Observational Astrophysics 1
Star Clusters and the Hertzsprung-Russell Diagram

Laboratory and Computational Physics 3

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THE UNIVERSITY OF MELBOURNE

Contents

1 Your logbook

You might be a bit confused about how to write your logbook. A logbook is usually a book of rough scribbles of dates, data and notes. However, since we need to mark you for this subject, your logbook will need to be a bit more orderly than a typical lab logbook. You should write your book as a sort of mix between a logbook and a report, where you keep notes of what you're doing each day but also present it in an orderly way so that your marker can understand what you've been doing. Even though your marker is very familiar with the content of the labs, we need to see the particulars of what you've done in the lab. References to the lab notes should be sparing. You should write your logbook/report as if someone doing third year physics, but not necessarily familiar with this lab content, wants to understand and replicate your experiment.

1.1 Format

You are welcome to either type or handwrite your logbook. If you choose to do both, e.g. handwrite notes and type tables, or type the logbook but have handwritten maths, please make sure to submit both in a single document, either by printing out the typed sections or scanning the handwritten sections. Your logbook should be submitted as a single document. Some people upload every file they make in the lab, but we are very unlikely to open anything that is not directly referenced in the logbook, and in that case it's easier if it's included there in the first place. A well-written, well-formatted longer logbook is far easier to read than a shorter, less-organised one.

1.2 Introduction

Your introduction should include your aim for the experiment at the beginning. It should also start with the title of your experiment, and your name and lab partners, if applicable.

Your introduction should also introduce a brief outline of the experiment you plan to do. It should also include background information about things like the objects you're investigating, the data you're using, and the mathematics you'll need for the experiment. We expect to see 2-3 pages of content for the introduction. Many people will want to leave writing their intro until later in the lab, when you are a bit more familiar with the content. This is perfectly acceptable.

1.3 Procedure/results/analysis/discussion

You may have written reports before where these sections are written out separately, but since this is a long project, we highly recommend writing these all in one big chunk as you complete parts of the lab. For example, you might have the procedure/results/analysis for day 1's activities, and then start on day 2 with the procedure for the second activity of the lab.

Plots should have axis labels and titles, an indication of the scale, a legend and visibly distinguishable markings for different sets of data. You can make your plots quite large, as they are often the cornerstone of your results. A teeny-tiny plot is very hard to mark!

Data tables are also very important. It's easy to disregard them, since they are often large and unwieldy. However, your data is very important, and the values help us to judge whether you've done things correctly. You should include a well-formatted data table, otherwise all your nice plots can't be verified by us. Make sure to include column labels and units for each value.

Units are extremely important. In many areas of physics, like astrophysics and particle physics, we use other units alongside SI units, and you may have to do some conversions along the way. A number should never be on its own, unless it's a ratio between two other numbers.

1.4 Conclusion

Your conclusion should make sense without reading the rest of the report. You should restate your aim, very briefly summarise your procedure, and give your main results, including any numbers you've calculated (e.g. "We calculated that the speed of light, $c = 2.5 \times 10^8 \pm 1.0 \times 10^8\,\mathrm{ms^{-1}}$").

1.5 Your demonstrators

Your demonstrators are happy to give you guidance, and will generally have points where they will give you extra information or be another set of eyes if you have a problem. We do expect that you will work with your fellow students to solve problems before coming to us.

1.6 A brief summary of this lab

1. Using Stellarium, familiarise yourself with stars and some of the terminology used to describe their properties.
2. Prepare and submit an observing plan for a target of your choice.
3. Access the observational data provided and process it using AstroPy and related Python packages.
4. Measure the brightness of all the stars in your processed data and your own observations at several different wavelengths.
5. Plot the Hertzsprung-Russell (HR) diagram and work out the properties of your stars.

2 The sky above us

Before we start on the main experiment of this lab, let's get to know how the stars move in the sky, and some of the terminology we use in observational astrophysics.

2.1 Exploring the sky with Stellarium

Before we jump in to taking observations, we'll first get a sense of how the sky moves above us. Everything on the sky can be thought of as *projected* onto a 2D sphere some arbitrary distance above us. This is called the **celestial sphere**. At any given time, we see half of this sphere. Since the Earth is spinning, and it is orbiting around the Sun, the sky changes both over the course of a night and over the year. This means that particular objects that we would like to observe (our "targets") are only visible at particular times of year and at particular locations on Earth. Let's explore this ourselves.

Stellarium is free software that simulates the night sky, and is often used to plan observing nights, as the location on Earth and date and time can be set by the user. Open the web version of Stellarium here: Stellarium Web Online Star Map (`stellarium-web.org`), or download a copy onto your own computer if you would prefer: `https://stellarium.org`. When the software loads, it should automatically find your location and current date. In the menu at the bottom of the screen, you will find many buttons to change your view of the sky. Take a small amount of time to test out these settings.

