Observational Astrophysics I

Laboratory exercise - HR diagram of a cluster

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1 Introduction

This is an exercise in observational astrophysics, using the one-metre telescope at Stockholm observatory to observe a cluster of stars. While the observations themselves are a good exercise,we will also use the images to derive some physical properties of both the stars and the cluster.

The first aim is to calculate the surface temperatures of a statistically significant number of stars in the cluster (at least 30). By observing the stars using two (a blue and a green) filters we can obtain the temperatures from their colours.

In general, stars are formed together in large clusters roughly at the same time (co-eval starformation). The second aim of the lab is to find the cluster age. This can be done by plotting the stars in a so-called Hertzsprung-Russell (HR) diagram, revealing the nature of the stars. Since the hot and bright high-mass stars have much shorter lives than the colder and fainter low-mass stars, we can find the cluster age by finding the hottest stars still remaining in the cluster, located at the so-called turn off point in the HR diagram.

There are two clusters to choose from in this exercise, both very popular targets for amateur astronomers using binoculars or small telescopes. These are called M34 (in the constellation Perseus) and M35 (in Gemini, the Twins). The front page of this instruction shows a colour-mosiac of the M35 cluster and the surrounding region taken with the 61 cm diameter Burrell Schmidt telescope, Kitt Peak. Both clusters are suitable for evening observations in February and March at Stockholm observatory.

Table 1: The two clusters and their calibration stars.

Cluster	RA (J2000)	Dec (J2000)	B	V	Reference
M34	02:42:10.08	42:45:12.1	11.49	11.23	Jones et al. 1996, AJ, 111, 1193
M35	06:09:05.11	24:20:38.7	11.68	11.40	Sung et al. 1999, MNRAS 306, 361

2 Theory

2.1 The magnitude system and colours of stars

Astronomers use the magnitude-system to measure the brightness (flux) of astronomical objects, such as stars.

The astronomical magnitude scale is often regarded as quite strange by people who are not used to it and mistakes are therefore easily made when starting out using the scale. First of all it is reversed to common sense, with a brighter star having a lower magnitude. The faintest star seen in a dark sky using only ones eyes has a magnitude of $m \approx 6$ while the full moon has $m \approx -13$. This also shows that the scale is not linear; in fact it is logarithmic and the difference between two magnitudes is defined as

$$m_1 - m_2 = -2.5\, log \frac{F_1}{F_2} \tag{1}$$

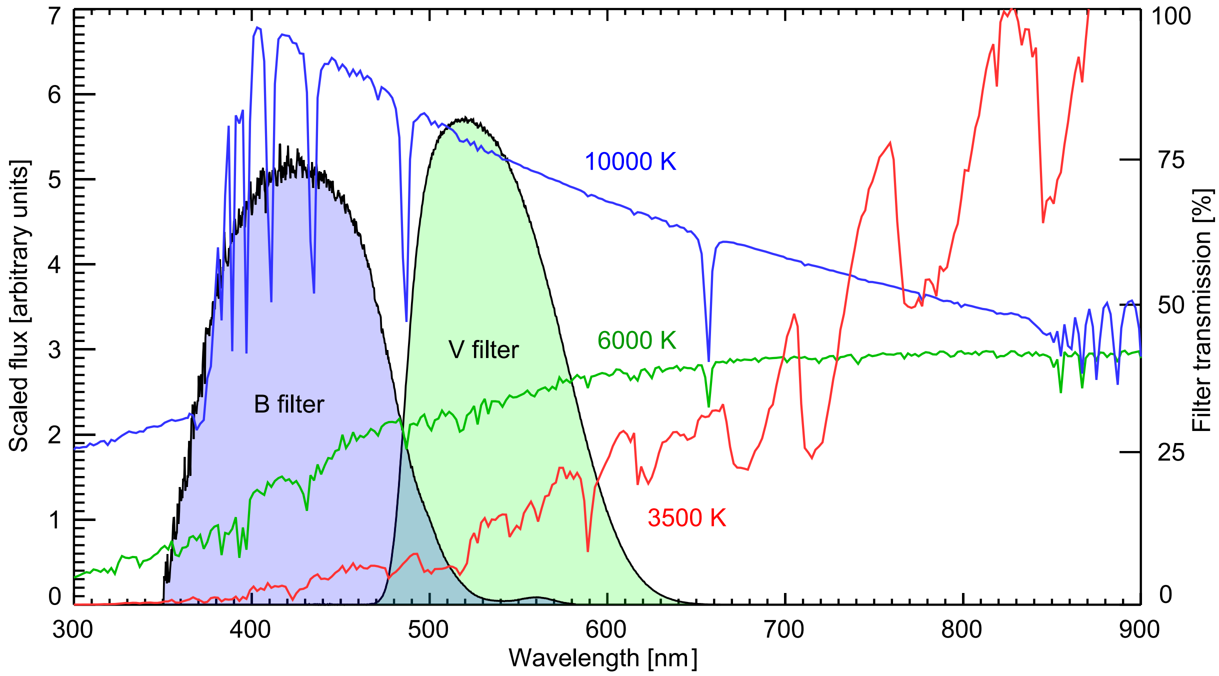

Figure 1: The spectra of stars of three different effective temperatures (3500, 6000 and 10000 K). The radiation from stellar atmospheres is similar to blackbody curves, but with lots of absorption lines and regions where radiation is absorbed and taken out of the curve. These spectra have different scales along the y-axis for clarity. In reality the hottest star is much brighter than the coldest star at all wavelengths. Using two filters, a blue (B) and a green (V) one, it is possible to find the temperature of a star by taking an image in each filter and comparing these. The 3500 K star would be much brighter in the V image, while the 10000 K star would be about as bright in both filters.

where F_1 and F_2 denotes the corresponding fluxes. This equation can be rewritten as

$$\frac{F_1}{F_2} = \sqrt[5]{100}^{m_2-m_1} \approx 2.512^{m_2-m_1} \tag{2}$$

A difference of 5 magnitudes thus means that a star is 100 times fainter than another star. Although the magnitude system is a relative measurement, there is indeed at zero-point in the system. It is defined so that the well-known star Vega (in the constellation Lyra, the Harp) has a flux of 0 magnitude when observed in any filter.

In Figure 1 the spectra of three stars with very different surface temperatures are shown. The energy distribution from a stellar atmosphere is similar to that of an underlying blackbody curve, specific to the effective temperature of each star, but with lines and regions absorbed and taken out of the curve. The effective temperature, T_{eff}, of a star is really the average temperature of the region of the star where the radiation is emitted (since the radiation we detect has escaped from a range of depths into its atmosphere). When light emitted from deep inside the stellar atmosphere is absorbed by (colder) layers further out, this light is re-emitted but with lower intensity since the region has a colder blackbody curve. The mass of a star, which is a very important parameter that determines most of its life, such as lifespan and its evolution, can be obtained from the effective temperature.

While taking a spectrum of a star would give the most detailed information about its energy distribution, this method is time-consuming since the spectrographs at most observatories can only obtain the spectrum of a single star at a time. In addition to this, by spreading the light of a star across the detector of a camera (one direction in a spectroscopic image represents wavelength) the S/N is lowered and a much longer exposure time is thus required. There is another, much faster, method for finding the effective temperature of many stars at the same time, such as those in a cluster. By taking two images, one in a blue (B) and another in a green (V) filter, such as those shown in Figure 1, it is possible to calculate T_{eff} for each star from its relative flux in each filter.

