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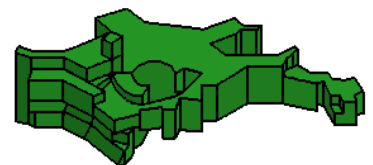
Max-Planck-Institut für extraterrestrische Physik

and the

Max-Planck-Institut für Astrophysik

Colour-Magnitude Diagrams of Star Clusters: Determining Their Relative Ages

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1 Course format

The tasks in this course include learning the astrophysical background, taking data, and analysing them. You will have two meetings with your tutor and a practical observing session.

- First meeting: You will meet with the tutor to ask questions after reading the manual. You will also test the analysis pipeline for the data.

- Second meeting: After handing in your report, you will again meet with the tutor, who will provide feedback and corrections, and ask questions about your final project. Finally, the tutor will grade your work.

- Observing: At some point after the first meeting, you will go to the telescope to get experience with practical astronomical observations.

2 Astrophysical background

2.1 Star clusters

There are two types of star cluster in the Galaxy. *Open clusters* are loose collections of typically a few hundred stars in the galactic disk. These clusters tend to be young with ages of several million to a billion years. Consequently, they typically contain (current generation) Population I stars. Typical cluster masses range between 100 - 1000 solar masses and their diameters are 1 - 10 pc. A well known example for an open cluster is the Pleiades cluster (see Fig. 1). In our Galaxy more than 1100 open clusters are known. The estimated total number of Galactic open clusters is $\sim 2 \cdot 10^4$.

Globular clusters, on the other hand, are tightly bound collections of a few hundred thousand to a few million stars, typically located in the Galactic halo. These clusters are generally old with ages of a few billion years. Their stars belong to the (older) Population II generation. The diameter of a typical globular cluster is about 40 pc. The stellar density increases strongly towards the centre of the cluster, with the average density being about a factor of ten higher than in open clusters. A prominent Galactic globular cluster, M 13, is shown in Fig. 1.

In this project you will construct colour-magnitude diagrams of two open cluster. Using these colour-magnitude diagrams you will investigate the differences in morphology in these clusters and explain them in terms of their relative ages.

Figure 1: The open Pleiades cluster (left) and the globular cluster M 13 (right).

2.2 Luminosities and magnitudes

For historical reasons, the "brightness" of a star is measured in magnitudes. The *magnitude system* originated from the first systematic studies of the night sky that were carried out only with the naked eye. The human

eye has a roughly logarithmic response curve (see Fechner's law), which means that the difference between a flux of 1 and 10 is perceived in the same way as the difference between a flux of 10 and 100. For stars, the scale was defined by assigning a magnitude of 6 to the faintest stars and a magnitude of 1 to the brightest stars. This means that, counterintuitively, the brighter the star the smaller the value of its magnitude. Later, the magnitude scale was slightly adjusted in a way such that a difference by 5 magnitudes equals a factor 100 in flux. Therefore, for two stars with fluxes F_1 and F_2, the difference in magnitudes is:

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right). \tag{1}$$

The zero-point of this scale was attached to the star Vega (constellation Lyra). However, these magnitudes are so-called *apparent magnitudes*, because they don't take into account the distance of the star, which of course has a large impact on the flux via the inverse square law. To be better able to compare the magnitudes of two stars they are hypothetically moved to a fixed distance of 10 parsec (pc). The apparent magnitude that the star would have if it were at this specific distance is called the *absolute magnitude*. One can readily see that the relationship between apparent and absolute magnitude of the same star at a distance D from the observer is the following:

$$m - M = 5 \log_{10}(D) - 5 \tag{2}$$

2.3 Colour-magnitude diagrams

A *colour-magnitude diagram* (CMD, see Fig. 2) plots the apparent magnitude of objects against their *colour index*; that is, the difference in magnitudes of a star in two different filters / wavelength bands (e.g. $M_B - M_V$ or $M_V - M_R$). It is the observational equivalent of a *Hertzsprung-Russell diagram* (HRD) [1]. On an HRD, absolute magnitude or luminosity is plotted increasing up the vertical axis against spectral type or temperature (reversed so as to increase to the left). This visualisation of the stellar parameters allows us to group stars effectively according to their evolutionary state (e.g. main sequence, giant branch), as is shown in the schematic HRD in Fig. 2.

Observationally, the apparent magnitude, proportional to the logarithm of flux, may be used as a proxy for luminosity in star clusters as all the stars in the cluster are at approximately the same distance and suffer the same amount of dimming due to interstellar extinction. Likewise, the *colour index*, e.g, $M_B - M_V$, reflects the stellar surface temperature because the magnitudes obtained through different filters sample different parts of the star's blackbody-like spectrum. A difference in magnitude corresponds to the ratio of fluxes.

