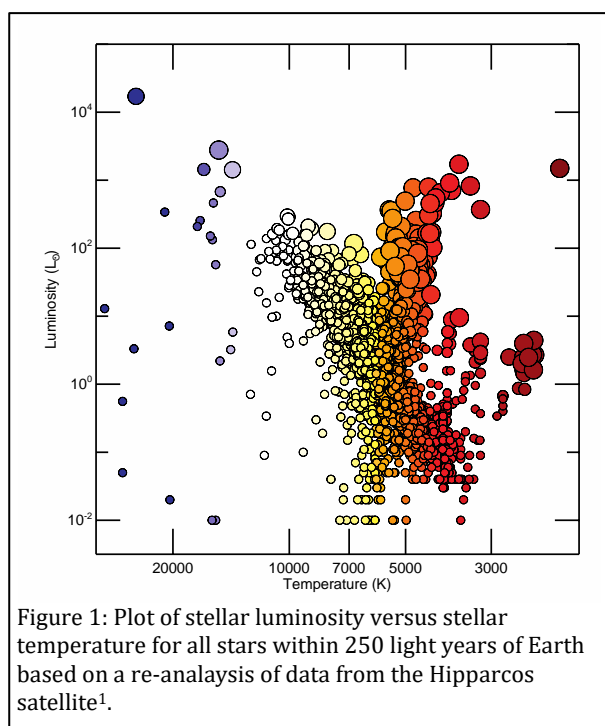


Analysis of Globular Clusters Using Colour-Magnitude Diagrams

Edward Meehan, George J. Bendo and Rebecca Freestone
Jodrell Bank Centre for Astrophysics, The University of Manchester
19 June 2019

Overview

The DS9 astronomical image viewing tool will be used to measure the brightnesses of stars in blue (g-band; 4770 Å) and near-infrared (i-band; 7625 Å) images of one of several globular clusters observed by the Sloan Digitized Sky Survey. These measurements will then be used to construct a colour-magnitude diagram, which is a variant of the Hertspung-Russell diagram. The locations of the stars in the diagram can be compared to model data to identify the age of the cluster and the amount of heavy elements in the stars.



General Astronomy Concepts

When a group of stars form out of interstellar gas, the stars have a range of luminosities (the total energy radiated per unit time) and colours that follow a relation called the main sequence, which appears as a diagonal line from the upper left to lower right in Figure 1. The bluest, hottest, and brightest stars on the main sequence have the shortest lifespans. They may live for a few million years before running out of hydrogen in their cores, which causes them to undergo a series of changes where they first become red supergiant stars and then supernovae. When stars change like this, they move towards the upper right of Figure 1. The reddest, coldest, and dimmest stars have the longest lifespans; they could continue to convert hydrogen into helium in their cores for billions of years.

Star clusters are gravitationally-bound groups of stars that formed together out of the same cloud of interstellar gas. Two different types of clusters are

found in the Milky Way Galaxy and other galaxies. Examples of each type of cluster are shown in Figure 2. Open clusters are star clusters with no well-defined shape that are found within the disc of the Milky Way Galaxy. Most of these clusters formed relatively recently, and most have ages less than 500 million years old. This is because gravitational forces within the disc of the galaxy tend to pull these clusters apart. Globular clusters are spheres of stars found outside the plane of the Milky Way Galaxy, although they still orbit around the centre of the Galaxy. Most of these clusters are over 10 billion years old.

All the stars within an individual cluster will have the same age, but the bluest ones will be the first to turn into red giants or supergiants. Later, the white main sequence stars will turn into red giants, then the yellow main sequence stars will do the same, and the orange and red main sequence stars will do this afterwards. As a result, the colours and magnitudes (or brightnesses) of stars within a star cluster will change over time. Figure 3 shows the expected colours and magnitudes for star clusters with different ages.