Using magnitudes to represent the relative flux in the two filters, one can define the *colour* of a star by taking the difference of the flux in two filters. For the B and V filters, we can use eq.1 to find the B and V magnitudes of each star:

$$B - B_{calib} = -2.5\, log \frac{F_B}{F_{Bcalib}} \tag{3}$$

$$V - V_{calib} = -2.5\, log \frac{F_V}{F_{Vcalib}} \tag{4}$$

where B_{calib} and V_{calib} are the known magnitudes (from literature) of a calibration star in the cluster, relative to which we make our measurements.

Thus, by measuring the flux of a star as seen through these two filters, in any arbitrary units, its B, V magnitudes and $B - V$ colour can be obtained from equations 3 and 4 - as long as we have measured the B and V fluxes of the calibration star F_{Bcalib} and F_{Vcalib} in the same units. Using such colour measurements, we can calculate T_{eff} of any selected star in our images.

2.2 Stellar evolution and the HR diagram

Stars usually form together in large clusters, having roughly the same age (so-called *coeval* star formation). This assumption is often valid for the majority of stars in a cluster, relative to the long lifetime of the cluster itself. Although, when comparing very high-mass and low-mass stars in a cluster, this assumption breaks down. Since, if both these types of stars start to form at the same time, the very heavy stars will have already lived their lives and died before the lightest stars have even finished forming. However, for the purpose of this exercise, we assume coeval star formation.

In Figure 2 there are two Hertzsprung-Russell (HR) diagrams, one (left) using observational parameters and another one (right) using theoretical parameters. These two diagrams are equivalent and contain the same information as long as some theory is used to find the effective temperature T_{eff} from the $B - V$ colour and the luminosity L (in solar units) from the absolute V magnitude M_V. Note that the T_{eff} scale increases to the left in the second diagram. T_{eff}(B-V) relations have been calibrated in large surveys and are readily available in scientific literature. The absolute magnitude of a star, M_V, is a measurement of how bright the star would look from a standard distance of 10 pc (1 pc is 3.26 lightyears). This is a necessary parameter since all

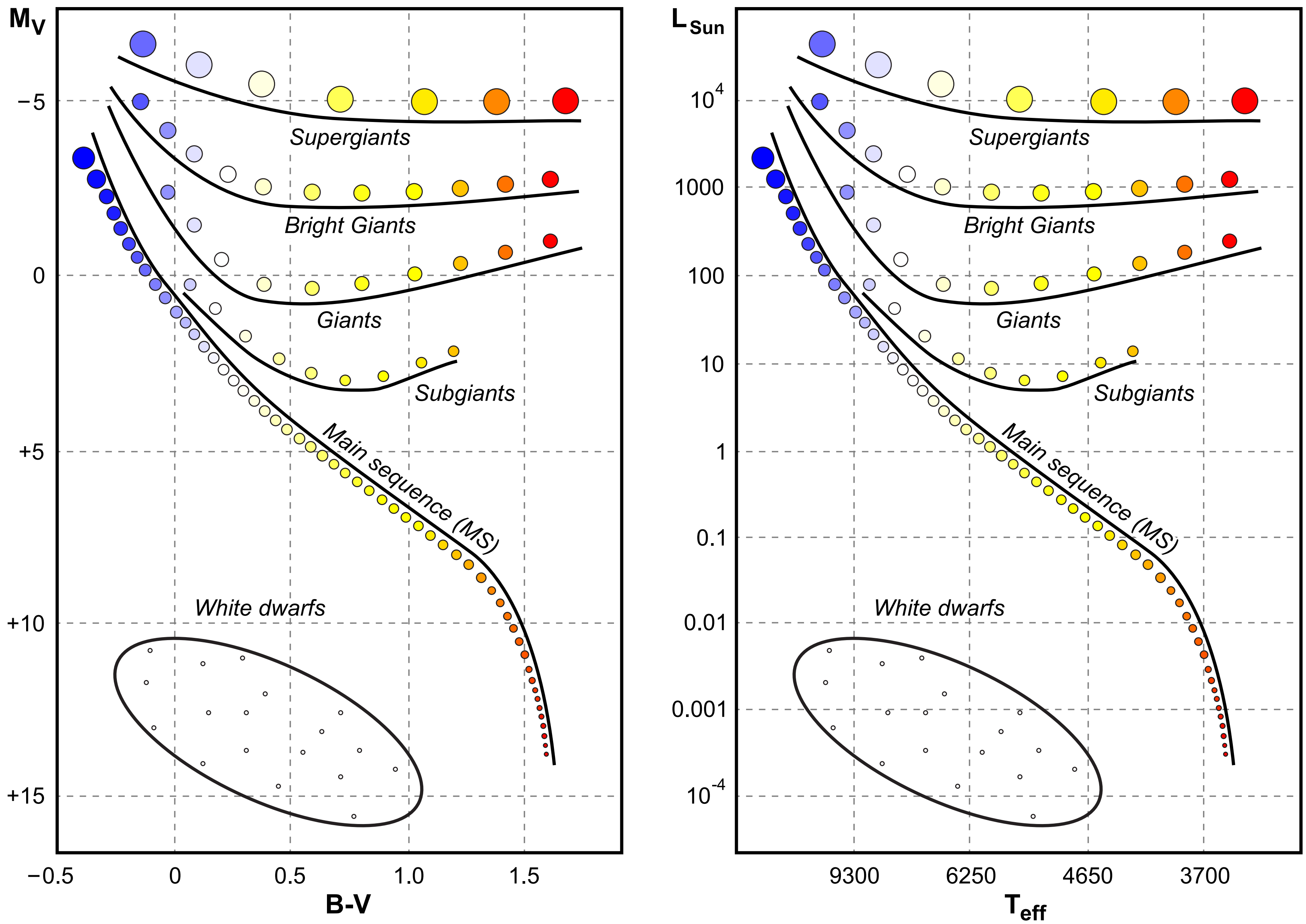

Figure 2: The Hertzsprung-Russell (HR) diagram in two popular versions (observational and theoretical parameters).

stars are located at different distances, and astronomers have agreed on this standard distance to be able to compare different stars with each other and to models.

All kinds of stars can be placed in the HR diagram, and equivalently, stars can be classified (T_{eff} and luminosity L) by observing them and putting them into a HR diagram.

Normal stars, so-called Main-Sequence (MS) stars, shine by nuclear fusion of hydrogen into helium. The pressure, from both radiation and the hot plasma, balances gravity, and the star is kept in equilibrium. As a star ages it becomes hotter and brighter, in order to burn the required amount of fuel (hydrogen) to balance gravity, while having less fuel available. Eventually, all the hydrogen has been used up at the centre of a star, causing it to expand greatly and become a so-called red giant. Heavy stars have short and very intensive lives. They shine very bright and exhaust their fuel in a short time (the most massive stars in only a few million years). Low-mass stars on the other hand (not too low, since stars need to have at least 0.08 times the mass of the Sun to start nuclear fusion) have long lives, lasting tens of billions of years.

