Analysis of Globular Clusters Using Colour-Magnitude Diagrams

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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 Hertsprung-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.

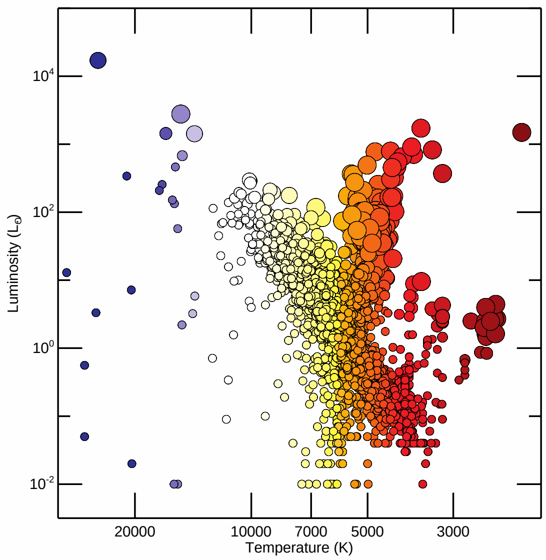

Figure 1: Plot of stellar luminosity versus stellar temperature for all stars within 250 light years of Earth based on a re-analysis of data from the Hipparcos satellite[1].

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.

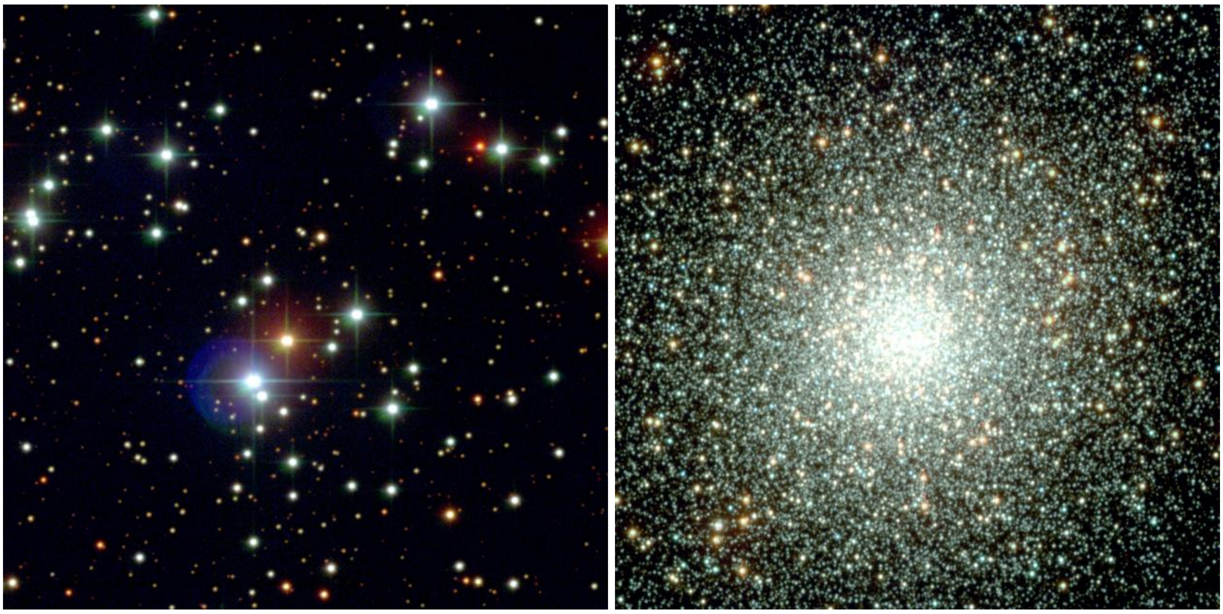

Figure 2: Visible light/near-infrared images of the open cluster NGC 2251 (left) and the globular cluster M5 (right). These images are based on data from the Sloan Digitized Sky Survey (SDSS) Collaboration (www.sdss.org).

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

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

where N_{Fe} and N_{H} are the number of iron and hydrogen atoms and where the ratio $(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*}$ for one or more stars is compared to the ratio $(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\mathrm{Sun}}$ 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