Now, set your location to Melbourne, and your time to midnight of the current date. Using the date and time controls, advance forward in one hour steps. How do the stars move over the course of several hours? In the bottom menu, find the "equatorial" grid. These are the coordinates that astrophysicists use to describe the locations of objects on the sky. The north-south direction is called the **declination**, and the east-west direction is called the **right ascension**. While declination is measured in degrees, minutes and seconds like most sexagesimal systems, RA uses *hours*, minutes and seconds, where one hour of RA is 15°, or the amount of angle the Earth spins around in one hour of time.

As you go forward in time, the lines of declination will not change, but the lines of right ascension will rotate around the Earth. Each object in the Universe has a specific right ascension and declination (called its RA and Dec).

Now, change the grid to the "azimuthal" grid. You will see that this grid is offset to the equatorial grid. **Azimuth** is a measure of the angle of an object away from North, while **altitude** is the angle of an object above the horizon. The horizon is at zero degrees altitude, while directly overhead at your location is $+90^\circ$. Click on an object (not a Solar System object though!). You should see that, as time passes, the object's RA & dec will remain constant, but its azimuth and altitude will change over time.

2.2 Stars

Now, click on a star. You should see a number of lines of information pop up about the star. They might include:

- **Name**: objects will often have several names, which come from different catalogues.
- **Magnitude**: this is a particular measure of brightness. We will go over the definition of this in Section 4.1.
- **Distance**: the distance to the object. Measuring distances to objects is very difficult and different methods will often give different distances to the same object. Distances are measured in **parsecs**, where one parsec is 3.26 light-years.
- **Spectral type**: this will be a letter followed by numbers. Stars are classified into different types based on their temperatures, in the sequence O (hottest), B, A, F, G, K, M (coolest). The numbers split each type into 10 levels, and subtypes are then added to the end.

Click on half a dozen stars. Brighter stars will show as slightly larger in Stellarium, and different spectral types will have slightly different colours. See if you can observe any trends in magnitude or spectral type between different stars in the sky.

You may remember from previous study in astrophysics that different types of stars have different life-cycles and ages. Massive blue stars are young stars, and they are burning through their hydrogen very quickly. Most stars fall on the **main sequence**, and smaller stars are fainter and redder. Bright red stars, on the other hand, are evolved stars that have run out of hydrogen and left the main sequence. As we go through this lab, you'll learn more about these relationships between brightness and temperature.

2.2.1 Star clusters

In this exercise you will observe an open cluster of stars, and measure their properties. You will use these observations to figure out how bright they are, how hot, how large and how old they are. In particular, you will plot your own Hertzsprung-Russell (HR) diagram, the famous plot of colour against brightness that allows you to classify stars into their myriad different types.

If you look at a random bunch of stars, you get a very messy HR diagram. The reason is the stars are all at different distances. Faint red nearby stars may appear brighter than bright blue background stars, just because they are closer. For this reason, we will look at a cluster of stars. This ensures that nearly everything we see is at roughly the same distance (though we might accidentally get an occasional star in the foreground or background). All the stars in a cluster form at once from the same nebula, so everything we observe will have the same age. There is also a third advantage; because stars are crowded together in a cluster, we can get images of lots of stars at once.

Clusters come in two types, open clusters (relatively nearby, and containing up to a few hundred stars) and globular clusters (more distant, and containing perhaps a million stars). Unfortunately globular clusters are so distant that with our telescope all the stars will seem to blur together. We will therefore observe open clusters.

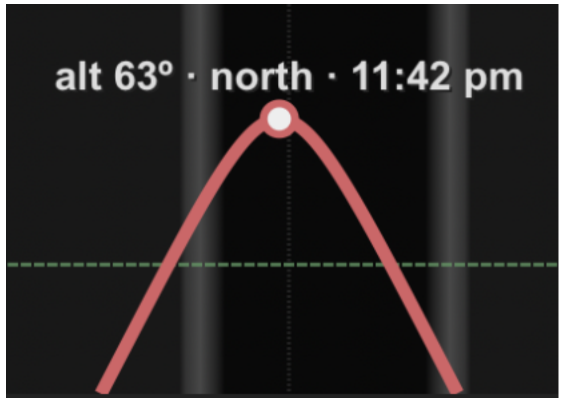

Figure 1: An example of an altitude-time plot from Telescopius.

2.3 Observing with iTelescope

We will now prepare our observing plan of an open star cluster. An observing plan details the different exposures we would like to take of our targets, so let's begin by choosing a target.

2.3.1 Target selection

Open up the website `http://telescopius.com`. With this, you can bring up different objects and see when they are visible in the sky, and what they will look like in the different iTelescopes. We will be using iTelescope T17 for this activity, which is located at Siding Spring Observatory in NSW, so we will be observing a cluster in the southern sky. Fortunately, the Milky Way is predominantly in the southern celestial hemisphere, giving us many potential targets to observe. In the menu at the top left of the screen, change the "Observatory settings" to "iTelescope Observatories ..." → "Siding Spring Observatory".