The Sun is a roughly average star; neither high-, nor low-mass. It will spend about ten billion years as a main sequence star (about 5 billion years spent on the MS already). It will then expand into a red giant with such a large radius that it reaches all the way out to the present orbit of the Earth. However, as the Sun ages it loses mass and thus gravitational pull, meaning that by then the Earth will have a large enough orbit to escape being engulfed [1].

The smallest and lightest stars, red dwarfs, burn so slowly that they can last up to a hundred billion years. They become dimmer and dimmer, fading into black dwarfs, but as the universe is currently about 13.7 billion years old no low-mass red dwarf star is expected to have died yet.

After the red giant stage, a star can become a white dwarf, a very compressed core of (electron-degenerate) matter, with the outer layers of the former red giant shed into space as a so-called planetary nebula. The highest mass stars continue with nuclear fusion of heavier elements, until a large enough iron core has formed that it cannot support its own weight, causing a core collapse when its electrons are driven into its protons (producing neutrons) and a supernova explosion of the matter outside of the core - an explosion from a single star that can be as bright or even brighter than all the stars in a whole galaxy.

2.3 Cluster evolution

Figure 3 illustrates how a cluster of stars evolves in the HR diagram, assuming that all the stars finished forming at the same time. This 4-step sequence at selected time periods is described below.

- At time zero, the main sequence is fully populated with all kinds of stars from red (low-mass) to blue (high-mass). The cluster has much more low-mass stars than high-mass stars, but to simplify things, an even distribution is shown in the Figure.
- After about 10 million years the most massive stars in the cluster have already exhausted their hydrogen fuel and moved on to become red giants. At the same time, the low-mass

[1] Long before the red giant stage, Earth's oceans, and eventually the atmosphere, will boil off into space due to the increased energy output and size of the Sun.

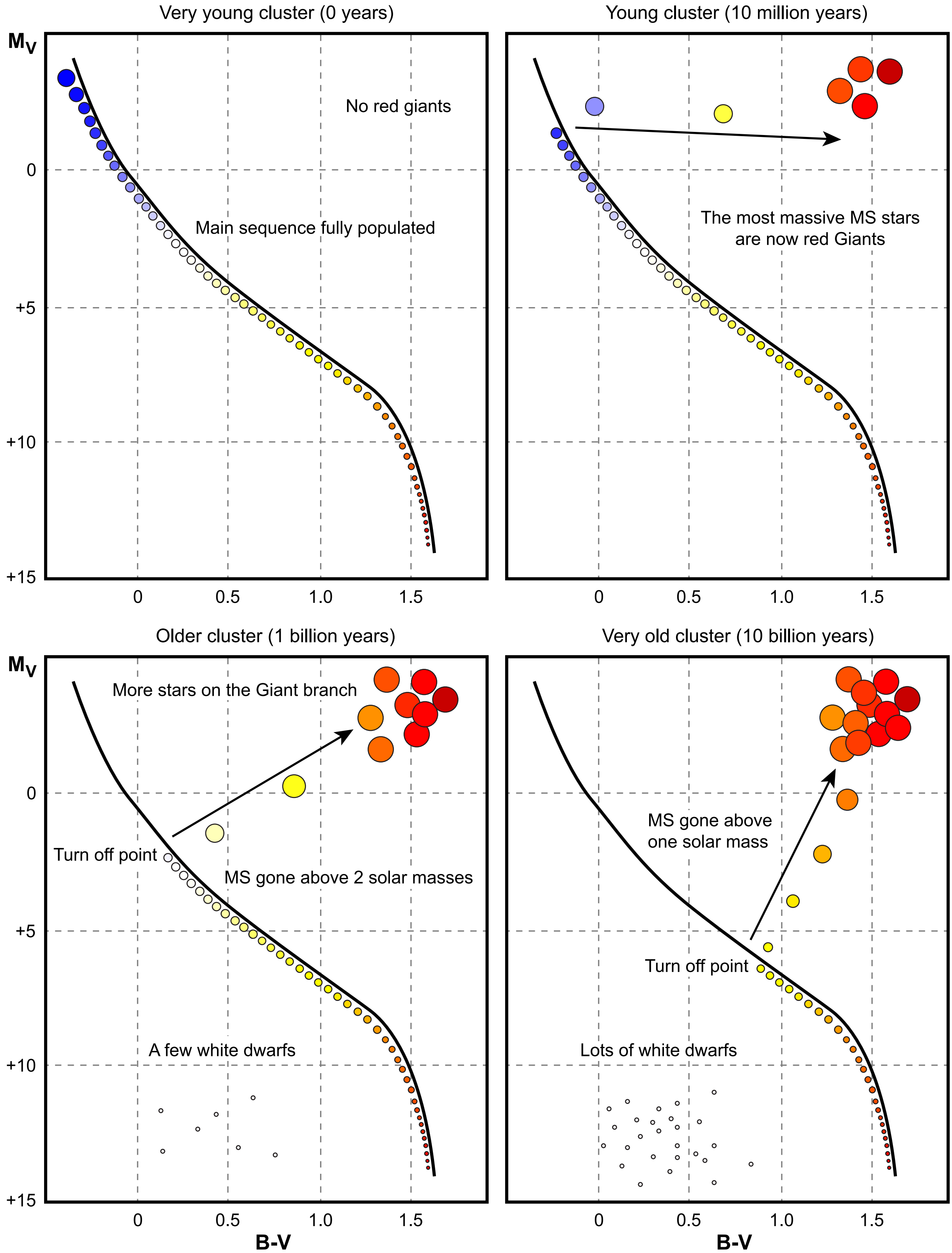

Figure 3: The evolution and MS depopulation of a cluster of stars.

