Project for Observational Astronomy 2018/2019: Colour-magnitude diagram of an open cluster

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1 Colour-magnitude diagram for an open cluster

1.1 Background

The *colour-magnitude diagram* is a very commonly used diagram in astronomy. As the name suggests, it has the colour of an astronomical object (typically a star) along the x-axis and the magnitude along the y-axis.

In this project you will produce a colour-magnitude diagram (hereafter CMD) for an open star cluster. Open star clusters are groups of stars that were born at the same time from a single gas cloud. All stars in a cluster share the same age, composition, and distance, but they have different masses.

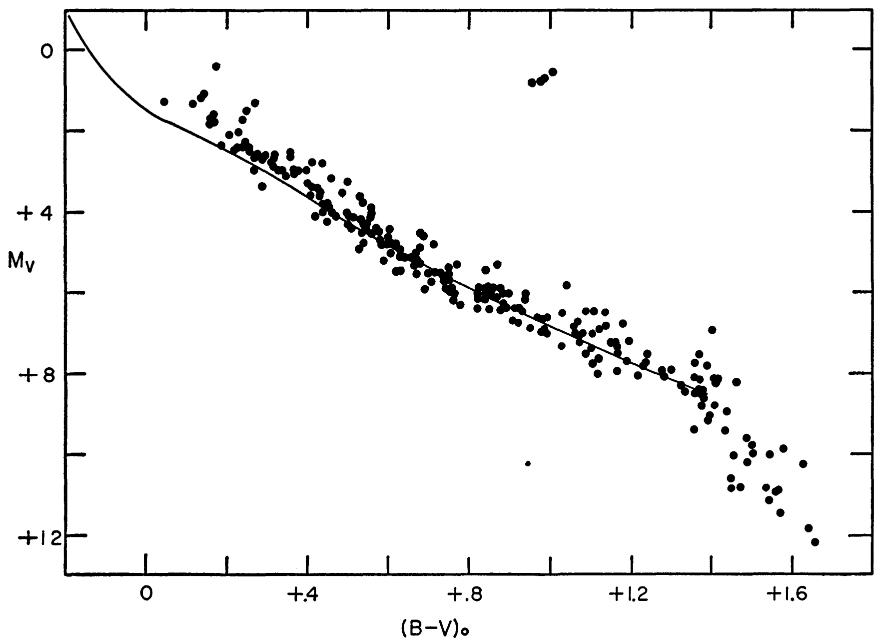

Figure 1: Colour-magnitude diagram for the Hyades.

The figure above shows the CMD for a typical open cluster, the Hyades (Johnson et al. 1962). The diagonal sequence of stars is the *main sequence*; these are stars that produce energy by converting hydrogen to helium in their cores by nuclear fusion (like the Sun). The fainter the stars on the main sequence, the lower their masses – the Sun has an absolute magnitude of $M_V \approx 4.8$ and a colour $B - V \approx 0.66$, so you can see that some of the main sequence stars in the Hyades must be more massive than the Sun. For stars on the main sequence, the luminosity L scales (roughly) with mass $\mathcal{M}$ as $L \propto \mathcal{M}^4$. Assuming that some fixed fraction of the total stellar mass, ηM, is available as nuclear fuel, we see that the lifetime on the main sequence scales as $T_{\rm MS} \propto \mathcal{M}^{-3}$ - massive stars have much shorter lifetimes than low-mass stars. The Sun will run out of fuel after about 10^{10} years; a star that is 10× more massive than the Sun will only live for about 10 million years! The point where the main sequence ends (the main sequence *turn-off*, MSTO) is thus a good indicator of the age of a star cluster.

In the Hyades, the main sequence turn-off is at $M_V \approx +2$. Stars above this point have used up all the hydrogen in their cores and therefore evolve off the main sequence to become *red giants*. Such stars produce energy by converting He to heavier elements (or, in some cases, by burning H in a *shell* outside the core). This phase of a star's life is much shorter than the main sequence lifetime, and the number of giant stars in a star cluster is therefore always much smaller than the number of main sequence stars. You can see a few red giants in the CMD of the Hyades too, at $M_V \approx 0$ and $B - V \approx 1.0$.

Note that the CMD of the Hyades has the *absolute V* magnitude, M_V, on the y-axis. The absolute magnitude is a measure of a star's *luminosity*, and thus independent of distance. What we can measure directly (after calibrating our photometry) is, instead, the *apparent* magnitude, which is a measure of the *flux* we receive from the star. Recall that the difference between absolute and apparent magnitude is the *distance modulus*,

$$(m - M)_0 = 5 \log_{10} D - 5$$

where the distance D is in parsec. A parsec is the distance from which the Earth's orbit around the Sun has an apparent radius of one arc second, corresponding to about 3.1×10^{16} meters. Hence, from the apparent magnitude of the main sequence (at a given colour) for an observed cluster, the distance can be found by comparison with the corresponding absolute magnitude (read off from a diagram such as the one above) via the above formula. Note that this assumes there is no absorption of light between us and the cluster!