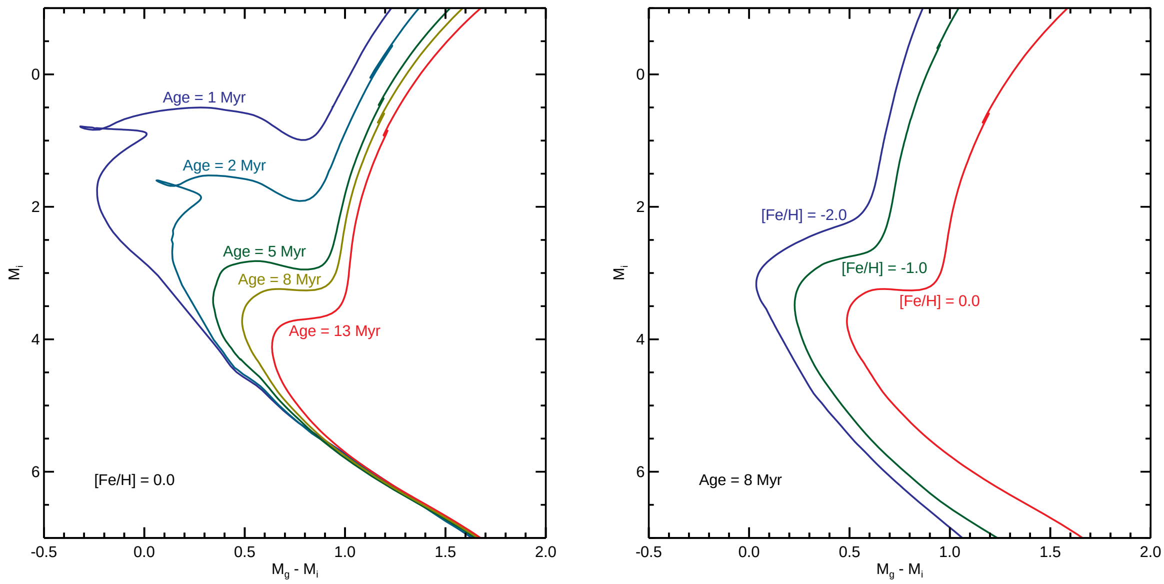

Figure 3: Lines showing colour versus magnitude for stellar populations with different ages (left) and heavy element content (right). The colours are based on the difference between blue (g-band; 4770 Å) and near-infrared (i-band; 7625 Å) magnitudes; bluer stars would appear on the left, and redder stars 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.

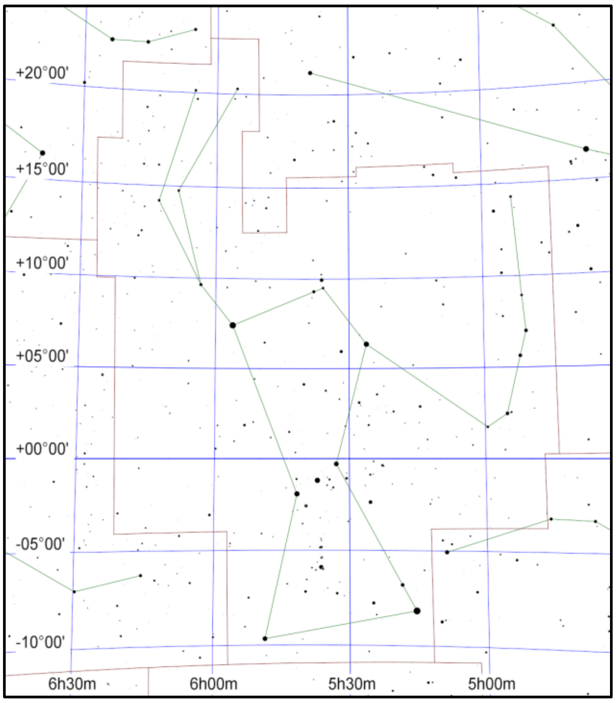

Figure 4: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

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 following globular clusters work well in this experiment:

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

   However, the experiment can also potentially be performed using other objects in the globular cluster catalogue at http://physwww.mcmaster.ca/~harris/mwgc.dat created by William E. Harris[3]. If the cluster was observed by the SDSS, an image of the cluster should appear. (The SDSS did not cover the entire sky, so images for some clusters may not be available.) Under this image, if it appears, 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 in your browser). These files are FITS files that are compressed in the bzip2 format. Save them with distinguishable names.

3. 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.
   c. On Linux computers, open a console and go to the directory where the files are located. For each file, type "bunzip2" followed by the name of the file to unzip it.

4. 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. Alternately, go to "Edit", select "pan", and then left 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 5, the zoom is set to 0.5.