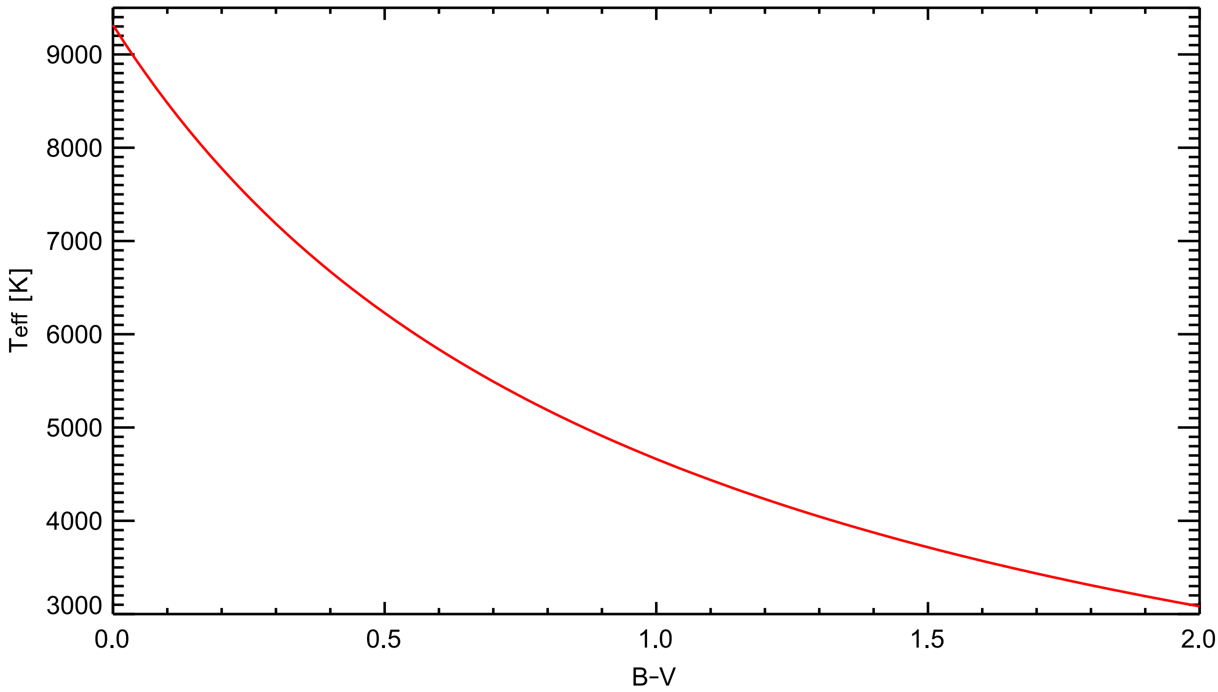

Figure 4: The relation between T_{eff} and stellar colour $B - V$ to be used in the exercise. This relation is given in equations 5 and 6 in the text.

stars have not even lived through 1/1000 of their MS lives. Red giants are redder (larger $B - V$) than the corresponding MS positions in the HR diagram.

- When the cluster is a billion years old, many more of the high mass stars have become red giants, and all stars heavier than 2 solar masses have moved away from the main sequence. A few white dwarf stars have appeared, forming from some of the red giants. The so-called turn off point is the point on the MS that represents the heaviest star still on the MS. This point can be used to measure the age of a cluster.
- Finally, at 10 billion years, the turn off point has moved down to solar-type stars. There are now many red giants and white dwarfs in the cluster. This depopulation of the MS will continue until all stars are gone from the MS. The lowest mass stars, however, have such long life spans that no such star has yet died in any cluster since their lifespans are greater than the age of the universe.

2.4 Calculating temperatures from colours

In order to convert our observations into physical parameters, a relation between T_{eff} and $B-V$ is needed. There are several large observational projects in literature that have found such relations, using e.g. spectra of many stars to confirm the effective temperatures. Alonso et al. (1996, A&A 313, 873) found the following relation:

$$T_{eff} = \frac{5040}{\theta_{eff}} \tag{5}$$

$$\theta_{eff} = 0.541 + 0.533(B - V) + 0.007(B - V)^2 \tag{6}$$

This relation is plotted in Figure 4 in the $B - V$ = 0.0-2.0 range (or roughly 3000-9000 K), which is the same interval for which relations 5 and 6 are valid. The interval includes most stars expected to be found in the two clusters in this exercise. The exception may be the brightest cluster stars which may have negative $B - V$, but for this exercise it is a valid approximation to extrapolate the relation if needed.

The $B - V$ colour in relation 6 is the *intrinsic* colour, i.e. the observed $B - V$ corrected for any reddening caused by interstellar matter between us and the star. This reddening is due to the fact that light of shorter wavelength is more likely to be absorbed by intervening insterstellar dust than photons of longer wavelength. Given that all stars of a cluster have about the same distance, we can assume that the interstellar reddening is a constant, valid for all stars in the cluster.

For M34 and M35 the interstellar extinctions are E(B-V) = 0.07 and 0.20 mag, respectively. These values should be *subtracted* from the observed $B - V$ in order to find the true, instrinsic $B - V$ to be used to obtain the effective temperatures.

2.5 Distance modulus and absolute magnitudes

The magnitudes we measure directly from observations are called *apparent magnitudes*, since how bright a star looks does not only depend on how much light it emits, but also on the distance to the star. In order to compare the brightness of different astronomical objects with each other we need a distance-independent flux measurement. For this purpose one uses *absolute magnitudes*, which is a measurement of how bright an object such as a star *would look* if it was placed at a standard distance of 10 pc (1 pc is 3.26 lightyears). Apparent magnitudes are often written with a small *m* and true, absolute magnitudes with a capital *M* followed by the filter letter within parenthesis, e.g. m(V) and M(V).

In order for us to calculate absolute magnitudes from our measured apparent magnitudes, we need to know the distance modulus $\mu = m - M$ of our cluster, which is the difference between observed and absolute magnitudes due to distance. So, for instance if we have a cluster with $\mu = 9.30$ and a star with m(V) = 12.50 the absolute V magnitude would be $M(V) = m(V) - \mu = 12.50 - 9.30 = 3.20$.

From literature[2] we know that the distance moduli of M34 and M35 are $\mu = 8.38$ and $\mu = 10.16$, respectively (this means that M35 is more distant than M34). We can now calculate the absolute V magnitudes of our selection of stars, which is needed to place them in the HR diagram.

[2] Jones et al. 1996, AJ, 111, 1193 (M34) and Sarrazine et al. 2000, A&AS 32, 742 (M35).

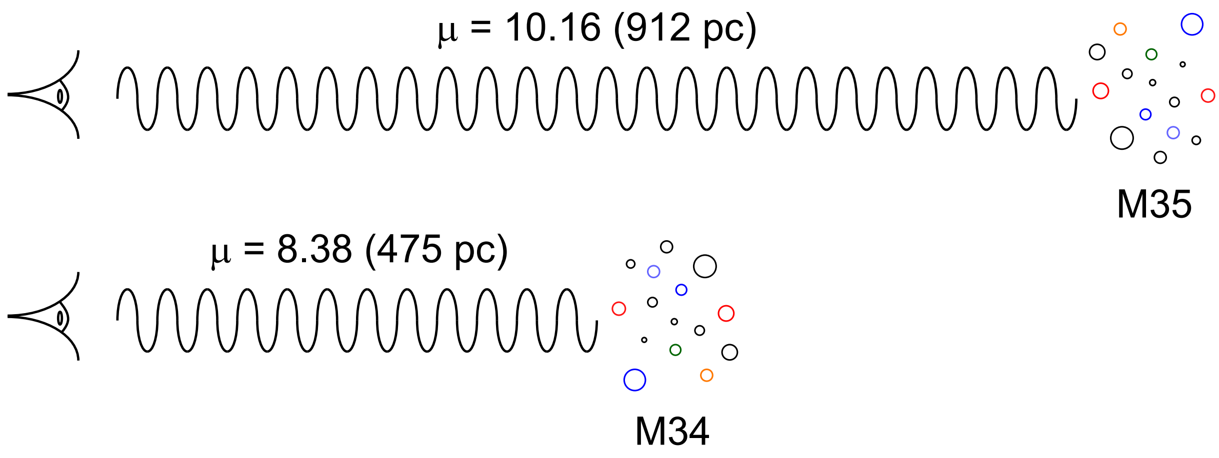

Figure 5: The distances and distance moduli of open clusters M34 and M35 used in the lab.