In stellar clusters, where all the stars are at the same distance, this is proportional to the ratio of the two luminosities in different parts of the spectrum. Since stars with different temperatures have different spectra, they also have different colours.

Hertzsprung-Russell diagrams and colour-magnitude diagrams are vital tools for understanding the composition of stars and their evolution. HRDs produced from theoretical calculations can be tested against observational HRDs to judge the accuracy of a particular theory. CMDs of star clusters can also be used to estimate distances and to indicate the ages of different stellar populations.

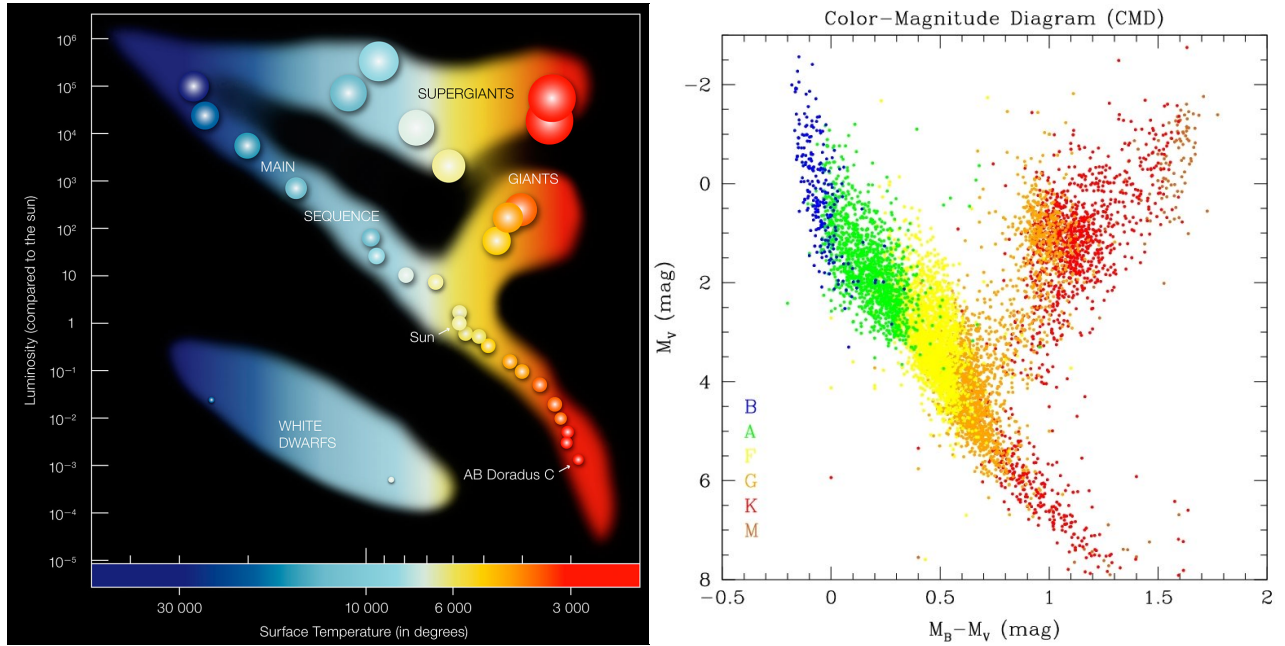[1] http://en.wikipedia.org/wiki/Hertzsprung{Russell_diagram

Figure 2: Schematic HRD (left) and observed colour-magnitude diagram (right).

3 Aims and objectives

This project aims to construct CMDs for two open clusters. These are the steps necessary for successfully finishing this project:

- Perform aperture photometry on the stars in two open clusters and obtain their relative magnitudes.

- Calibrate the magnitudes relative to a sample of reference stars in the same fields.

- Construct the colour-magnitude diagrams from the calibrated data.

- Analyse and interpret the colour-magnitude diagrams to estimate the relative ages and distances of the clusters.

- Gain practical observing experience at the telescope and learn how the data were taken.