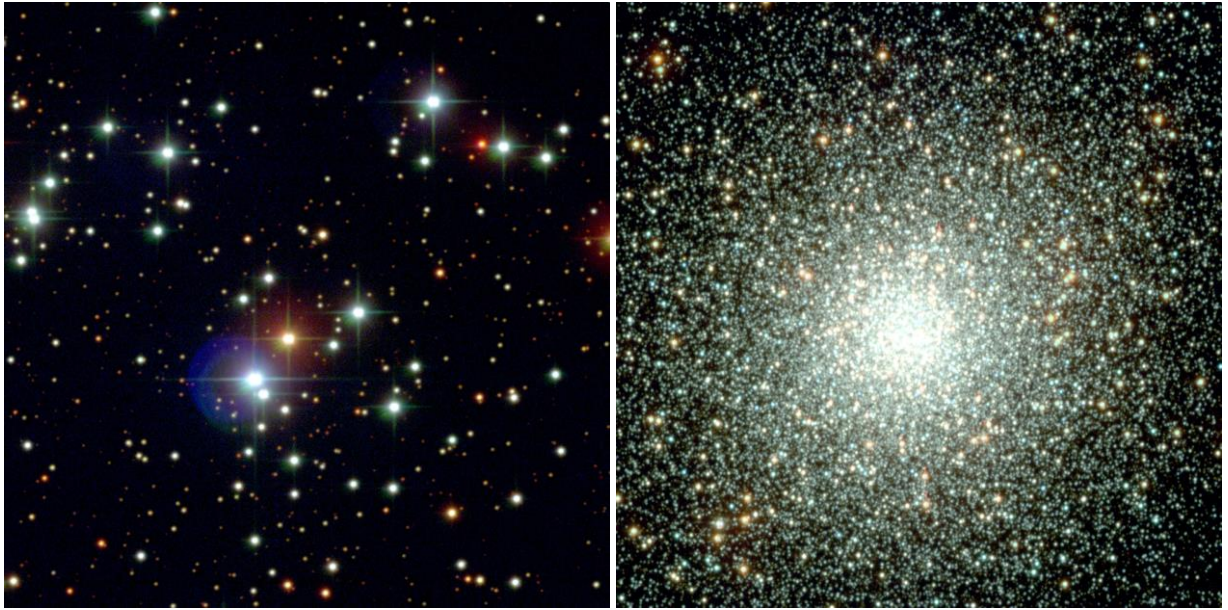


Figure 2: Visible light/near-infrared images of the open cluster NGC 2251 (left) and the globular cluster M5 (right). These images are based on data from the Sloan Digitized Sky Survey (SDSS) Collaboration (www.sdss.org).

Additionally, the colours of stars can change depending on the amount of elements heavier than hydrogen and helium in the stars' atmospheres. One metric of the relative amount of heavy elements is the quantity $[Fe/H]$ as given by the equation

$$[Fe/H] = \log \frac{(N_{Fe}/N_H)_*}{(N_{Fe}/N_H)_{Sun}}$$

where N_{Fe} and N_H are the number of iron and hydrogen atoms and where the ratio $(N_{Fe}/N_H)_*$ for one or more stars is compared to the ratio $(N_{Fe}/N_H)_{Sun}$ for the Sun. If the stars contain large amount of heavy elements, the atoms will tend to absorb blue light from the interiors of the stars, which also causes the stars to expand and cool. These effects make stars appear redder. When the oldest globular clusters formed, the universe contained very few elements other than hydrogen and helium. As a result, the stars contain few heavy