3 The observations

3.1 Some background and finder charts

This section is written with the Albanova Telescope in mind, however as this telescope is currently out of commission, we will use one of the available telescopes at iTelescope.net for this lab. This means that you will have to look up the corresponding numbers to your telescope of choice when observing.

The goal is to make observations of the open star cluster M34 or M35, which is a multi step process that we will go through here. Our choice in telescope location is limited by the fact that both of these objects are in the Northern sky. The imaging will be done with a monochrome CCD camera, using a blue (B) and a green (V) filter. The Field Of View (FOV) of the telescope/camera combination varies per telescope and can be looked up under the 'about' page of the website, under 'telescopes'. We will have to choose a telescope with a field of view that is not too small or too big. Both clusters have an angular size of roughly 30 arcminutes, but our main interest lies with the cluster's core. For example, the Albanova Telescope has a FOV of approximately 5.4×7.9 arcminutes. We have marked this in Figure 6 by a red square. As can be seen in the figure, the field of view is much smaller than the angular size of the Moon. In other words, the FOV is much smaller (and the magnification thus much higher) than most camera/telephoto lens combinations or amateur telescopes.

Magnification is a term that professional astronomers do not like to use since it has several misconceptions associated with it. A high magnification might sound like a nice bonus of a large telescope, however, the atmosphere at sea-level such as at Stockholm observatory is very turbulent and humid when compared to the high mountain tops across the world where most giant telescopes are located. Just as turbulent air can make things look fuzzy above a hot road in the summertime, even small temperature differences between layers of air, and humidity can make a star look fuzzy. A measurement of this phenomenon (i.e., how large a star looks in an image even though it should essentially look point-like) is called *seeing* and can vary a lot over both very short (less than a second) and long timescales (days) but on average the seeing

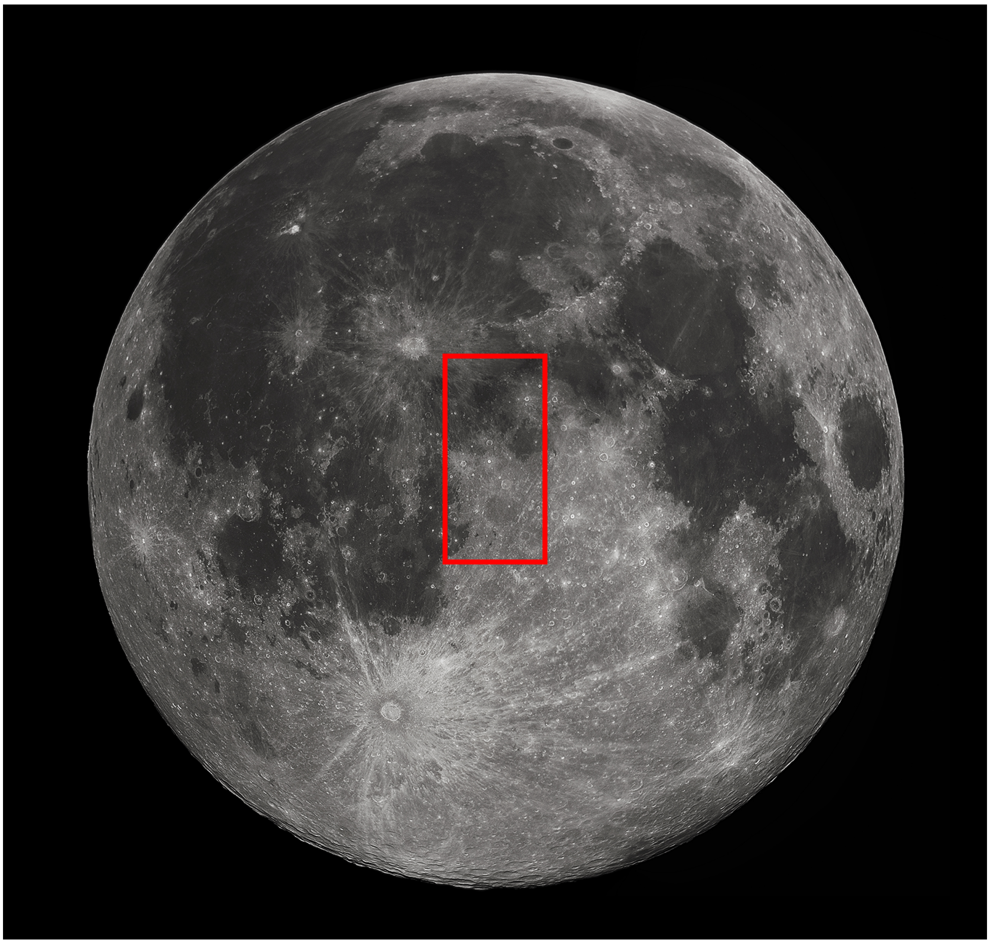

Figure 6: The field of view of the Stockholm 1-metre telescope compared to the Moon. The full Moon has an angular size of about 0.5 degrees (30 arcminutes) while the telescope & camera combination at the observatory yielded a field size of 7.9×5.4 arcminutes.

is much worse at sea-level. This means that ”high magnification” is often not a good thing, but can instead limit the field of view so that only part of an object can be imaged at once (such as a star cluster).

At the end of February, both M34 and M35 are possible to observe from sunset throughout the evening, with M35 being somewhat higher in the sky. Also, because of the smaller apparent size of M35 (because of its larger distance, Fig.5) it might be a slightly better target for the exercise than M34. Both clusters are famous objects that can be observed with binoculars or a small telescope, but given that we will use a larger telescope some of the stars will look very bright in the images, possibly saturating the camera in less than a second. On the other hand, there are many faint stars in these clusters, so several images will be needed in each filter - short exposures for measuring the bright stars and long exposures for measuring the fainter stars.

Finder charts for stars in the clusters are shown in Figures 7 and 8. Both clusters are clearly larger than the telescope field of view (illustrated by the red square). There will probably be enough stars for the exercise at the FOV marked at the centre of each cluster. The calibration