4 What you need for this course – software requirements

You don't have to install any software to do the analysis. We recommend that you run the necessary jupyter notebook on Google Colab: `https://colab.research.google.com/drive/1IOEcw8dIWgxtVq_TCtbpdOrPYoOPwj_Q?usp=sharing`

You can also do the analysis on your own computer if you want to. To do that, you need to have **python** installed. Specifically, the programmes were tested with Python 3.7.15. You can download the version you need from the webpage (`https://www.python.org/`), or install it using miniconda (`https://conda.io/miniconda.html`). After installing python, you need the following packages: astropy, ccdproc, pandas, photutils, ipywidgets, matplotlib and jupyterlab. For a complete list of required packages with exact versions see the .yml file at `https://github.com/Csogeza/FoPra85`. You can install everything using conda:

conda install -c astropy ccdproc photutils ipywidgets matplotlib jupyterlab

or by downloading and using the above .yml file through:

```
conda env create –name envname –file=environment.yml
```

Once you have installed the packages with the above line, you can activate the environment using 'conda activate envname'. To open the jupyter notebook, you have to put in the terminal:

```
jupyter notebook FoPra85_Photometry_notebook.ipynb
```

If you are having problems installing the programs, we can help you in the first meeting.

5   The targets

Table 1 summarises basic properties of the two open clusters that you are going to work on. Cluster names are given with both 'M' and 'NGC' prefixes, denoting the names of the objects in the Messier catalogue and New General Catalogue of nebulae, respectively. The approximate right ascension (RA) and declination (Dec) of the clusters are given in the second and third columns. The fourth column lists the constellation in which the cluster may be found, while the fifth column states the approximate diameters of the cluster in arcminutes. Columns six, seven and eight indicate the previously measured interstellar extinction of the cluster in the B, V, and R filter, respectively.

Table 1: Names, parameters, and approximate coordinates of the target open clusters. The values have been taken from Karchenko et al. (2005).

Name	RA (J2000)	Dec (J2000)	Const.	Diameter [arcmin]	A_B [mag]	A_V [mag]	A_R [mag]
NGC 1960 (M 36)	05:36:18	+34:08:27	Aur	11	0.90	0.68	0.56
NGC 2099 (M 37)	05:52:18	+32:33:11	Aur	16	1.23	0.93	0.77

6   The telescope

The instrument used for this experiment is an advanced robotic telescope of scientific quality and capability. It is positioned on the roof of the Max-Planck-Institut für Astrophysik [2] to be easily accessible for students.

The telescope is installed within a 4.5 m dome[3] protecting the telescope from the environment. It automatically closes in case of an emergency (power failure, rain, etc.). The dome as well as all the other components of the telescope can be operated from within the dome or from any place with internet access. The telescope itself is a commercially available, reflecting telescope with a 24 inch (610 mm) primary mirror. Fig. 3 shows the schematic light path.

The light from a star enters the telescope and gets focused by the main mirror onto the second mirror. The secondary mirror redirects the light towards a pair of correcting lenses. A focuser is attached to the telescope after the lenses in the light path. It positions the detector, a CCD-camera in this experiment, to the focal plane. As the ambient temperature will vary during the night of observation, the thermal elongation of the telescope and its optical components will change the position of the focal plane; refocusing will be necessary. It is good practise to add a refocussing step before observing a new target.

The CCD-camera is the heart of our experiment. We use a CCD chip with 4096×4096 pixels and a pixel size of 9 µm^2. The field-of-view of the CCD-camera is given by

$$\text{field-of-view} = \frac{\text{linear size of the detector}}{\text{focal length of the detector}} = \frac{4096 \cdot 9 \ 10^{-3} \ \text{mm}}{3962 \ \text{mm}} = 9.30 \ 10^{-3} \ \text{rad} \approx 32 \ \text{arcmin}. \quad (3)$$