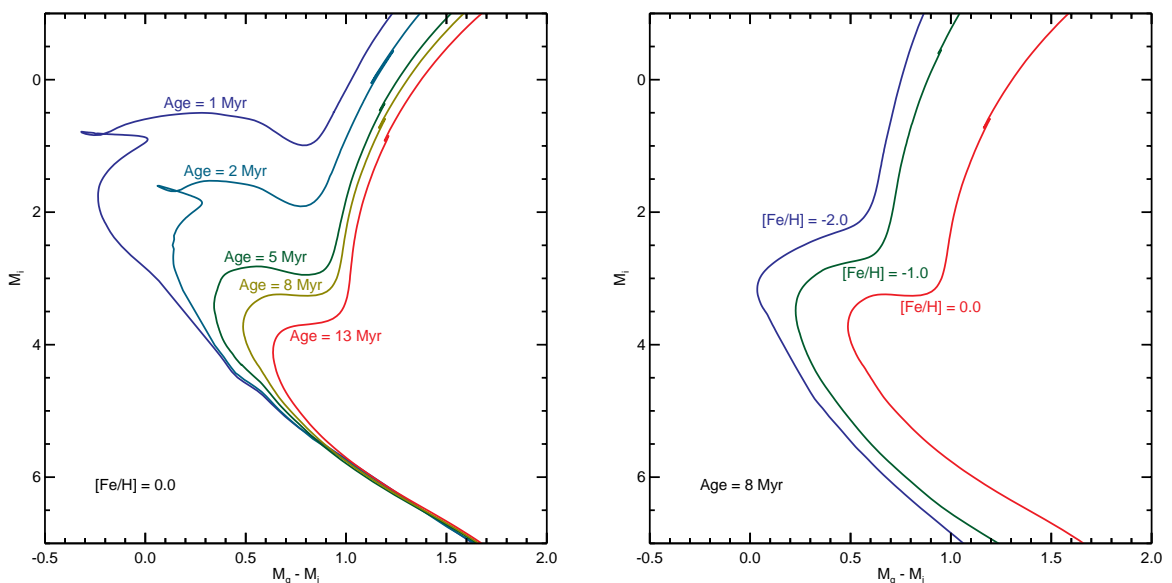


Figure 3: Lines showing colour versus magnitude for stellar populations with different ages (left) and heavy element content (right). The colours are based on the difference between blue (g-band; 4770 Å) and near-infrared (i-band; 7625 Å) magnitudes; bluer stars would appear on the left, and redder stars would appear on the right. The magnitudes are near-infrared magnitudes; brighter stars appear near the top, and fainter stars appear near the bottom. These plots are based on simulations from the Dartmouth Stellar Evolution Database (<http://stellar.dartmouth.edu/models/index.html>)².

elements, causing both their brightnesses and colours to look different from equivalent stars that have formed more recently.

The goal of this experiment is to measure the magnitudes of stars within a subregion of a nearby globular cluster. These measurements can then be used to construct a colour-magnitude diagram. By comparing the diagram to model results like those in Figure 3, it will be possible to identify the age of the cluster and the quantity [Fe/H].

Additional Information: Magnitudes

Some branches of astronomy use magnitudes to describe the brightnesses of objects. These magnitudes are based on a logarithmic system where adding or subtracting 2.5 from a magnitude corresponds to a 10× change in the total amount of light emitted by an object. Two types of magnitudes are used for different types of measurements: apparent magnitudes and absolute magnitudes.

Apparent magnitudes are used to describe the relative brightness of objects as they appear in the sky. The system is set up so that the magnitude increases when the objects get fainter. In visible light, the brightest star in the northern half of the sky (Vega) is magnitude 0, the faintest stars that can be seen without a telescope are magnitude 6, Venus at its brightest is magnitude -5, and the Sun is magnitude -27.

Absolute magnitude describes how bright objects would appear if they were located at a distance of 10 parsecs from the Earth (where 1 parsec is equal to 3.26 light years). Apparent magnitude can be converted to absolute magnitude using

$$M = m - 5 \log_{10} (D/10)$$

where m is the apparent magnitude, M is the absolute magnitude, and D is the distance in parsecs. Absolute magnitudes are useful for comparing how much energy is produced by different astronomical objects. Like apparent magnitudes, absolute magnitudes increase as objects become fainter. In visible light, for example, the Sun has an absolute magnitude of 4.83, the star Vega has an absolute magnitude of 0.58, and the Milky Way Galaxy has an absolute magnitude of -20.5.