There are thousands of open clusters, so to choose the best one to observe you can take a look at `https://telescopius.com/deep-sky/objects/tonight/type:open-clusters`, which shows all of the clusters visible from Siding Spring tonight (check that the location says "Coonabarabran").

You will see a plot similar to Figure 1 next to the name of each cluster. This plot shows the time on the x-axis, and the altitude above the horizon on the y-axis. The times of day when the Sun is up are shown in mid-grey, while the times when it is down and we can observe are in black. Between these times are two light-grey columns, which show the twilight periods. Once the Sun has gone below the horizon, the sky is still too bright for us to observe, so we wait until it is 18° below the horizon. This is called **astronomical twilight** and means we can be reasonably sure the sky is dark enough to observe.

You will notice a horizontal green dashed line on the plots, which marks 30° altitude. We want our targets to have the highest altitude possible, as when they are low on the horizon we see through more of the atmosphere than when they are closer to directly overhead. This can blur our images, so look for a target that gets to at least 60° altitude. Sorting the list by "Next Opposition" will show the targets that reach the highest altitude.

Next, we want to filter by magnitude. This is a measure of the brightness of the cluster, and we want to

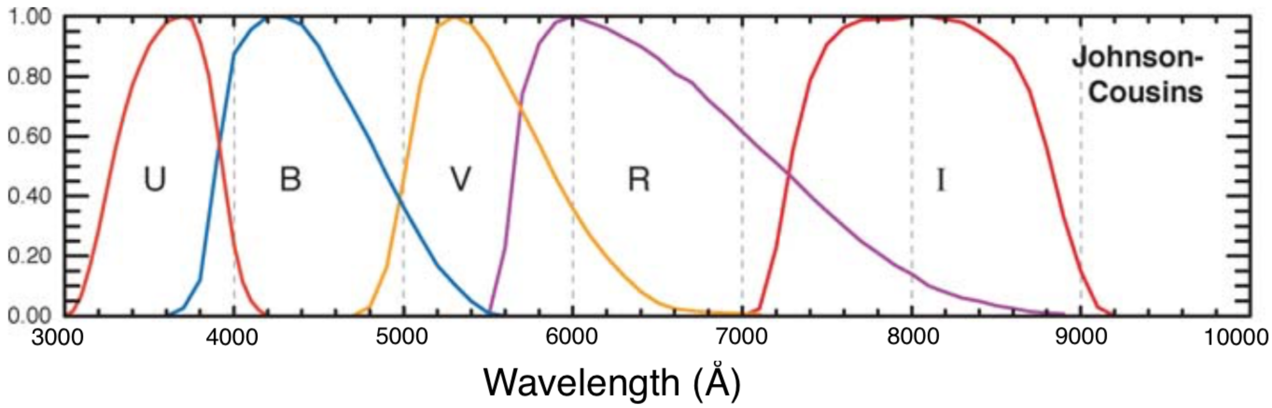

Figure 2: The filters of the Johnson-Cousins filter system. Adapted from Bessell (2005).

choose a cluster that is not too bright or too faint. Set the "Apparent magnitude" filter to between 4 and 7. Apparent magnitude is a system that is in reverse from our usual understanding of number systems, so lower numbers are targets that are brighter, while higher numbers are fainter targets.

Open up some of the potential targets in your list. You will be taken to a data page for the target, which shows a **Telescope simulator** and a **Data sheet**. We will set up the telescope simulator now. Click the "Telescope Partners" $\rightarrow$ "iTelescope" button in the top menu of the simulator. Then, click the first square box under this menu (it shows a telescope dome). Choose telescope T17. The image should update to show a green dashed box with the caption "FOV $0.26^\circ \cdot 0.92''$/pixel". FOV 0.26° is the **Field of view**, and means that the telescope can see a square $0.26^\circ \times 0.26^\circ$ on the sky. You will need to check the size of your star cluster in the data sheet section, and it will ideally be smaller in size than the FOV. "$0.92''$/pixel" is the **pixel scale** of the image, which we will need later on.

2.3.2 Filters

Unlike images taken with a camera, astronomical images are generally taken with different filters placed in the optical path, so that only certain wavelengths of light are recorded in the image. Different telescopes and instruments use different filter systems, depending on their intended use, and the filters on T17 use the **Johnson-Cousins** system. This is five different filters that cover the wavelengths from $3000 - 9000$ Å. The different filters are named with a single letter to distinguish them. From shortest to longest wavelengths, they are U (ultraviolet), B (blue), V (visual, green), R (red), and I (infrared). Figure 2 shows the transmission curves of these filters. A value of 1.00 on this plot indicates that 100% of the light at that wavelength passes through the filter.

When observing using ground-based telescopes, the atmosphere blocks some light, and it blocks more at certain wavelengths (where molecules in the atmosphere are excited by these wavelengths). Most visible light passes through the atmosphere, but in the U and I filters we expect to see some dimming of the light (called **attenuation**). While the U filter is available to take images with, we will concentrate mainly on the four longer-wavelength filters in our observing plan.