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[2]Karl-Schwarzschild-Str. 1,85748 Garching
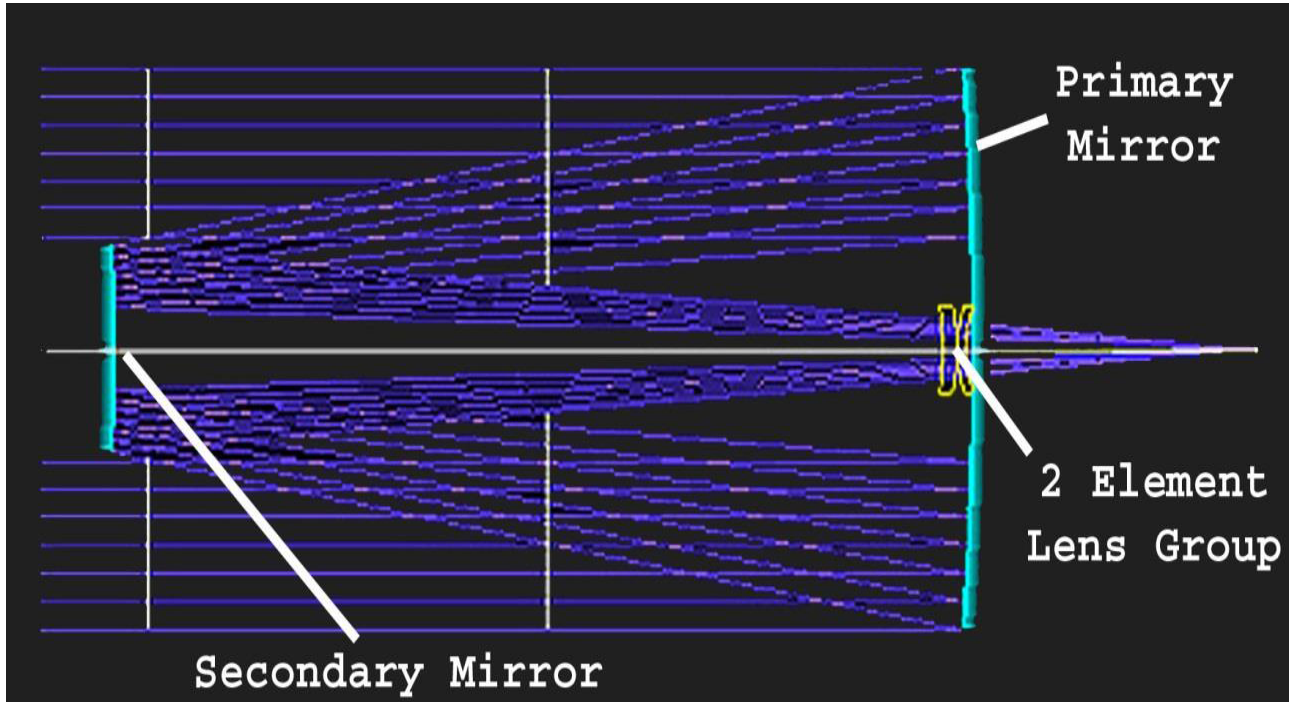[3]Baader AllSky Dome

Figure 3: Schematic of the optical layout of the CDK 24 inch telescope. *Source: Telescope Manual*

This corresponds roughly to the size of the moon on the night sky. If we calculate the resolution we find 0.5 arcsec per pixel. This translates to roughly a kilometer on the lunar surface per pixel.

A pixel on the CCD chip is a 16 bit ADC (analogue to digital converter), which stores a value between zero and 2^{16}, depending on the amount of light falling on it during the exposure time (taking an image). If a pixel receives to much light during an exposure, it will saturate. Saturation is when a pixel's counting value exceeds 2^{15}, in which case the image cannot be used, if the saturated pixels are within the object of interest. Be mindful of this when taking your images: do not allow pixels of your object of interest to saturate.

In order to determine the colours of the stars, the CCD-camera is connected to a filter wheel which can place different filters in the light path. Three broad-band filters (RGB) and also one narrow-band H-alpha filter are installed. Only two of the broad-band filters will be needed to construct the CMDs of the star clusters.

The CCD chip is also connected to an active cooler. The cooler will reduce the temperature of the CCD to about -30 °C in order to reduce the thermal noise. A good signal-to-noise ratio is necessary to be able to observe stars with low magnitudes. One of the main tasks of the data analysis will be to correct the images for CCD-related errors (compare section 7).

Finally, we need to locate objects on the night sky and point the telescope towards their positions. This is an easy task as the mounting[4] is very precise and automated. It has a database of known objects including catalogues like Messier or NGC. Another advantage is that the mount always knows its absolute position and can point to the stored objects. Neither calibration nor a guiding system are necessary to find objects on the night sky.

The mount is a German Equatorial mount. One rotation axis of the mount is aligned with the rotational axis of the earth, while the other is perpendicular to it. This mounting is called equatorial mounting. The advantage is that following an object on the night sky only requires the movement of one of the axes with constant speed. In case of an observation with a CCD-camera and long exposure times good tracking is critical.

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[4]10 Micron GM 4000 HPS GoTo

7 Data reduction

Below, we are going to explain how the CCD images taken at the telescope are calibrated. You will **NOT** have to do these steps in the course, but instead work on already reduced data.

7.1 Why the data need calibration

Images of an astronomical object taken with a CCD camera will include many unwanted signals of various origin. The goal of the calibration is to remove these effects, so that the pixel values of the calibrated images are an accurate representation of the sky light that fell on the camera during your observations.

The following CCD-related effects need to be corrected for:

- When the CCD images are read, a small voltage is applied to all pixels. This electrical offset is called **bias**. It has to be subtracted, so that the zero points of the CCD output and the pixel-value scales coincide.