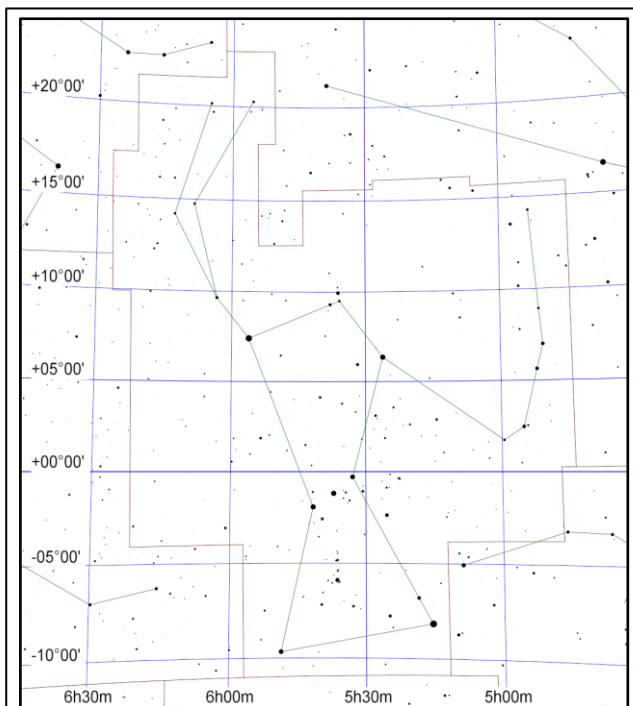


Figure 4: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

Magnitudes measured at different wavelengths can be subtracted from each other to describe the colours of objects. For example, the expression $M_B - M_R$ could be used to describe the difference between a magnitude measured in blue light (M_B) and a magnitude measured in red light (M_R). If an object is much brighter in blue light than red light, M_B could be lower than M_R , and $M_B - M_R$ would be negative. Conversely, if an object is very red, $M_B - M_R$ would be positive.

Additional Information: Coordinate Systems

Astronomers use a coordinate system similar to the latitude and longitude system applied to Earth. The astronomical equivalent coordinates are called right ascension and declination. Right ascension is equivalent to longitude, and it is often measured in hours, minutes, and seconds with a range from 0 to 24 hours, with 60 minutes in an hour, and with 60 seconds in a minute. Sometimes, however, right

ascension is measured in degrees instead (with 1 hour equivalent to 15 degrees). Declination is equivalent to latitude, and it is measured in degrees, minutes, and seconds, with 60 minutes in a degree and 60 seconds in a minute. Declination ranges from +90:00:00 (at the point directly above the Earth's North Pole) through 00:00:00 (the location directly above the Earth's equator) to -90:00:00 (at the point directly above the Earth's South Pole). See Figure 4 for an example of this coordinate system overlaid on the constellation Orion.

Lengths and distances in the sky are often measured in degrees, arcminutes, and arcseconds, with 60 arcminutes in 1 degree and 60 arcseconds in 1 arcminute. For reference, the Sun and Moon are both 0.5 degrees (or 30 arcminutes) across. The Andromeda Galaxy, which is the nearest spiral galaxy, and the Pleiades cluster of stars are both 3 degrees across.

Preparation Procedure

1. Download and install DS9 from the DS9 download page (<http://ds9.si.edu/site/Download.html>). This software is available for Windows, Mac, and Linux.
2. Go to the DR12 Science Archive Server for the Sloan Digitised Sky Survey (<http://dr12.sdss3.org/fields/>). Enter the name of a globular cluster into the "Search by Object Name" box and click Submit or, if that does not work, enter the coordinates of a globular cluster into the text box under "Search by Object Coordinates" and click Submit. The table below provides suggested globular clusters for this experiment. However, the methods in this lab script may work with other star clusters.