2.3.3 Observing plan

Once you are satisfied with your target, we can set up your observing plan. Your demonstrator will submit it for you and manage rescheduling the observations if there is poor weather[1], but the process is:

- Your demonstrator will create an iTelescope account for your group. Ask them for these details.
- Open `https://go.itelescope.net` and log into your account. Then, select telescope T17 from the "Telescopes" drop-down menu. Log in again.
- In the T17 website menu on the left, click "Imaging / Plan" $\rightarrow$ "Deep Sky Objects". This will bring up the planning tool. Give the plan a unique name, and type the name of the target into the target field. Then you can press the blue button to retrieve the target's coordinates automatically. A pop-up will calculate the times when the target is visible tonight, check these times against your altitude plot in Telescopius.
- The details of each exposure are then added to the table under "Targets". You will want to take four images, in the filters B, V, R and I. The quantity and binning for each image will be 1, and the duration or exposure time will vary depending on the magnitude of your object.
- The "Create plan for later" button will save your plan for later.
- Choose "Make a Reservation" in the left menu. A calendar will appear, and you can click on the time you want to observe the target. Reserve 15 mins and choose the plan you want to execute. Click "Reschedule" before submitting the reservation to ensure your plan will be automatically rescheduled if it fails the first time.
- Your demonstrator will forward any iTelescope emails about your observations to you. Once they are complete, you can download the calibrated files at `https://data.itelescope.net` using your account login.
- **Important!** Your data might look a bit crummy, which can be disappointing. Unfortunately this is part of the process of observing, where the weather and conditions can play havoc on our data through no fault of the observer.

3 CCD reduction and analysis

We will now prepare some images for analysis. We have some sample data of the star cluster M93 that you will process. This data contains many light sources that are not the light from stars themselves, so we will go through the steps of the "reduction" process on this sample data while we wait for our iTelescope data to be taken. Your iTelescope data, like most data from telescopes these days, will be processed by an automated process for you, so you will not need to follow these steps for your own star cluster data.

[1] Ideally, your data will be taken the same night that you submit it, but clouds and rain are common reasons that observations may be rescheduled. Telescope malfunctions are also relatively common, since there are many, many components to a telescope/imaging system. Unfortunately, you may have to wait several nights for your data to be taken.

3.1 CCDs

Astronomers don't look through telescopes any more. In fact, it is anatomically impossible to look through most large telescopes! Starting about 1880, photographic plates replaced the human eye as the most common astronomical instrument. The reasons for this are the same as for using any camera: a permanent record is created and long exposures mean that objects too faint to see with the eye can be recorded in detail. Starting about 1975, electronic detectors began replacing the photographic plate.

The reason for the change is efficiency. A high quality astronomical photographic plate will record about 2% of the photons falling on it. The latest research-grade electronic detectors record more than 90% of the photons. They have other advantages too; since they generate digital data you can subtract off background light (a big advantage in a site like central Melbourne), and use all sorts of techniques to sharpen up your image. Most important of all, electronic detectors allow you to quantitatively measure the radiation coming from sources because they are linear devices— the number you get out of a CCD is directly proportional to the number of incident photons.[2] At their most basic, CCDs are simply photon counting devices. If you know how many photons an object has emitted, then you know how much energy it has emitted and you are on your way to understanding what it is/how it works.

CCDs are basically silicon chips, with a very special circuit pattern etched on their surfaces. When photons hit the surface they generate electron-hole pairs. The electrons are attracted to a grid of electrodes etched into the chip. Each of these electrodes forms a potential well, and it traps and stores all the electrons produced in its part of the chip. So as time goes on, a pattern of charge builds up near these electrodes. The more light falls on a given part of the chip, the more electrons will accumulate near the electrodes there. The pattern of electrons building up on the chip is thus an image of whatever the CCD is looking at.

When the observations are finished, the pattern of electrons on the grid of electrodes has to be measured and stored on computer. To do this, one end of the chip is connected to a set of wires. Under computer control, the voltages on the electrodes are set oscillating, so that a set of ripples of potential move across the chip. All the electrons are swept along by the ripples, moving to the edge of the chip where they are 'counted' (the potential they generate is measured) and the result is sent to the computer.

CCDs are now the dominant technology used in astronomy. The same technology is now widespread in devices such as video recorders and digital cameras. They are relatively cheap and reliable. It won't hurt them if you expose them to light accidentally. And they can be very efficient; most astronomy grade CCDs can collect and store an incredible 99% of the photons that fall on them. With a CCD attached, a little telescope on the roof of the School of Physics is as powerful as the biggest telescope in the world would be using naked eye observations.

3.2 Images to Analyse

You will need following sample images to do the analysis:

[2] Hence, the raw CCD output is usually expressed in units of 'counts'. Typically, this is just an integer between 0 and $2^{16} - 1 = 65535$ because the electronics on the chips utilise analog-to-digital converters with 16-bit resolution.