- The thermal agitation of silicon in the CCD can promote valence band electrons to become conduction band electrons, even when no light falls on the CCD (hence the name **'dark' current**). Dark current is always present, i.e. also in your sky images. It scales linearly with exposure time, at a rate dependent on the CCD temperature, and needs to be subtracted

- The conversion of light to an electrical signal varies with position on the CCD chip, both on small scales (pixel-to-pixel), due to changing quantum efficiency of individual pixels, and on larger scales, because of vignetting and dust shadowing. To correct these effects, we need to divide the data by the normalised sensitivity of each pixel. This is estimated by observing a (theoretically) uniform source of light. The variations observed in this exposure, called a **flat-field**, are a measure of the non-uniformities of the camera. Note that the flat-field(s) need to be first corrected for the two effects described above.

- **Cosmic rays** (CR) produce a stream of high-energy particles that interact with the camera's CCD chip, leaving bright spots or tracks in the images. By combining multiple images using the average, or better, the median of the pixel values at each pixel, the extreme values produced by CR hits are easily spotted and removed. The image combinations are often done with a rejection algorithm to remove extreme variations. If an obvious CR track remains in a combined image, it is better to find out from which individual image it originates, and remove this image prior to combining the images.

7.2 How CCD data reduction works

To calibrate one's science data, one needs a set of calibration frames. They should be taken close in time to the science observation. Flat fields are taken during dusk, while bias and dark frames are usually taken during daytime.

- Bias frames.

  These are zero-second exposures (the shutter remains closed). In principle the bias is constant, but statistical fluctuations introduce noise. It is best to combine several (e.g. 10) bias frames. The root-mean-square noise will decrease as the square root of the number of bias frames.

- Dark frames.

  These are long exposures taken with the shutter closed. One can either match the exposure time of the dark frames to that of the science observations, or use a scalable dark frame, from which the bias has been subtracted.

- Flat fields.

  These are images of a uniform source of light. Usually the twilight sky is the best choice. The exposure times are set such that the pixel values are a good fraction ($\sim$50%) of the dynamic range of the ADC. These good statistics allow to reveal the desired level of detail. Note that because vignetting and CCD sensitivity are wavelength-dependent, flat-fields must be taken with the same filter as used for the science image to calibrate. As before, several exposures are taken to be eventually combined.

8 Photometry

Below, we are going to explain how we obtain the magnitudes for our CMDs. In this FoPra you will **HAVE** to carry out these steps on already reduced images of two open clusters that you can download from the FoPra webpage (`https://sites.google.com/view/tum-fopra85/home`).

8.1 Techniques

Photometry is the technique of measuring the brightness of astronomical objects. To do so, we quantify the signal from a given source collected on our camera during the exposure. In other words, we only measure the instrumental flux of a source. Various methods are available to perform photometry:

- The simplest is **aperture photometry**. The signal is integrated over a circular aperture defined around the star of interest. To compensate for a non-zero background brightness (e.g. due to natural night-sky emission or artificial light pollution), the sky brightness is estimated in a concentric annulus around the aperture and subtracted from the object signal. A number of problems limit the use of aperture photometry for some purposes:

    - Choice of aperture: An aperture too small will ignore the fraction of the flux of a star that is in the wings of the point spread function. An aperture too large will include noise from the sky background, or, in case of crowded fields, flux from nearby stars.
    - Crowding: It becomes increasingly difficult to define source and background regions in crowded fields, where stars are close to one another. In some cases (poor seeing, globular clusters, ...), aperture photometry might even be impossible, because stars are blended and cannot be separated anymore.

- The way to go beyond the limits of aperture photometry is to perform the so-called **PSF-fitting photometry**. Here, a model of the point-spread function (PSF) is determined for an image using some representative isolated stars. This model is then fitted to all the stars detected in the image. It is then possible to know the contribution from an object and from the sky in a given region. Even if several stars are present in that region, their signal can be separated by fitting the PSF to each of them. This method is more demanding than simple aperture photometry. In particular, it requires a careful job while preparing the PSF model.

For the star cluster experiment it is feasible to use simple aperture photometry. In the densest regions of our open clusters, crowding can still be an issue, but for the majority of the stars the simple aperture photometry is accurate enough for a qualitative analysis. In the case of a globular cluster, on the contrary, one would have to use PSF photometry. To carry out the aperture photometry, a python notebook written by the tutors will be used that can be run on Google Colab.

8.2 In practice

Below we describe the analysis sequence that can be carried out using the provided notebook. The goal is to use the pre-reduced images to perform aperture photometry and obtain the magnitudes of all the stars in the images.