Globular Cluster	Right ascension (RA)	Declination (Dec)	Distance ³ (pc)
M5	15:18:33.22	02:04:51.7	7500
M13	16:41:41.634	36:27:40.75	7100
M15	21:29:58.33	12:10:01.2	10400

3. If the cluster was observed by the SDSS, a jpg image of the cluster should appear. Under this is a list of links to FITS files. Right click on the g-band and i-band FITS links and select "Save Link As..." or the equivalent. These files are FITS files that are compressed in the bzip2 format. Save them with understandable names (for example m13_g.fits.bz2 for the M13 g-band image).
4. Follow one of the procedures below to extract the image from the bz2 file.
 - a. On Windows computers, follow these steps.
 - i. Install either PeaZip (<http://www.peazip.org/>) or 7-Zip (<http://www.7-zip.org/>).
 - ii. Open each bz2 file using PeaZip or 7-Zip. Extract the fits file from the bz2 file.
 - b. On Mac computers, click on each downloaded bz2 file. This will extract the fits image from the bz2 file.
5. If, after unzipping the files, the files do not end in ".fits", add this to the end of the filename.

Measurement Procedure

1. Start DS9.
2. Under "File" in either the menu or the button bar, click on "Open". Find and open the g-band FITS file.

3. Under "Scale", select "log". This will change the way the image values are displayed on the computer screen. See Figure 5 for an example.
4. If it is necessary to change the brightness and contrast of the image to see the stars better, first move the cursor to the image window, then hold down the right mouse button (or, on a Mac laptop, hold down the mouse button and the cmd key at the same time), and then move the cursor either up and down or side to side in the window.
5. To re-center the image, middle click on the image.
6. To zoom in or out, either use the scroll wheel on the mouse or go to "Zoom" in the menu or button bar and select one of the options. In Figure 4, the zoom is set to 0.5.

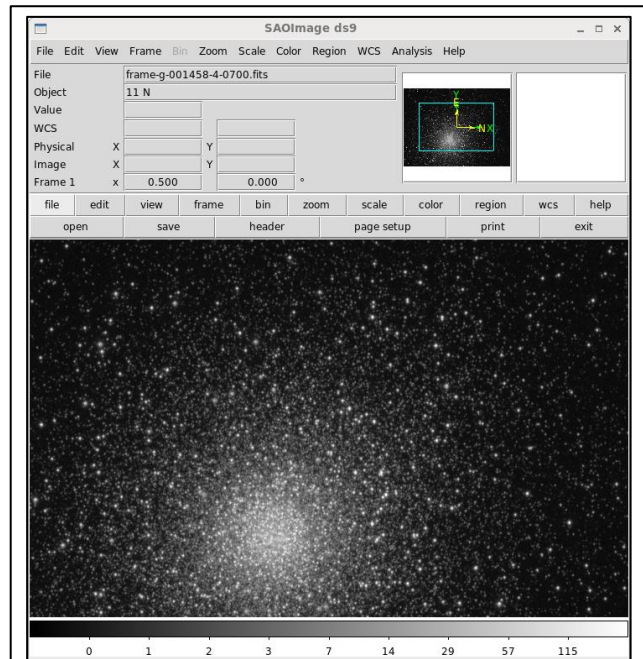


Figure 5: The g-band image of M5 as displayed in DS9 after setting the scale to log and adjusting the zoom.

7. As an additional option, change the colours by clicking on an alternate scheme under "Color" in the menu or button bar. (It may be necessary to repeat step 4 after doing this.)
8. To identify an area within the image to use for the analysis, it is useful to create a coordinate grid that will show the locations of pixels in the image.