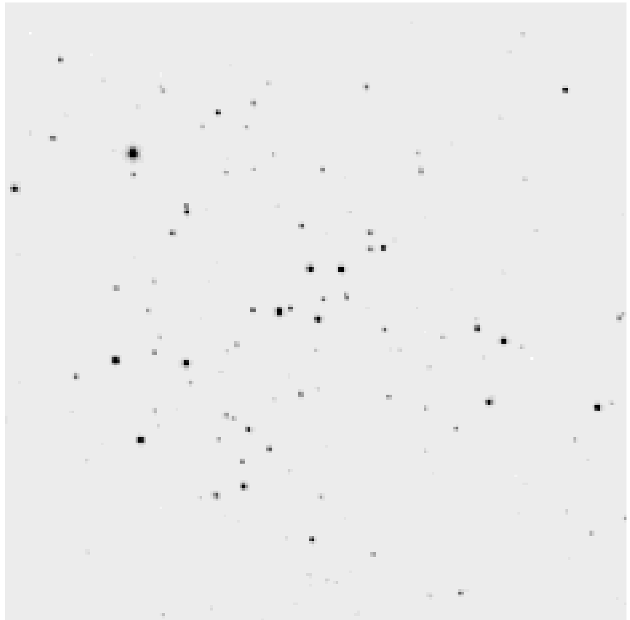

Figure 3: An image of the star cluster M93, with colours inverted. Black points are areas with more light detected, i.e. the stars.

- Images of the cluster M93, in the filters B (blue), V ('visual', green), R (red) and I (infrared).
- A "flat field" image, to go with each filter used.
- A bias frame.

This data was taken by Dr Alicia Oshlack using the 40 inch telescope owned by Mount Stromlo and Siding Spring Observatories. This telescope has now been decommissioned, and is no longer used for astronomical research. The exposure times for these images were not all the same. The B, V, R and I images had exposure times of 60, 7, 5 and 3 seconds respectively. These images have a pixel scale of $0.5''$/pixel. This is different to the pixel scale of T17, so keep this in mind!

3.2.1 Bias frames

Since CCDs are photon counters, one would expect that if an image was taken of nothing (i.e. just blackness) then the readout would be zero in all pixels. But this is not the case. In order to trap electrons in the pixels of the CCD, a voltage (or 'bias') must be applied across the pixels. This bias generates some additional counts in each pixel when read out. If this bias is known, then it can be subtracted from the real exposures so that only counts from real photons remain. Astronomy grade CCDs are designed so that this bias varies as little as possible between exposures so it can be accurately subtracted.

Thus, the bias frame is simply the readout from a zero-second exposure. You will notice when you examine the bias image that it is not perfectly uniform– there are random variations of a few counts between pixels. This is the "readout noise" of the CCD and is an unavoidable part of making measurements with CCDs. Astronomical CCDs are usually cooled with liquid nitrogen to minimise this readout noise.

Since the same CCD was used for all four exposures, only a single bias frame is necessary for all of the images.

3.2.2 Flat fields

Now, our telescope + CCD system, while very good, is not perfect. One fault is that the response to a uniform illumination will not be a uniform response across the CCD. Instead, there will differences in the response between different regions, and these differences will persist into observations of real sources. Typically, the throughput at the centre of the field is slightly higher than the throughput at the edges.

To account for these variations, so-called "flat field" images are taken. These images are of a uniformly illuminated source – such as a lit screen inside the telescope dome, or, as was used for these images, the sky at twilight (however, you have to be careful with twilight flats not to get too many stars appearing).

3.3 Reducing the Data

This section describes how to get your data into a suitable state to measure the magnitudes. This process is known in astro-speak as reduction (although sometimes it might create more images in the process!).

3.3.1 Basic Command Line

You will be using the command line in the terminal emulator which runs on the UNIX operating system. Your friendly demonstrators will be able to help you should you get stuck with using it. Your terminal will be very fussy about spaces and capitalisation, so keep an eye on this. For those who are not familiar, here are some basic command line for this lab:

- `cd DIR` — change directory to DIR
- `ls` — list directory contents
- `mkdir DIR` — make directory named DIR
- `cp FILE LOCATION` — copy FILE to LOCATION
- `pwd` — print current working directory

3.3.2 Accessing the data

First, log in to the Linux computer with your student credentials. Then, we'll make a copy of the data we need in a new directory in your home directory. This directory can have any name you like, it's indicated in the command below as `obsastrolab`. Open up a terminal and type[3]:

[3] ">" indicates the terminal prompt, you shouldn't type this character!

```
> mkdir obsastrolab
```

Open the "Observational Astrophysics" module in the LMS page for this subject. On the "Resources" page, you will be able to download the sample data and some sample code in the folder **XXXX**. Copy this data into your `obsastrolab` folder on the Linux computers.