1. Make an initial star list with a source detection algorithm. This typically searches for local brightness enhancements having a peak amplitude greater than a given threshold above the local background.

2. Find the right aperture for each of the stars. This is done by carrying out the aperture photometry iteratively with increasing aperture radius and taking a look at the sum of the counts enclosed within the aperture at each step. Once this levels off, a good estimate for the optimal aperture size has been found.

3. During the aperture size calculation, one has to make sure that the target star will not be blended with close field stars.

4. After determining the optimal aperture size, perform photometry for every star in the image using this aperture.

5. Limit the analysis area to the cluster on the image, i.e. remove objects that are farther away from the centre of the cluster than a reasonable limit. This will avoid the inclusion of too many unrelated field stars (which are at a different distance than the cluster) and hence reduce the scatter on the resulting CMD.

8.3 Photometric calibration

To calibrate the (relative) magnitudes you obtain you will use a sample of reference stars of known magnitude in each image. By comparing their observed magnitudes to the catalogue magnitudes you will estimate an average magnitude offset. This offset needs to be applied to all stars detected in the image to obtain the calibrated magnitudes. In every finding chart (Appendix A) you are required to identify 2–3 stars with a visual magnitude $V \simeq 8 - 12$ that are clearly visible close to each cluster. There are some important criteria to consider when selecting your reference stars:

1. They should not be too bright as bright stars will saturate the CCD when you use the correct exposure time for the cluster.

2. They should not be too faint or they will be too weak to give a good signal-to-noise ratio.

3. They should not be too close to other bright stars, or the nearby stars will contaminate the surroundings making the brightness difficult to measure accurately.

4. They should not be too close to the crowded inner parts of the cluster or to similarly crowded regions.

5. You should check that none of your reference stars are known to be variable stars.

Individual stars can be found in the SIMBAD database through Aladin (`https://aladin.u-strasbg.fr/AladinLite/`). Identify your selected reference stars by matching characteristic patterns of stars. If your reference star is included in SIMBAD you will find information on its variability. If a star is not included in the catalogue the most likely reasons are that it is (a) too bright or (b) too close to the centre of the cluster.

8.4 Further information

More on aperture photometry, and the scripts used in the notebook can be found here:
`https://photutils.readthedocs.io/en/stable/aperture.html`

9 Colour-Magnitude Diagrams

9.1 Construction

A colour-magnitude diagram is usually plotted with apparent magnitude increasing downwards and colour index (e.g. $B - V$) increasing to the right. Apparent magnitude, V, increases downwards, so the stars' apparent brightness increases upwards. The value of the $B - V$ colour index increases towards the right, so stars on the left have a numerically smaller value of $B - V$ than stars on the right.

With the apparent magnitudes you measured in the previous section, you should create a scatter plot of apparent magnitude in the V band (vertical axis) versus the $B-V$ colour (remember that is the difference of the apparent magnitudes in these two bands). Remember to reverse the vertical axis to conform to the traditional CMD, because a larger magnitude corresponds to a lower brightness. You should plot a separate CMD for each cluster, as your assumptions regarding all stars being roughly equally far away will only be valid within a single cluster.

9.2   Interpretation

Each CMD you create reflects a single population of stars, thought to have formed at around the same time. Each cluster should have a relatively narrow band of stars, which either rises or falls across the diagram, corresponding to the main sequence and the giant branch. Remember that a *smaller* $B - V$ colour index indicates a *hotter* star, i.e. the temperature of the star decreases towards the right of the CMD.

Describe the shape of each cluster's CMD in terms of the trend of brightness with temperature. Stars evolve from the main sequence onto the giant branch, which therefore represents a later stage of stellar evolution. The most massive stars are also the hottest. They burn their hydrogen fuel faster than less massive stars and evolve onto the giant branch more quickly. In a given star cluster CMD, you might be able to see both the main sequence and the giant branch. If they are visible, mark them in each CMD. Describe the scatter of these correlations. Are there any obvious outliers? What could be their cause?

The uppermost part of the main sequence is called the *main sequence turn-off*. Stars that were initially hotter than this have already evolved onto the giant branch. The position of the main sequence turn-off contains information on the age of the stellar population (i.e. the age of the cluster).

9.3   Relative distances and ages of clusters

To determine the relative distances and ages of clusters from your CMDs, you need to correct them for interstellar extinction. Interstellar extinction is caused by dust in the line of sight. It leads to a reddening of the star's light. Therefore, the measured $B - V$ colour needs to be corrected for this effect. This will shift the data points in your CMD horizontally.