1.2 Theoretical isochrones

One way to determine physical parameters for stellar clusters is to compare observations of their colour-magnitude diagrams with theoretical models for stellar evolution. Figure 2 below shows examples of such models, in the form of *isochrones* for ages between 10 Myr (10^7 years) and 10 Gyr (10^{10} years). Each isochrone shows the relation between colour and absolute magnitude for stars of a given age, but with different masses. You can obtain such isochrones yourself from the MIST website at `http://waps.cfa.harvard.edu/MIST/index.html`. The models shown in Figure 2 assume that the chemical composition of the stars is similar to that of the Sun, which is typically a reasonable assumption for open clusters in the Milky Way.

In the figure, the main sequence parts of the isochrones are drawn with solid lines, and the post main sequence phases are drawn with dashed lines. It can be clearly seen that the M_V magnitude of the MSTO becomes brighter at younger ages. In principle, the age and distance of a star cluster can thus be determined by comparing the observed CMD with isochrones like those in Figure 2.

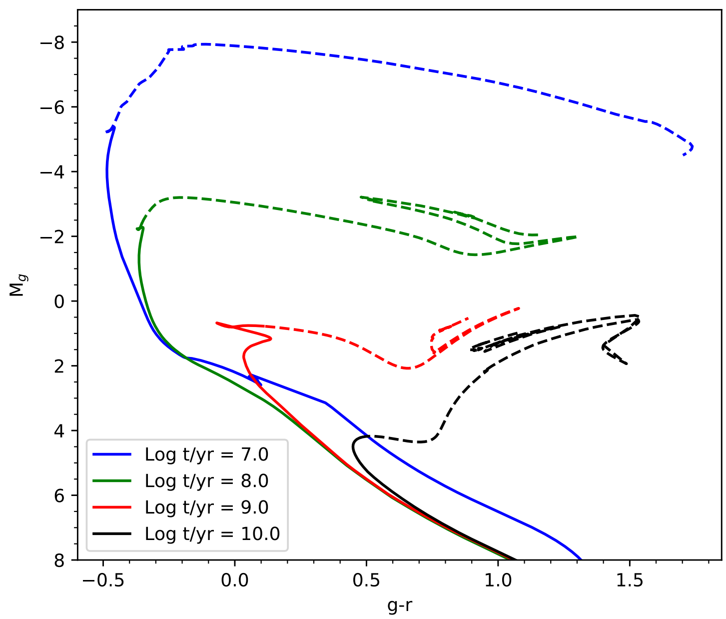

Figure 2: Theoretical isochrones from MIST (MESA Isochrones and Stellar Tracks) for ages of 10 Myr, 100 Myr, 1 Gyr, and 10 Gyr. Solid and dashed lines indicate the main sequence and post-main sequence phases, respectively

In Figure 3 we plot the M_g magnitude of the MSTO as a function of the (logarithm of) the age. The relation can be fairly well by a linear fit,

$$M_g(\mathrm{MSTO}) \simeq 3.18 \times \log(\mathrm{age/yr}) - 27.75$$

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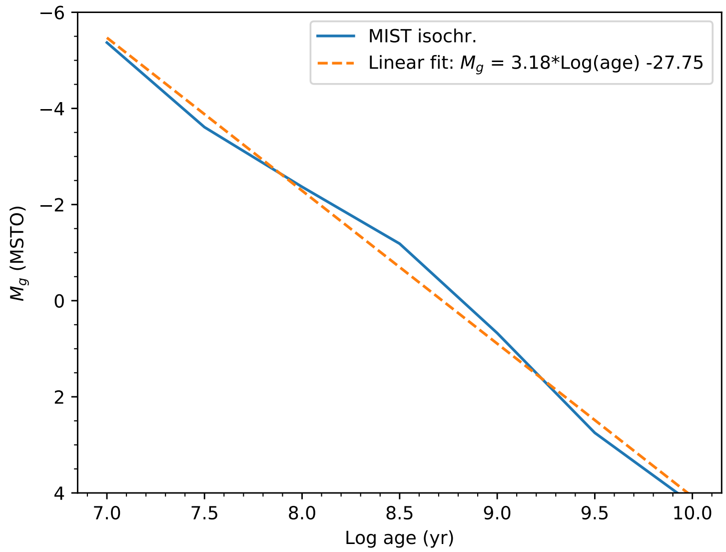

Figure 3: The relation between the M_g magnitude at the main sequence turn-off and the age. The blue curve shows the relation according to the MIST isochrones and the orange dashed line is a linear fit.

1.3 The project

1.3.1 Preparation

Before actually carrying out the observations, some planning is required. This is best done well ahead of time – do not postpone this until the last moment! You can use the on-line tools you have learned about in the course, most of which are linked from *Brightspace*.