- a. Go to "Analysis" in the menu or button bar and click on "Coordinate Grid".
- b. Next, go to "Analysis" and click on "Coordinate Grid Parameters", which will open a new Coordinate Grid Parameters window. In the menu of that window, go to "Coordinate" and click "Image".
- c. After doing this, type in the number "200" into each box under "Grid Gap".
- d. Click "Apply" and then "Close" when done.

See Figure 6 for an example.

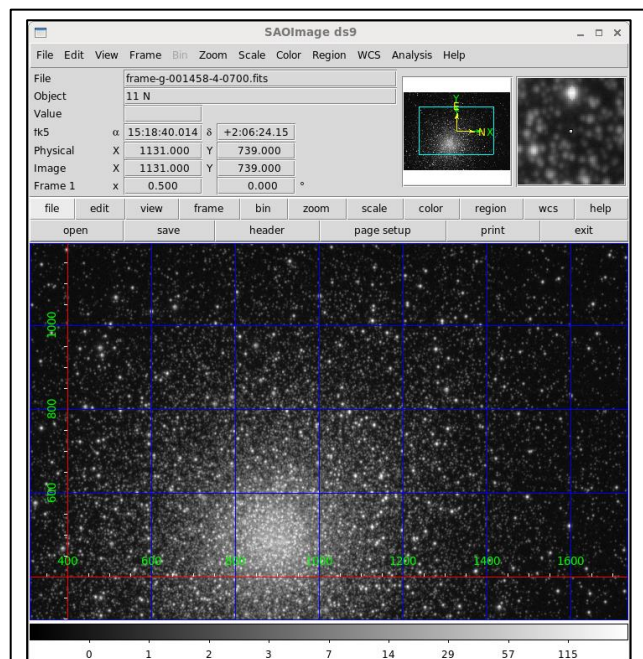


Figure 6: The g-band image of M5 displayed with a coordinate grid.

9. Identify a 200×200 pixel box within the coordinate grid to use for the analysis. It is recommended to look for a location between 500 and 1000 pixels (or between approximately 200 and 400 arcseconds) from the centre of the cluster. It may be necessary to follow the instructions in steps 5 and 6 to find an appropriate area and to zoom in on it.
10. Under "Edit" in either the menu or button bar, click on "region".
11. Under "Region" in either the menu or button bar, select "Shape", and then select "Annulus".
12. Left click on the image to draw an annulus centred on one of the stars. When this region is selected, it will have four small squares around it. Move the annulus so that it is centred on a star. This can be done

by clicking on the annulus with the left mouse button and, while holding the left mouse button down, dragging the annulus across the image. Alternately, use the arrow keys. See Figure 7 for an example.

13. Double click on the annulus, which will open a new window labelled "Annulus". See Figure 8 for an example.
14. Click on the drop-down menu to the right of the row of boxes listing the centre of the annulus. If check marks are not visible next to "WCS" and "fk5", click on these options. After doing this, record the coordinates of the annulus.
15. Click on the drop-down menu to the right of the row of boxes listing the radii of the circles in the annulus. If check marks are not visible next to "WCS" and "degrees", click on these options.

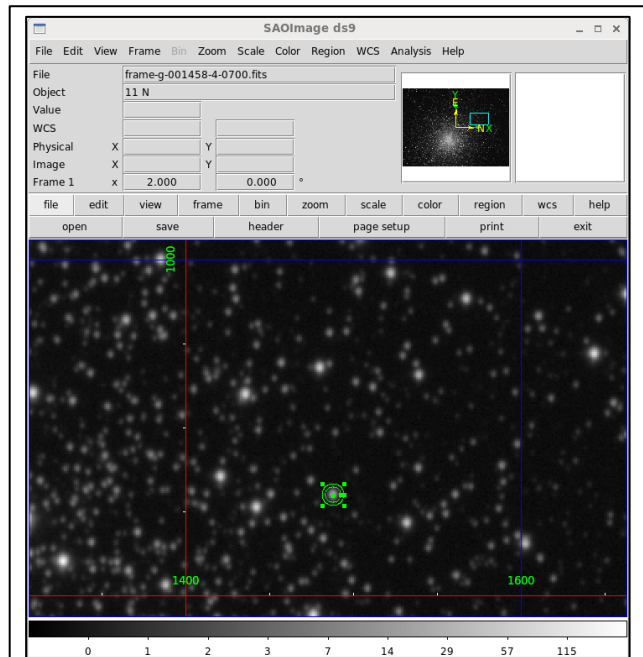


Figure 7: An off-centre location in the g-band image of M5 with annulus drawn around one of the stars.