Extinction also affects the brightness of the stars, leading to dimmer magnitudes than otherwise expected for the given stellar luminosity and distance. This effect can be included in Eqn. 2.2 in the following way:

$$m_X - M_X = 5 \log_{10}(D) - 5 + A_X \tag{4}$$

Here, A_X is the extinction coefficient for the band X (where X can be B, V, or R), which can be found in Table 1. Correcting for extinction will therefore also shift your data points vertically.

In this experiment we are not interested in the absolute distances of each cluster. However, after correcting your measured magnitudes and colours for extinction you will be able to determine the relative distances of your two clusters (i.e. rank them by distance). Any remaining vertical difference between the respective main sequences and/or giant branches is due to a different distance (see Eqn. 4). Rank the two clusters by increasing distance.

By shifting the two CMDs vertically with respect to each other you can qualitatively adjust the measured magnitudes for the different distances by making the main sequences and/or giant branches overlap. The major difference between the two CMDs will now be the location of the main sequence turn-off, which is a measure of cluster age. Remember that hotter stars evolve faster away from the main sequence than cooler stars. Rank the two clusters by increasing age.

A   Finding Charts for Star Clusters

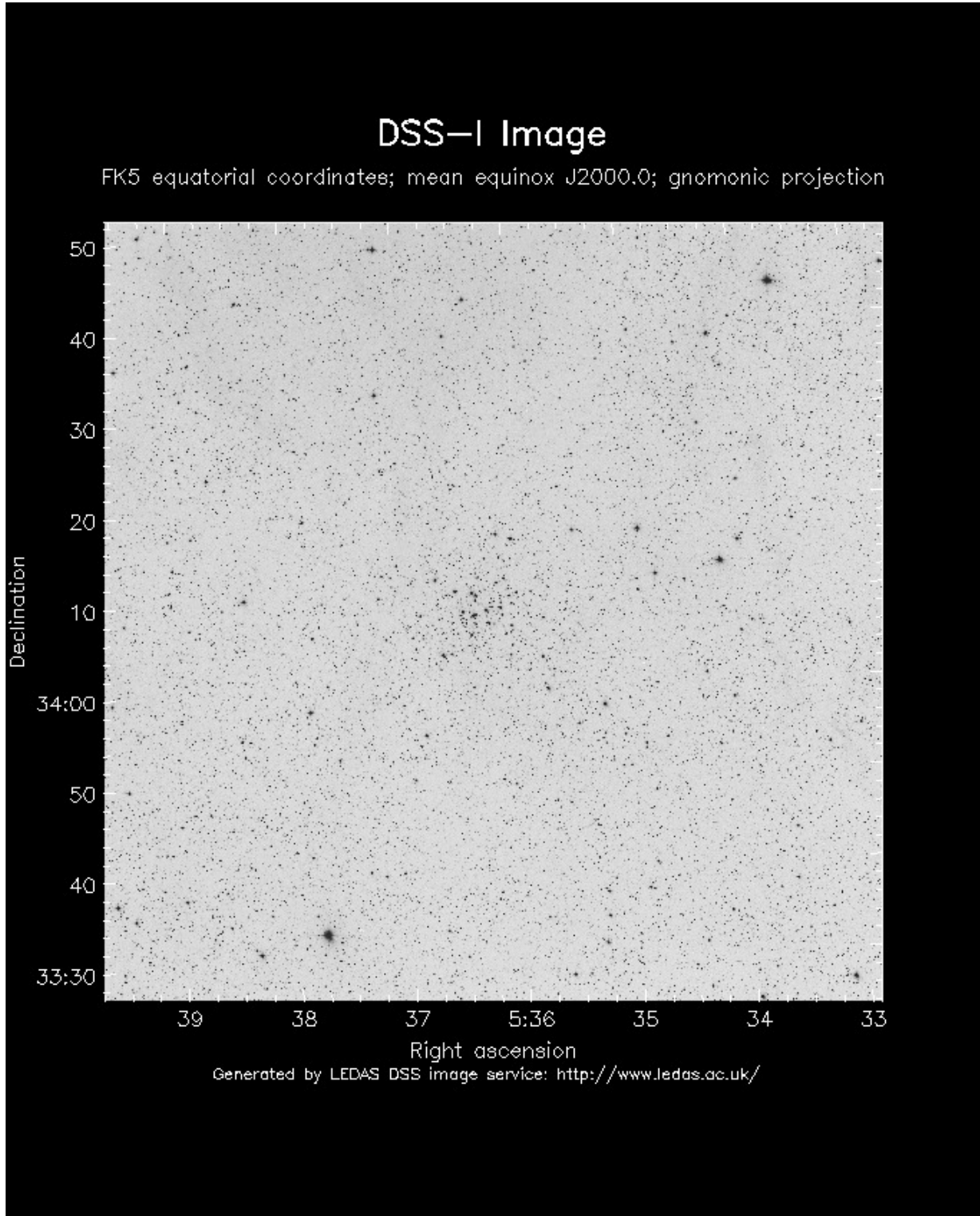These finding charts were created using the DSS web interface at `http://ledas-www.star.le.ac.uk/DSSimage`.