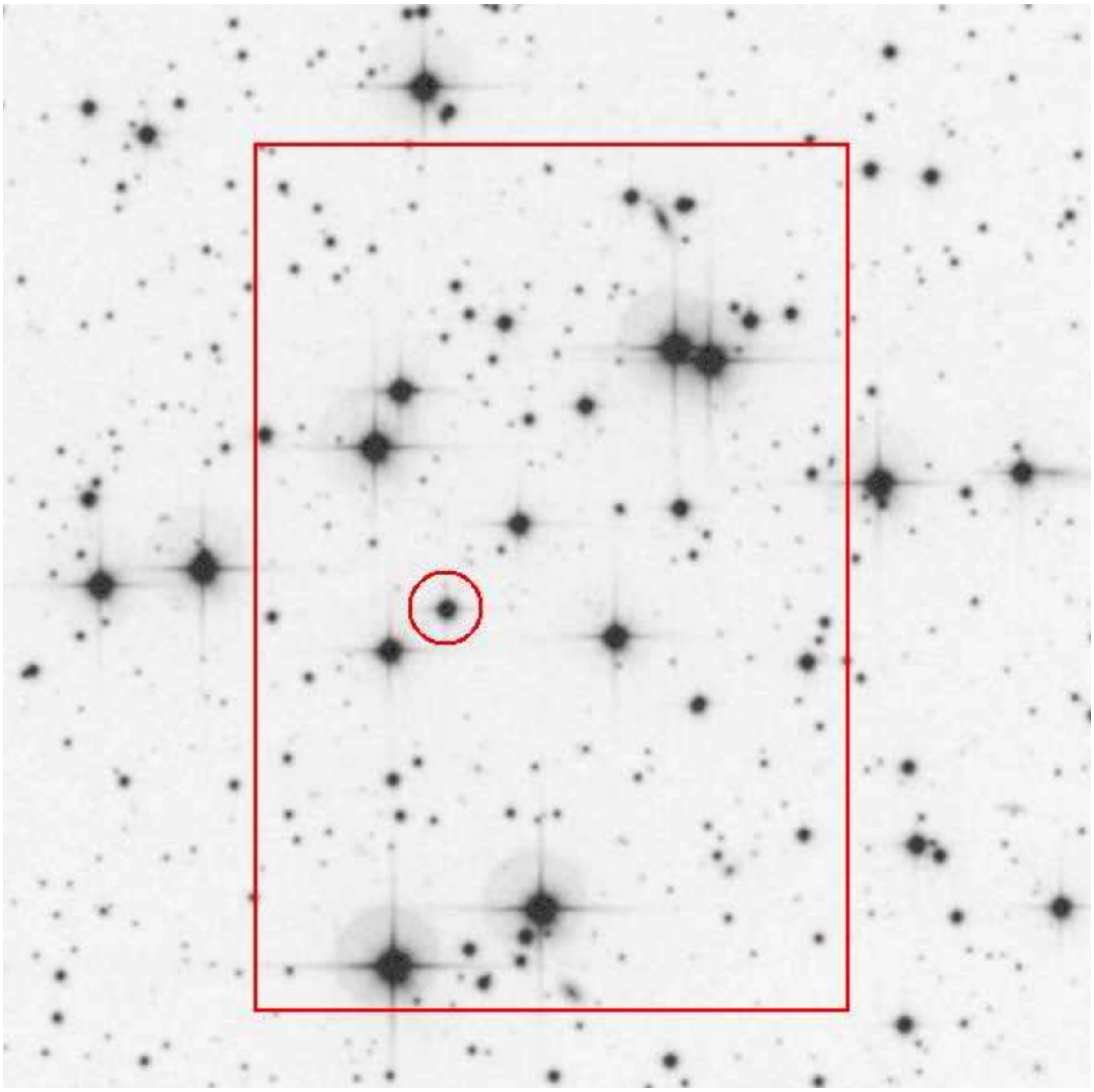

Figure 7: Finder chart for stars within the open cluster M34 (NGC 1039). This optical image has the dimensions 10×10 arcminutes, and the telescope/camera field of view is illustrated by the red square. Our calibration star is marked by a red circle.

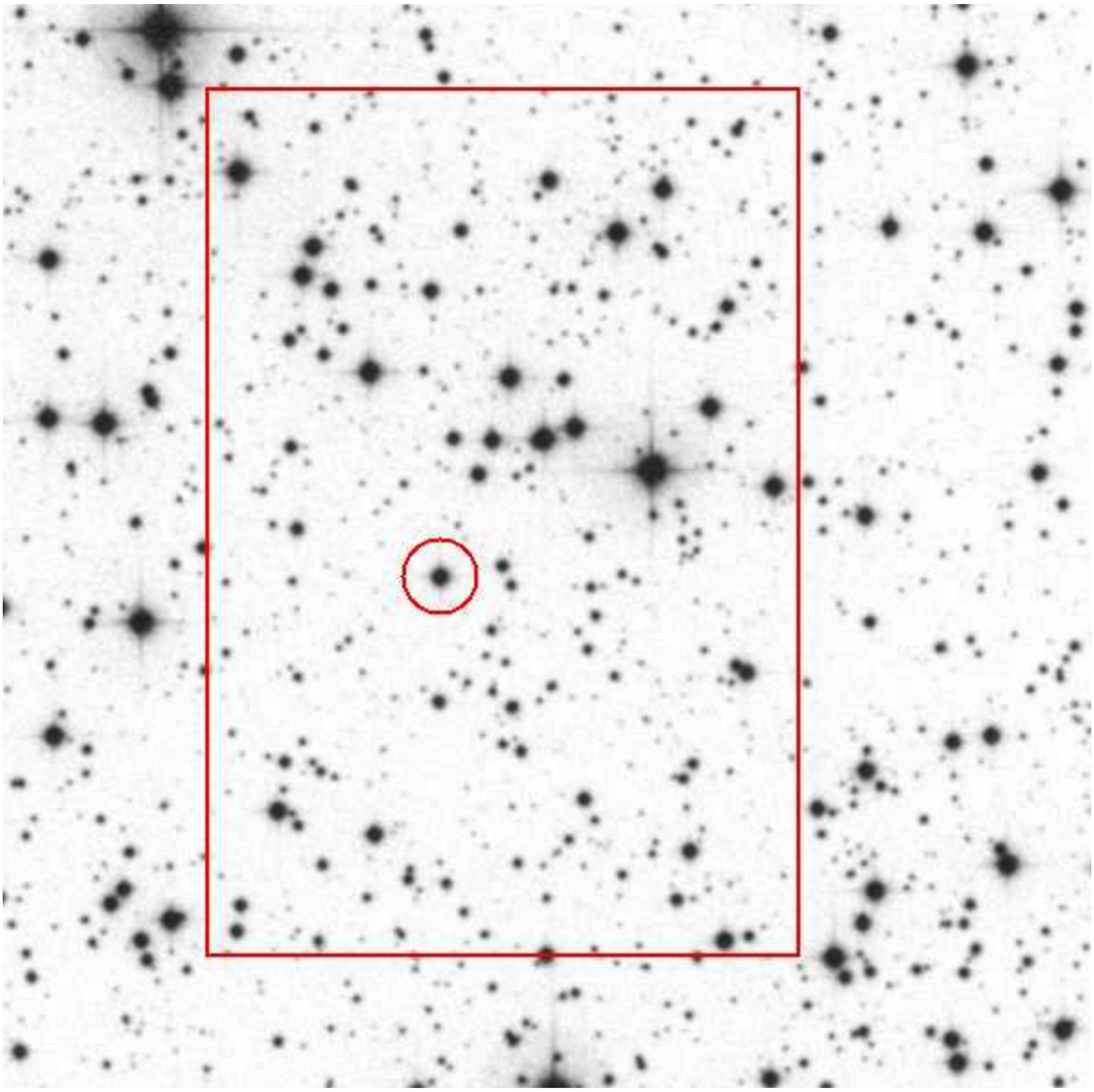

Figure 8: Finder chart for stars within the open cluster M35 (NGC 2168). This optical image has the dimensions 10×10 arcminutes, and the telescope/camera field of view is illustrated by the red square. Our calibration star is marked by a red circle.

stars (with known *B* and *V* magnitudes) are marked by a red circle in the Figures and their photometry given in Table 1. Other than that, feel free to move the telescope to several positions in the finder charts and take several images, **just as long as one of the positions includes the calibration star**. As mentioned previously (for each position) several exposures will be needed in each filter. A suggestion might be 0.5, 10, and 150 seconds.