16. In the tall box labelled "Radius" on the right hand side of the "Annulus" window, enter 0, 0.0005 and 0.000707 (hitting return after typing each number so that each number appears in a separate row). For reference, see the example in Figure 7.
17. Under "Analysis" in the menu, select "Statistics". This will open a new window; see Figure 9 for an example. Record the sum for the inner circle (region 1) and the outer annulus (region 2) for this region as listed in the top table. The first value is the target emission in the g-band, and the second number is the background emission in the g-band.

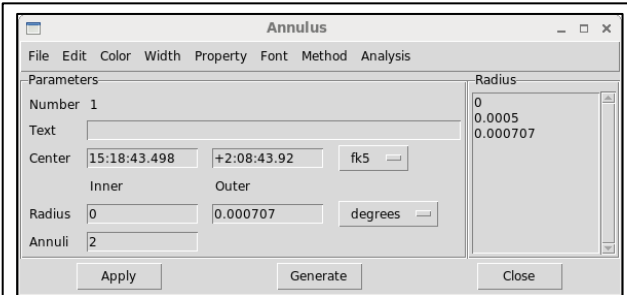


Figure 8: An example of the information window for a region displayed in DS9.

18. Repeat steps 12-17 to make measurements for at least 20 stars but preferably more in the 200×200 pixel analysis area. Attempt to select stars with a range of brightnesses. In the example in Figure 10, 50 stars have been selected.

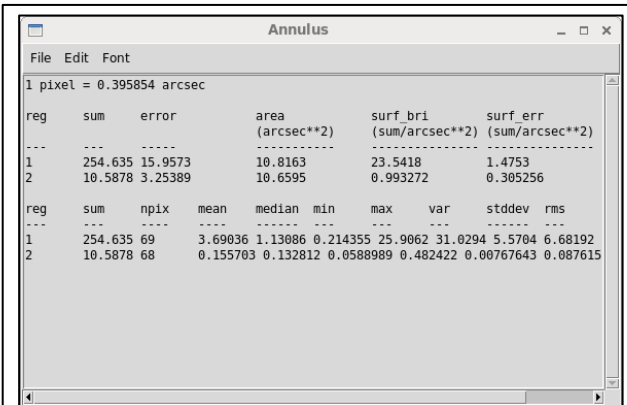


Figure 9: The statistical information for the region displayed in Figure 7.

19. Under "Region" in either the menu or button bar of the main DS9 window, click on "Save Regions". In the next dialog window that appears, give the region file a name and click "Save". In the second dialog window that appears, make sure that the format is set to "ds9" and the coordinate system is set to "fk5" and click "OK".
20. Repeat steps 2-7 to open and display the i-band FITS file.
21. Under "Region" in the main DS9 window, click on "Load Regions". Load the region file that was saved in step 19. (If a dialogue box appears, just click "OK".)

22. Double-click on each region one at a time, and then repeat step 17 to record the i-band target and background measurements for these regions. Ensure that the i-band measurements for each region are listed next to the corresponding coordinates and g-band measurements.

