightness of an astronomical object either at a particular wavelength or as a composite quantity. The scale is defined so that a lower magnitude object is brighter than a higher magnitude one. For example, an object with R magnitude = -7 is brighter than an object with R magnitude = -6 (by roughly 2.5 times) at wavelengths centred around red.

²Colour Index: In astronomy, colour is assigned a numerical value, called Colour Index, by calculating the difference between magnitudes at two different wavelengths. For example, G-R represents a particular colour. An object with a higher value of G-R is redder than one with a

lower value. An important point to note is that Colour Index provides a measure of the temperature of a star. This is because a star can be approximately considered to be a Blackbody and hence the ratio of luminosities at two different wavelengths (magnitudes form a logarithmic scale and hence G-R actually corresponds to a ratio of luminosities at green and red) is only a function of the temperature.

³Inverted colour image: An inverted colour image is one in which the colours and brightness values are reversed so that the bright areas appear dark and vice versa, just as in a negative. We have used inverted colour images for M 3 and NGC 2420 as they help emphasise the differences in the structures of the two clusters.

⁴Spectral class: It is an alternative method to Colour Index for specifying stellar temperatures. The spectrum of a star is obtained and the absorption lines it contains give information about the relative abundance of ions of various chemical elements in the star's outer surface. By assuming that temperature is the main factor for determining these ratios and by using our knowledge of the atomic energy levels, the surface temperature can be calculated. Accordingly, there are 7 main classes (and several sub-classes) into which stars are classified (in decreasing order of temperature): O, B, A, F, G, K, M. For more details, consult [1].

⁵RA and Dec: Right ascension and declination form a system of coordinates widely employed in astronomy to specify the location of objects in the night sky. For details, consult any resource on introductory astronomy.