- You will first need to identify a suitable open cluster. You can easily find lists of open clusters on-line. Keep in mind that the cluster should be observable at a reasonable airmass ($x < 2$, so zenith distance $z < 60°$) during the time you are planning to carry out the observations. Also, make sure that a good fraction of it fits on a single CCD image.

- To calibrate your photometry, we recommend that you choose a cluster for which magnitude measurements are already available for some stars. You can check this in SIMBAD. Note that not all clusters have SDSS magnitudes tabulated in SIMBAD. If your cluster only has B and V magnitudes, you will need to transform these to SDSS magnitudes, as discussed in Lecture 3 on photometry (see the lecture viewgraphs).

- When looking for a suitable cluster, it may be useful to check if someone has already published a CMD. With the 35 cm telescope, the magnitude limit that you can reach in a few minutes of exposure time is typically $g' \approx 13$–14. To get a nice CMD, this means that the brightest stars in the cluster should be a few magnitudes brighter than this.

- We recommend that you make a *finding chart*, showing a larger area of the sky around the cluster, to help you locate your target. This can be done, for example, with SAOimage DS9.

1.3.2 Observations

The weather can be unpredictable, so please make use of all available clear nights and do not postpone the observations to the last moment. Sometimes things go wrong, and you may need to repeat the observations. Occasionally the telescopes may be occupied by other users. You can use both the 20 cm and 35 cm telescopes! Remember to make a reservation.

- In order to produce a CMD, you will need observations in at least two filters (for example, g' and r'). The exposure time of individual exposures should be kept relatively short (a minute or so). However, to be able to measure the fainter stars in the cluster, you will need to obtain many short exposures in each filter and add them together later. You may need to experiment a bit to find the optimal exposure time – in particular, you want to avoid that the brightest member stars saturate the CCD.

- If you have doubts about whether the telescope is pointed in the right direction, you can use the website `http://nova.astrometry.net` to upload the images and get an astrometric solution. This only takes a few minutes, so may be worth it in case you do not recognise the field.

- Remember to obtain all the necessary calibration data (dark exposures, flatfields, etc)

1.3.3 Data analysis

- Once you have reduced the data, use the aperture photometry tool (APT) to measure the magnitudes of as many stars as possible in both filters. It is a good idea to align the images in all bands to a common reference so that the same APT source list can be used for all images. This will make it much easier to match the different measurements for each star afterwards (the output from APT can then simply be saved to Excel CSV files and read into Excel in adjacent columns).

- Measure the magnitudes of the standard stars and use these to calibrate your photometry of the star cluster. Make sure you understand the difference between *instrumental* magnitudes (output by APT), *apparent* magnitudes (calibrated to the SDSS standard system), and *absolute* magnitudes (normalised to a reference distance of 10 pc).

- Make a plot of magnitude vs. colour (e.g. g' magnitude vs. $g' - r'$ colour). What can you say about the age and distance of the cluster?

1.4 The report

Describe how you selected the cluster, what is known about it already, how you planned and carried out the observations, and how you reduced the data. Then comment on what you see in the colour magnitude diagram.

There is no hard limit on the length of the report, but keep in mind that it should satisfy two primary requirements:

- Like a scientific paper, the report should allow other people to *reproduce your results*. That means you need to provide sufficient information that someone else could, in principle, carry out the same observations and do the same analysis that you did.

- The second purpose of the report is for you to demonstrate that you understand what you did. Do not just mention which computer programs or IRAF tasks you used to manipulate the data - please also explain what these programs and tasks do.

Apart from these general requirements, your report should include:

- Discussion of what you can learn from your observations. Based on your observations, what can you say about the cluster? For example, can you make an estimate of the age and distance? Can you find other published CMDs for this cluster? Do they look similar to yours?

- Discussion of *uncertainties*. How accurate are your magnitude measurements? How well do the zero-points agree for different standard stars?

- Remember to cite the *sources* for any information you provide in the report.

- On the title page of the report, please mention the number of your group and the names of the other students you worked together with.

As a general guideline, this will probably require about 10 pages or so, but this will depend on a variety of factors such as how many figures you include, text size, etc.

Finally, we emphasize that each student *must* hand in an *independently written* report. You are allowed to work together on the observations and data analysis, but each student must hand in a unique report. Reports that are identical or very similar to each other will result in a failing grade. In such cases, no distinction will be made between the "original" and the "copy". Needless to say, it is also not allowed to copy from other sources without proper attribution.

The deadline for handing in the report is **5 April 2019**. The report can be written in English or Dutch. If, for some reason, you are unable to complete the report before the deadline (for example, because of bad weather), you must contact Søren Larsen *before the deadline*. Without prior agreement, reports received after the deadline will not be accepted. In particular, the "second attempt" is *not* a new chance to submit your reports if you missed the first deadline.