At least two types of images other than the selected cluster itself needs to be taken in order to improve the image quality, and thus the measurements themselves. First of all you will need a *bias* image, i.e. a 0-second exposure with the camera shutter closed. This is needed since the pixel values would not be zero even though no light falls on the detector. There is an offset current (bias current) that needs to be removed from all the cluster images in the reductions. In addition, two *flat field* images will be needed, one in each filter. This is an image of the sensitivity variations across the camera pixels (ideally the flat field would be constant everywhere). The most common feature that shows up in a flat field image are out-of-focus dust specks on the camera window or vignetting (sensitivity dropping at the image edge) due to the filter size. For long exposures, the so-called dark current might also need to be removed (and a *dark frame* then needs to be taken). Dark current is additional counts (electrical noise) across the whole detector, but especially in so-called hot pixels, caused by heat in the camera (the dark current increases with CCD temperature, meaning that we want the detector to be as cold as possible).

Figure 9 shows what a typical flat field looks like (taken with the Nordic Optical Telescope on La Palma). An evident feature is the ring shaped out-of-focus dust specks that is very common in imaging systems. A flatfield is a kind of sensitivity-map, since it is observed using a constant background flux. If defects are not compensated for, the measurement of a star located on a dust feature will look fainter than it should.

The lab assistant will show you how to submit an observing plan to the remote telescope and how to access the data afterwards. When planning your observations, try to pick times that have calibration frames available. For example, if we log onto data.iTelescope.net and inspect the 'calibration-library' folder, we can find that most telescopes have darks available for integration times of 60, 120, 300 and 600 seconds.

An observation step-by-step guide might look something like this:

- Login to iTelescope.net and choose a telescope.
- Make an observing plan by clicking the 'Deep Sky' button on the left menu.
- Save the plan and confirm if it is correct with the lab assistant.
- Click the 'Make a Reservation' button on the left menu and plan an observation for your plan.
- See if observations were successful after the slot has passed, they regularly get cancelled due to bad weather and telescope problems
- Note: We will not take dark, flat or bias frames, as these are already available in the calibration library.

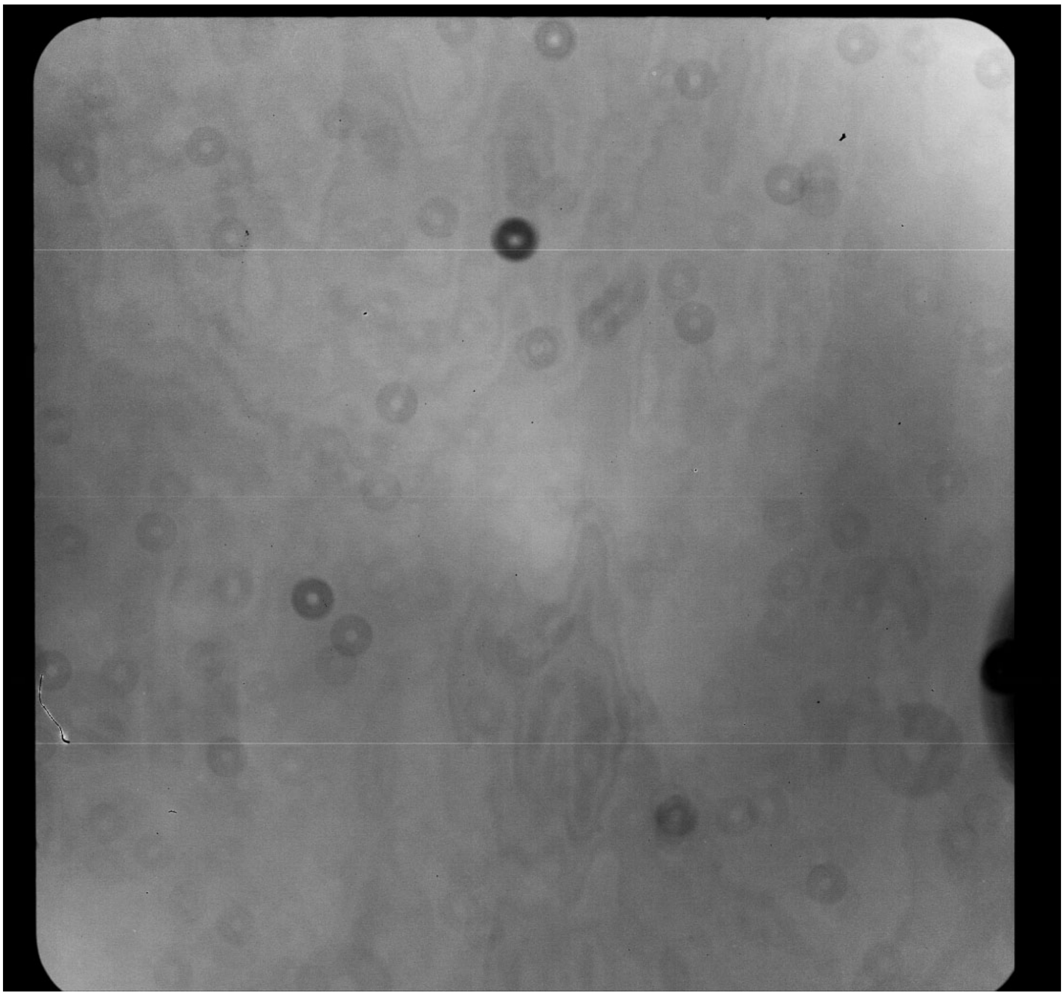

Figure 9: An example of a typical flat field image (NOT telescope).

3.2 Basic data reduction theory

Mathematically and simplified we can write the flux of a pixel at coordinates (x,y) on the detector as

$$flux(x,y) = bias(x,y) + dark(x,y) \cdot t + flat(x,y) \cdot signal(x,y) \tag{7}$$

Solving this for signal(x,y) we get

$$signal(x,y) = \frac{flux(x,y) - bias(x,y) - dark(x,y) \cdot t}{flat(x,y)} \tag{8}$$

where t is the exposure time [s] for a certain image *signal* [ADU]. *Bias* is a zero exposure without opening the shutter, and *dark* is the dark current [ADU/s] found by taking a long exposure with the shutter closed and dividing with the exposure time. *Flat* is the normalized flat field (dimensionless), describing the pixel-to-pixel sensitivity variations across the detector.