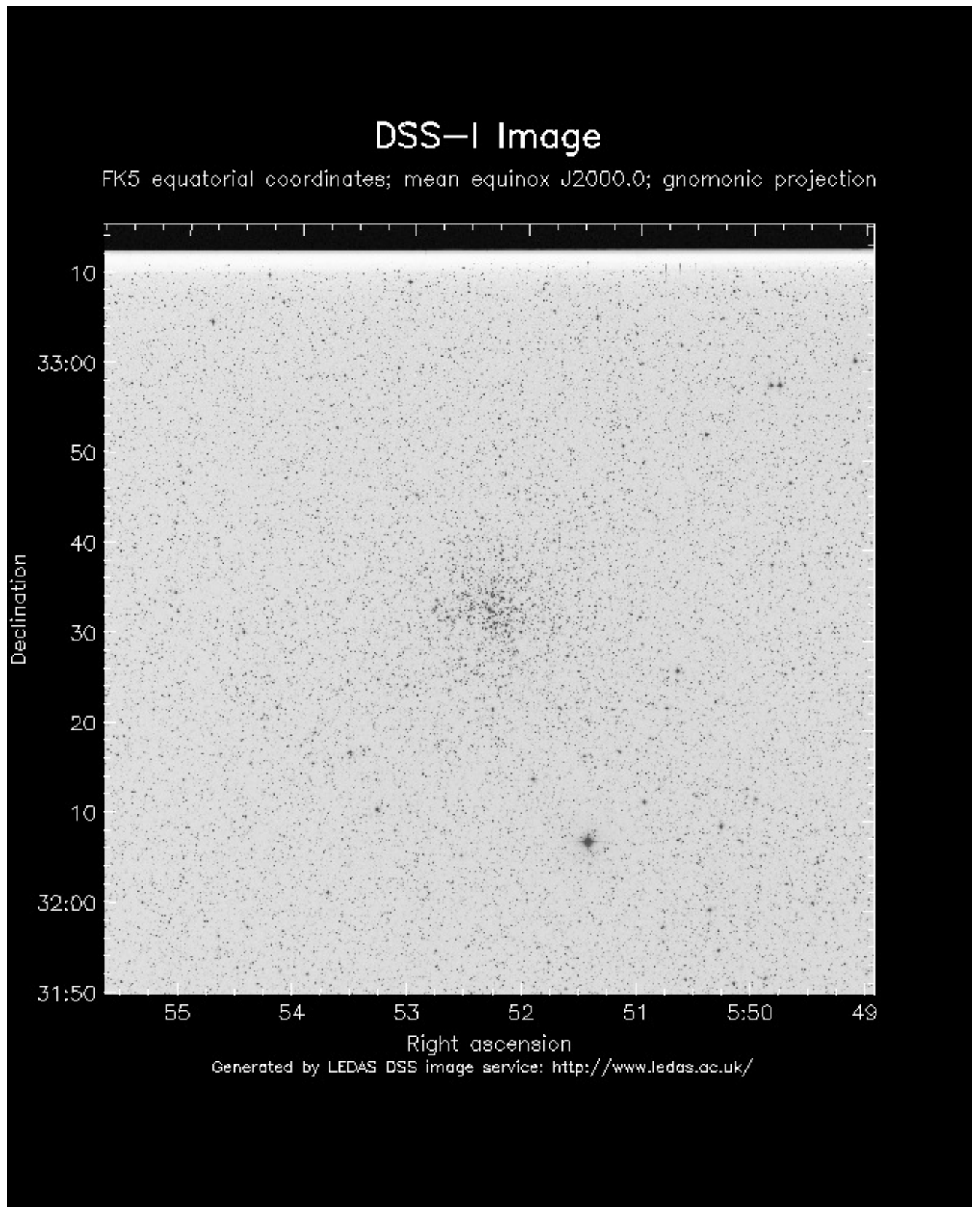Figure 4: The open cluster M 36. The field of view is 85′x 85′.

Figure 5: The open cluster M 37. The field of view is 85$'$x 85$'$.