Click the icon in the Gnome Launcher called Astroconda. This will open a preconfigured terminal that will allow you to work with AstroPy.

You now want to start the image display tool, called DS9. In the terminal, type:

```
> cd obsastrolab
> ds9 &
```

You can use the "File" → "Open" menu in DS9 to open images. You can open multiple images in the same DS9 window by opening a new frame. Choose "Frame" → "New frame" in the top menu bar to do this. Open up all of the `M93_[filter].fits` images in separate frames. Set the "Scale" to "zscale". Also check that "Edit" → "Region" is checked.

3.3.3 An Initial Look at the Data

Using your mouse, move the cursor slowly over the image. You'll notice a few things changing as you do this. The "Image" X and Y numbers are the X and Y pixel location of your cursor. The "Value" box gives the brighness of that particular pixel.

At this point it is worthwhile considering exactly what you are looking at. Consider the following questions.

1. When an image is displayed, some stars appear to have a larger diameter than others. What is going on? Is the size of the image of each star different?
2. Each pixel on this CCD has an angular size of 1/2 arcsecond. Assuming these stars are the same size as the Sun and 1104 pc away, calculate their angular size. How does this compare to the size you measure in the images? What is causing their images to be larger than this on the CCD?
3. You can move the cursor over the display window and the count value for pixels will be displayed in the "Value" box. Is there are difference between "large" stars and "small" stars?

We'll now make a star list of all of the stars in the image. This is just a list of all of the stars and their locations. In DS9, zoom in on the image with your mouse scroll wheel, and mouse over the standard star indicated in Figure 4. If you click on the star, a green circle or **region** will appear. Clicking on the edge of this circle will allow you to move it around on the image. Make sure it is centred over the standard star. Then, place regions on all of the stars in the image. You should have around 80-100 stars in M93, so this may take a little time.

Once you have placed regions on all the stars, you can save them as a text file:

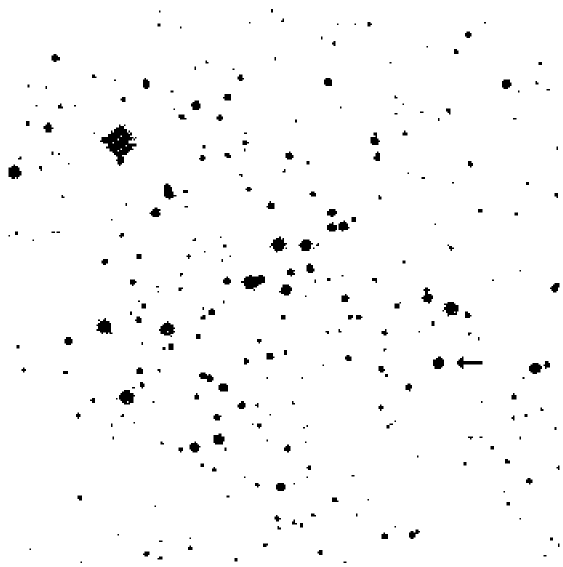

Figure 4: Open cluster M93, the arrow points to the standard star.

1. Click “Region” → “Save Regions...”
2. Name the file as `M93_starlist.txt` or similar. The default name will be `ds9.reg`, and we will make another starlist with our own data once it has been taken, so including the name of the target is good practice.
3. Choose “Format: X Y” to save the file as a list of coordinates.
4. Save another copy of the regions as a regular `.reg` file, in case you need to load them into DS9 again later on.

Important! You only need **one** star list for all of the filters for one target. So, you won’t need separate star lists for the $BVRI$ filters for M93, but you **will** need a separate star list for your object that you observe with iTelescope, which will then be used for all of the filters that object was observed in. You can follow these same directions to make that star list when your data is taken.

3.3.4 Processing the data with AstroPy

In order to reduce our sample data[4], we’ll use the free Python package, AstroPy, and some other associated/affiliated packages. Since our FITS data is essentially a three-dimensional array, we can read in the data and store it as an array and perform calculations on it. We will be using the package `ccdproc` to reduce our data.

All you need to do to your images is to remove the effects of both the bias and the flat field. The total number of counts in a particular pixel (x, y) is given by

$$C(x, y) = S(x, y) \times F(x, y) + B(x, y),$$

[4]The iTelescope data does not need to be reduced, since it is already processed before we download it.

where S is the signal (the interesting part), F is the flat field contribution and B is the bias. As you go through this procedure, use DS9 to make a note of how the background noise changes as you first account for the bias, and then the flat field.

We have provided a sample script that guides you through the reduction process with `ccdproc`. It is written in Jupyter notebook, an easy way to write small scripts in many different languages. To use it, in your Astroconda terminal, type:

```
> jupyter notebook &
```

This will open a web browser with a file system. Search for the file `XXXX` and open it up. You will write your code for the rest of this lab in here. Each new chunk of code can be written in its own cell. You can add notes as well by changing the cell type to "Markdown". To run a cell, press either the "Run" button or type Shift+Enter. The first cell has all of the packages you will need for the rest of this lab. Make sure to run it first!