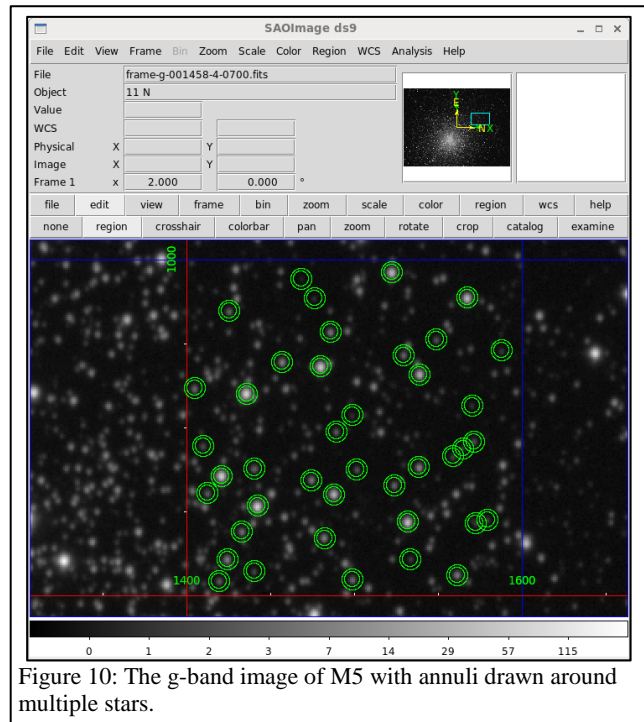


Figure 10: The g-band image of M5 with annuli drawn around multiple stars.

Numerical Analysis Procedure

1. For each g-band and i-band measurement, subtract the background measurement from the target measurement.
2. The measurements, which are in units of nanomaggys, need to be converted into magnitudes before they can be used for analysis. For the conversion, use

$$m = -2.5 \log(10^{-9}f)$$

where f is the flux in nanomaggys and m is the apparent magnitude. (This equation uses a base 10 logarithm.)

3. Next, the apparent magnitudes need to be converted into absolute magnitudes. Use the equation given above in the section on magnitudes. Distances to M5, M13, and M15 are listed in the Table in the Preparation Procedure section.
4. Create a plot where the i-band absolute magnitudes (M_i) of all of the stars are plotted on the y-axis and the g-band magnitudes minus the i-band magnitudes ($M_g - M_i$) are plotted on the x-axis. (Invert the y-axis so that smaller values, which correspond to brighter stars, are at the top.)
5. Select a set of model g-band and i-band magnitudes for a stellar population with a given age and a given [Fe/H] from the stellar population template file (either isochrones.txt or isochrones.xlsx). Two versions of the data are available: a plain text version, and an excel version. Both are based on data from the Dartmouth Stellar Evolution Database². Overplot the g-band absolute magnitudes and g-band minus i-band magnitudes on the plot from step 4. See if it matches the curve created by the data. Do this with multiple sets of g-band and i-band magnitudes until the template data that most closely matches the measurements is found.

Discussion Questions

1. Try searching for other reported age measurements for the cluster. (Try finding professional astronomy publications and avoiding Wikipedia or amateur astronomy websites if possible.) How do the age measurement from the numerical analysis in this experiment compare to other references' measurements?
2. Was it easier to determine the age of the cluster or the relative amount of heavy elements ($[Fe/H]$) in the cluster? Why?
3. Did any stars that do not follow the template curves? If so, try to identify why these stars do not appear to follow the curve. Some stars could be stars that have evolved from red giants into protoplanetary or planetary nebulae, which will appear bluer and brighter and will tend to follow a line across the top of the plot. Foreground stars could appear abnormally bright for their colours. Some stars could also saturate the detectors in one or more of the images, which could affect the measurements.

Acknowledgments

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

References

- ¹ McDonald I. et al., *Fundamental parameters and infrared excesses of Hipparcos stars*, 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 343
- ² Dotter A. et al., *The Dartmouth Stellar Evolution Database*, 2008, *Astrophysical Journal Supplement Series*, 178, 89
- ³ Harris W. E., *A Catalog of Parameters for Globular Clusters in the Milky Way*, 1996, *Astronomical Journal*, 112, 1487