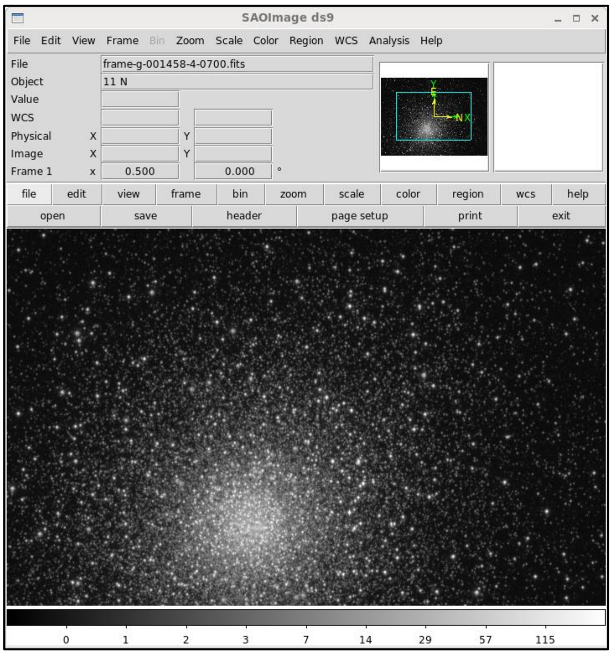

Figure 5: The g-band image of M5 as displayed in DS9 after setting the scale to log and adjusting the zoom.

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.

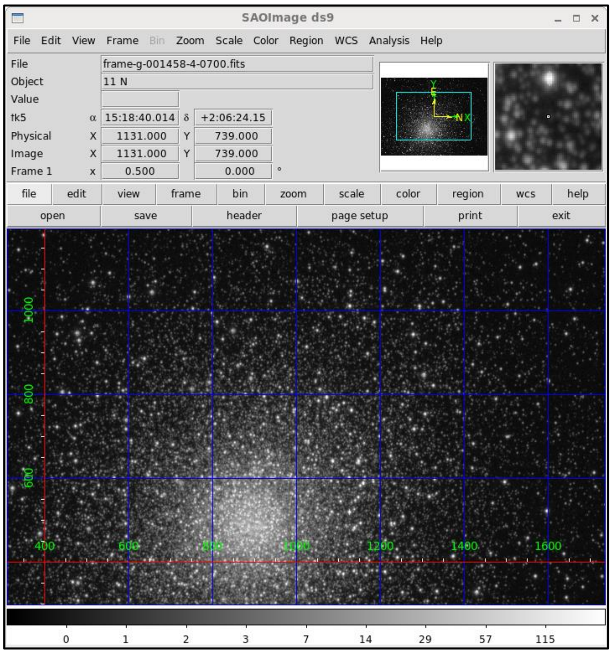

Figure 6: The g-band image of M5 displayed with a coordinate grid.

9. Identify a 200 × 200 pixel box within the coordinate grid to use for the analysis. For some very bright, very large, nearby clusters, it may be appropriate to close a location up to 1000 pixels (or 400 arcsec) from the centre of the cluster, as the centre of the cluster may be too crowded to perform photometry correctly. For relatively small or distant clusters, the central 200 × 200 pixel region in the centre may produce the best results.

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. 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. Set the coordinates of the centre of the annulus to "fk5". Make sure that "WCS" in the drop-down menu has a check mark next to it. In the other drop-down menu in the row labelled "Radius", make sure that "WCS" and "degrees" have check marks next to them. After doing this, record the coordinates of the circle. In the box on the right hand side labelled "Radius", enter 0, 0.0005 and 0.000707 (hitting return after typing each number so that each one appears in a separate row).

14. Under "Analysis" in the menu, select "Statistics". This will open a new window. Record the sum and the number of pixels for the inner circle (region 1) and the outer annulus (region 2) for this region. Also record the standard deviation in region 2. The first sum corresponds to the target emission, and the second sum corresponds to the background emission. The standard deviation in region 2 indicates the background noise.

15. Repeat steps 12-14 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. See Figure 9 for an example.

16. 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".

17. Repeat steps 2-7 to open and display the i-band FITS file.

18. 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".)

19. Double-click on each region one at a time, and then repeat step 14 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.

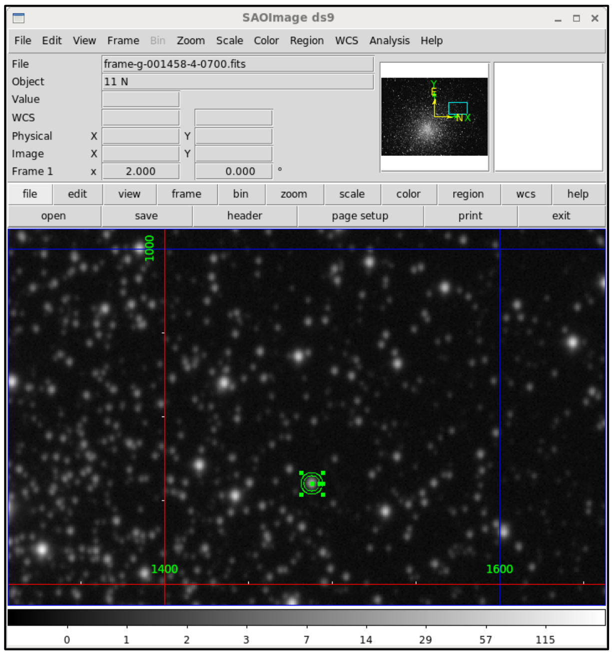

Figure 7: An off-centre location in the g-band image of M5 with annulus drawn around one of the stars.