This sample file contains the steps for the B-band only. You will need to add to the code to reduce the V, R and I images. The steps for reducing the data are:

1. Read in the FITS files with `CCDData`
2. Subtract the bias frame using `ccdproc.subtract_bias`
3. Flat-field correct the image using `ccdproc.flat_correct`
4. Save your reduced image as `M93_[filter]_reduced.fits`

Open up your reduced image in a new DS9 frame. Is there any noticeable difference between image before and after bias/flat-field correction? What about the background levels (i.e. blank spaces between stars), are they zero now? Is the background the same for all filters? The background is due to *sky brightness*. During the day, the Sun excites molecules in the atmosphere, which re-radiate at night. Most of the re-radiation is at specific (quantised) wavelengths in the V, R and I bands and the near-IR. Hence, the counts in your CCD measurements of stars also contain counts from the night sky. Luckily, the night sky uniformly illuminates the CCD just like a flat field. Your flat field corrections should make this background uniform across the CCD, hence it too can be compensated for in the next step.

3.4 Measuring the Brightness of your Stars

For this section, we will do the same process for both our sample reduced data for M93, and for your own iTelescope data. Be sure to keep these separate! You can just make two copies of the code, or make sure to tag your variables to keep them distinct.

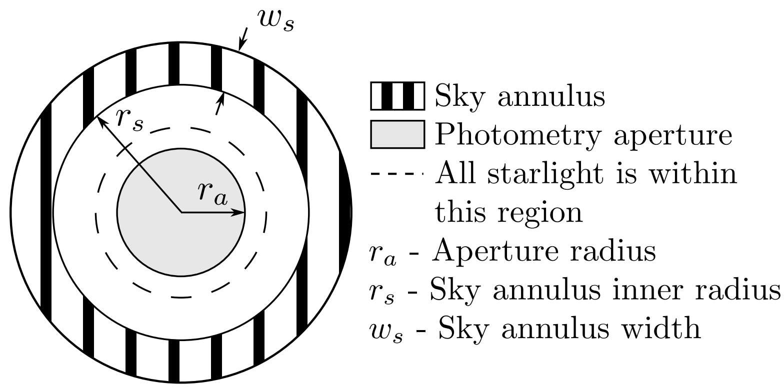

Figure 5: Parameters for aperture photometry

3.4.1 Aperture Photometry and the Point Spread Function

Once your images are fully reduced, you can go about measuring the brightness of the stars in the cluster. We will do this using a process called **aperture photometry**. Photometry basically means "measuring light", and an aperture is a hole placed over the image that defines the area covered by each star. We need to determine three parameters before we can run the photometry: the aperture radius, the inner radius of the sky annulus, and the width of the sky annulus. These parameters are shown in Fig. 5.

To measure our photometry, we will use the Python package `photutils`. This will take our star list we made earlier, and our reduced image, and add up the "value" of all of the pixels in an aperture that we set around each star. We use a circular aperture for the sample M93 data, since the stars appear as circles (and this is typical for stars generally), but `photutils` can also do elliptical apertures, which are useful for extended sources like galaxies, or if your telescope optics blur the stars.

In general, the steps for photometry are:

- Find the location of the centre of the star
- Add up the total flux within a circular aperture around this point
- Add up the flux within a surrounding annulus to determine the underlying sky brightness
- Subtracts the sky brightness from the aperture sum to determine the brightness of the star

Continuing in your Jupyter notebook you used in the reduction steps, you will find that the syntax for using `photutils` has been included for you. Using the FITS data stored in the `reduced` variable, we can simply pass our star list (which should be purely a list of (x, y) coordinates), and `photutils` will find that pixel in the FITS image, place an aperture r pixels in radius, and add the values for all the pixels in this aperture. We have set $r = 4.0$ pixels as the default, but you should check your image to find an appropriate number. For example of the considerations that go into determining the size of apertures, what is the seeing at Siding Spring Observatory currently? Find the radius in pixels of this number. You might notice for your iTelescope observation that the stars look more like ellipses than circles. `Photutils` can handle this as well.

Print out your photometry in the notebook. These numbers are purely the photons from that area of the sky that have reached the detector, and still contains light from the sky that we need to subtract. To subtract this light, we'll need to set an annulus around the centre of the star. Fortunately, `photutils` can easily make an annular aperture too! For the inner radius of the sky annulus, find the point at which there's essentially no stellar light, where the light gets to the background level. Record this as the inner radius of your sky annulus. In determining the width of this annulus you need to ensure that you include enough pixels to get a good statistical median of the local sky background, while not including too many neighbouring stars (don't worry if a couple of stars sneak in here and there – they shouldn't affect the median too much). We have used $r = 6.0 - 8.0$ pixels as the default.

Once you have both the 'raw' photometry and the sky annulus, all that's left is to subtract one from the other. Have a think about how to do this. Can you subtract one from the other directly?