This means that to recover the signal from our target, we should first remove the bias frame from the CCD read-out. Then remove the dark current (often negligible, except for very long

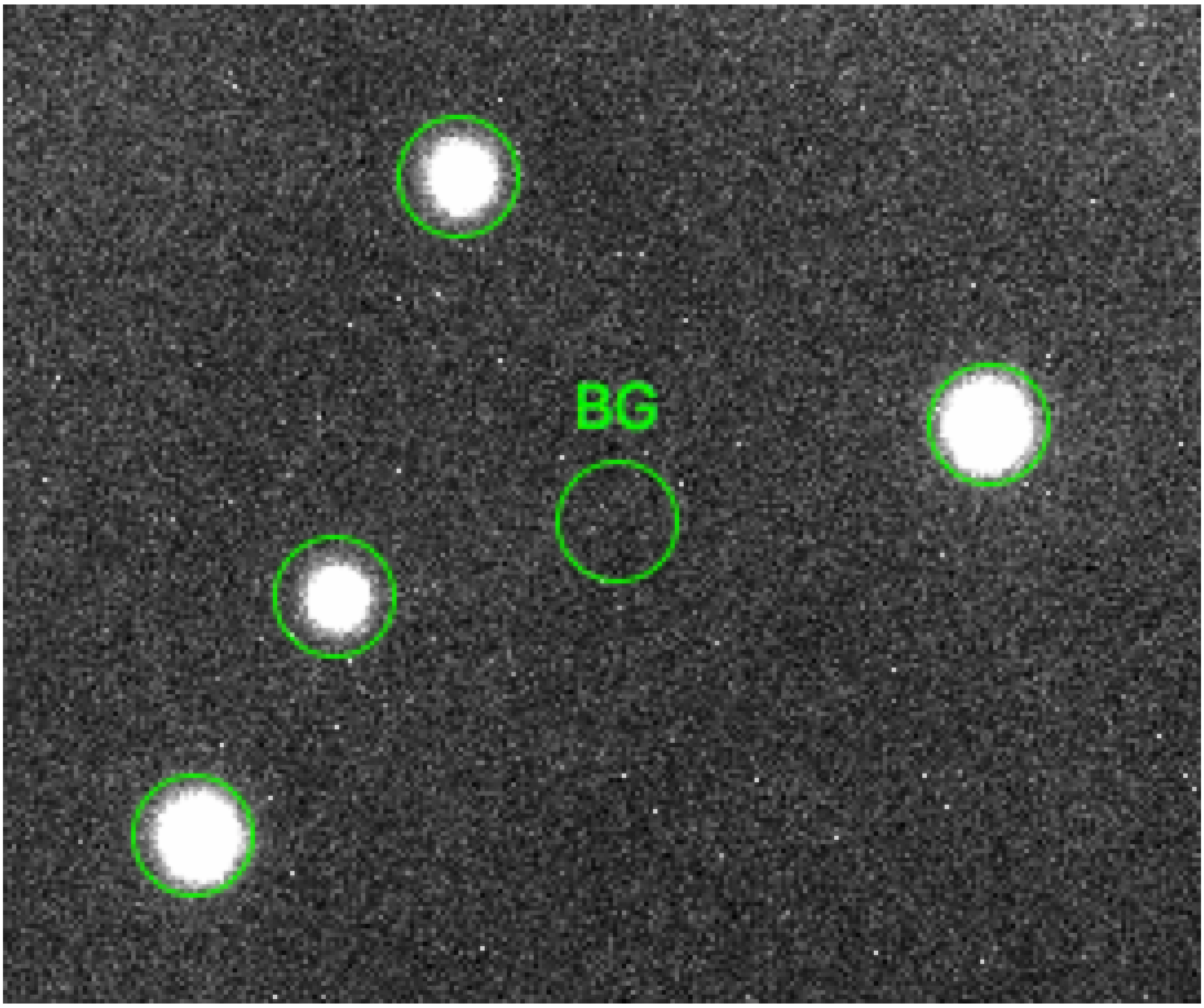

Figure 10: Aperture photometry. For each a circle is centred with constant radii if possible. By adding the flux of all pixels inside the (aperture) circle the total flux is found. However, we want the flux from the star, and not the star + background, so we need to subtract the sky inside the aperture. This is found by calculating the mean (or median) flux of an area that contains no objects. Typically this is achieved by making larger circles around the stars and getting the background from the same area. However, in densely populated images like this one, it is better to sample the background where possible and simply take the average of that.

exposures) and finally divide by our (normalized) flat field. Usually, in serious observations used for publications, one takes several bias, dark and flat field exposures (in each filter) to produce *master frames* (such as a master bias). This is done to remove cosmic rays from these images.

The brightness of astronomical objects, especially stars, is often measured using *aperture photometry*. Figure 10 illustrates this technique. An inner circle defines the *aperture*, which is basically an area that includes most of the light from the star. The flux of a source cannot be found by simply adding the flux from all pixels within the circle since the background is not completely black (due to street lights, the Moon, scattered Sun light etc.). We therefore define two outer circles with some distance from the aperture circle, which we will use to calculate the background flux. Denoting flux **F** and area **A** we then have

$$F_{star} = F_{ap} - \frac{F_{back}}{A_{back}} \cdot A_{ap} \tag{9}$$

4 The exercise

4.1 Preparing Observations

You will be making your own observational plan as described in Section 3. This plan should be finished before the agreed date, after which we will discuss and compare the plans. You will then schedule your observations and obtain your own data. If the observations were sccessful, you will be able to download your data at data.iTelescope.net.

4.2 Step-by-step reductions with Python

Make sure that you have python on your computer and a program called SAOImage DS9. Then download the associated files and start up a Jupyter notebook by typing 'jupyter notebook' in a terminal. Then navigate to the folder that contains the downloads and click on 'Datareduction_obs1.ipynb'. This should open the notebook. Come back here after you have completed it.

4.3 Questions to be answered

From the reduced data of your observations (see previous chapter) you should now have a photometry list of roughly 30 selected stars (including the calibration star). This list should contain photometry (in ADU/s units) for both the B and V filter.

- How did you obtain the data? Describe the process and the telescope.
- What is your estimate of the seeing? (B and V seeing if you measured it in both filters). The seeing (FWHM) is usually given in arcseconds ("). The Albanova telescope has a field of view of 3.82 arcminutes (229") corresponding to 512 pixels. Telescope11 (The remote telescope used in 2020) has a pixel scale of 0.81 arc-secs/pixel.

- Use relative photometry, as described in equations 3 and 4 to calculate the B and V magnitudes of all the selected stars. The calibration star has known calibrated magnitudes (B_{calib} and V_{calib}) given in Table 1.
- Calculate the $B - V$ colours of the stars. Correct for the interstellar extinction in these calculations, assumed to be constant E(B-V) = 0.07 and 0.20 mag for M34 and M35, respectively.
- Use the distance modulus (Fig. 5) to calculate the absolute V magnitudes M(V).
- Plot the stars in an observational style HR-diagram, with $B - V$ on the x-axis and M(V) on the y-axis.
- Comment on the types of stars that you have found using the HR-diagram. Remember that there may be (faint) background stars that do not belong to the cluster.
- Can you estimate the turn-off point of the cluster in the HR diagram? Remember that the hottest (bluest) stars are the most massive MS stars still remaining in the cluster (and that they have the shortest lifespan).
- Estimate the age of the cluster using the turn-off point and the age versus $B - V$ relation given in Table 2.

Table 2: Cluster age vs. turn-off point.

Age [Myr]	Colour B-V	Cluster example
5	-0.30	NGC 3324
10	-0.25	NGC 3293
25	-0.20	IC 2602
50	-0.10	IC 2391
100	-0.05	NGC 2516
500	+0.00	IC 4756
750	+0.10	M44
1000	+0.20	NGC 2660
2500	+0.30	M67
10000	+0.40	—