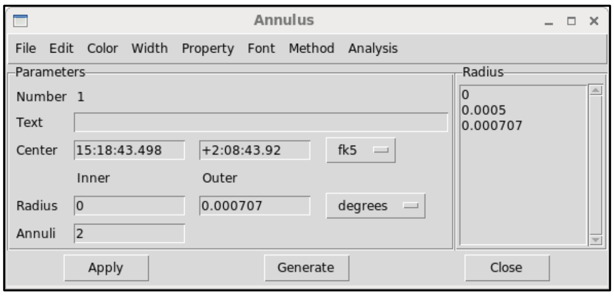

Figure 8: An example of the information window for a region displayed in DS9.

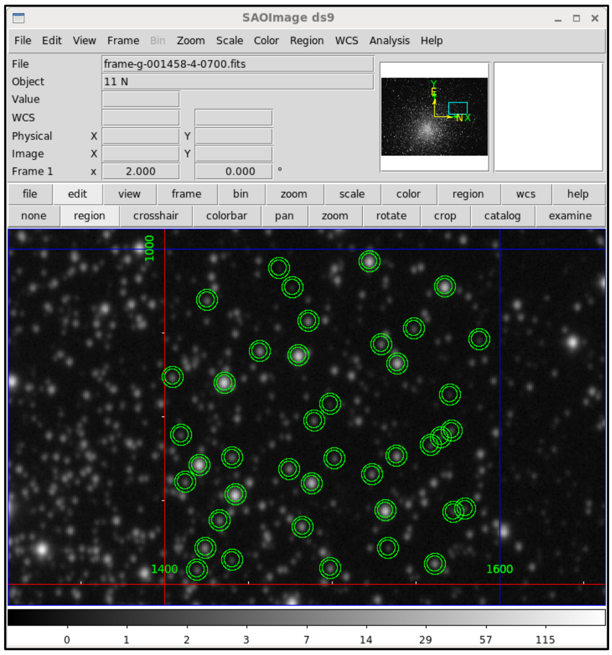

Figure 9: The g-band image of M5 with annuli drawn around multiple stars.

Numerical Analysis Procedure

1. For each g-band and i-band measurement, subtract the background measurement from the target measurement. Also, use the standard deviation in each background region and the number of pixels in each target region to calculate the uncertainty in the target measurements.

2. The SDSS g-band and i-band data have calibration uncertainties of 1%[4]. Incorporate these uncertainties into the overall measurement uncertainties.

3. 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.)

4. The apparent magnitudes need to be corrected for foreground dust attenuation (a combination of dust extinction and scattering). Go to the Galactic Dust Reddening and Extinction page in the NASA/IPAC Infrared Science Archive (https://irsa.ipac.caltech.edu/applications/DUST/), type in the name of the cluster, and click Submit. This will open a new webpage. Click on the Extinction by Bandpass link. The attenuation will be listed under a column with A^C at the top; use the S and F (2011)[5] values. Find the A values for the SDSS g- and i-bands and then subtract this value from each apparent magnitude.

5. Next, the apparent magnitudes need to be converted into absolute magnitudes. Use the equation given in the additional information section on magnitudes. Distances are listed at http://physwww.mcmaster.ca/~harris/mwgc.dat.

6. 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.)

7. Go to the online version of the Dartmouth Stellar Evolution Database[2] (http://stellar.dartmouth.edu/models/isolf_new.html). Use this tool to create a set of isochrones to compare to the colour-magnitude plots created in step 6. To begin with, input values for the age and [Fe/H], set the "Colors" to "SDSS ugriz", and click on "Generate Isochrones". This will go to a new page with a link to a text table. Save the text table. When saving, give the file an easy-to-understand name that ends in ".txt".

8. Overplot the g-band absolute magnitudes and g-band minus i-band magnitudes from the model on the plots from step 6. See if it matches the curve created by the data.

9. Repeat steps 7 and 8 with different values for the age and [Fe/H] to find the models that best describe the globular cluster.

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.

4. What are the largest sources of uncertainty in the data? Do the calibration uncertainty or background uncertainties dominate?

5. Are the uncertainties larger for the M_i values or the M_g - M_i values? Why?

6. What are the magnitudes and colours (M_g - M_i) of the faintest stars that can be detected in these regions? What are the limiting factors in detecting stars in the cluster? Is it easier to detect stars in the g-band or i-band image? Why?

Acknowledgments

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