3.4.2 Error analysis

You might be wondering how to find the error in your photometry measurements. This is a good question! To get an idea of the range of counts you could get for each star, repeat the photometry calculation for both the smallest and largest radius apertures you think are reasonable. Then, find an appropriate error for your counts.

4 Physical Properties of Stars

You will now have the brightness of each star in your image, and can now convert these 'counts' of photons into some physical properties of the stars.

4.1 The Magnitude System

The magnitude system is a holdover from the ancient Greek method for categorising stars. In this system the brightest star in the northern sky, Vega, was classed "magnitude 0". Fainter stars had higher magnitudes, with each increment in magnitude roughly corresponding to a factor of two reduction in brightness. With the advent of electronic detectors it was found that the ancient Greeks weren't all that good determining "a factor of two in brightness". However it turned out that they were very good at being consistent in their inaccuracies — each magnitude corresponded very closely to a factor of 2.51 difference in brightness. (More precisely, 5 magnitudes turned out to be factor of 100 in brightness, and $100^{1/5} = 10^{0.4} \approx 2.51$). In other words, the magnitude m of an object is related to its brightness f by

$$f = 2.51^{-m+c} \tag{1}$$

where c is a constant which we're going to determine. In practice, this equation is usually rearranged to give:

$$m = -2.5 \log_{10}(f) + c. \tag{2}$$

Derive this form. For two sources, the difference in their magnitudes is proportional to the ratio of their fluxes:

$$\Delta m = m_1 - m_2 = 2.5 \log_{10}(f_2/f_1) \tag{3}$$

4.2 Calibrating your data

To figure out the magnitudes of our stars we need to calibrate the arbitrary flux units ('counts') we've measured into something more physical. In essence, we need "c" from the above equation. This constant depends on the size of the telescope (big telescopes collect more light, so you get more counts), the efficiency of the CCD (more efficient detectors get more counts), the filter (even the best filters loose some of the light), and the atmosphere (haze or dust absorbs or scatters the starlight before it reaches the telescope). Astronomers use images of standard stars to perform this calibration. These are stars of known (non-variable) brightness, whose magnitudes and locations on the sky are catalogued in long lists.

4.2.1 M93 sample data

In our case we don't need a separate standard star image, because we know the exact brightness of one of the stars in M93. This is the star indicated with an arrow in Figure 4, which, hopefully, you placed at the top of your list. The apparent magnitudes for this star in our four bands are:

- $B = 10.23$ mag
- $V = 10.14$ mag
- $R = 10.15$ mag
- $I = 10.18$ mag.

Use your measured counts for this star, along with these apparent magnitudes, to determine the calibration constant c for each filter. Each constant is valid for all the other stars in that image. Now calculate the apparent magnitudes of all your stars in each image. You can use the calibration constants and Equation (1) to calculate the apparent magnitudes of all of your stars, or you can just take the ratio of fluxes and use Equation (3).

From apparent magnitude we can calculate absolute magnitude (M). Absolute magnitude is defined as the magnitude a source *would* have if it were at a distance of 10 parsecs. You can find absolute magnitudes using this equation:

$$M = m + 5 - 5\log_{10} d \tag{4}$$

where d is the distance to the star in parsecs. This, of course, relies on the assumption that all the stars are at the same (known) distance. Can you figure out how this relation is derived? Since magnitudes are logarithmic, the distance scaling factor $(d/10\,\mathrm{pc})^2$ becomes an additive constant $(5\log_{10} d - 5)$ between apparent and absolute magnitudes. This factor is called the "distance modulus", $\mu = m - M$. Using the known distance (1104 pc) to the cluster, calculate the absolute magnitudes of your stars for all filters.

4.2.2 iTelescope data

Since you had the choice of open clusters to observe, you will need to find your own standard star for your iTelescope images. Fortunately, almost every star has been imaged and catalogued, so we can look up stars using the service Simbad.

Open up `https://simbad.cds.unistra.fr/simbad/` in your browser, and choose to search "By identifier". Type in one of the common names of your star cluster (e.g. the NGC, Messier or Caldwell number) and you should be taken to the main data page for the cluster. Scroll down to "Hierarchy" and click on the "Children" button with "Display criteria" set to "stars". This will give you a list of all of the stars in the cluster. Find the brightest star and open up its catalogue page[5]. From here you should have magnitudes in several different filters available. Find this star in your star list (you may need DS9 up to find its coordinates). Repeat the calculations from the previous section to find the magnitudes of all of your stars.

4.3 Plotting the Hertzsprung-Russell Diagram

You now have magnitudes for a group of stars, using two or more filters. You can use them to create a Hertzsprung-Russell diagram, a plot of 'colour' against brightness. (Hence, the HR diagram is also often called a 'colour-magnitude' diagram or CMD.)

'Colour' in astronomy is not colour like the colours of the rainbow. It is defined as the *ratio of how bright a star is when viewed through two different filters*. Remember that ratio of brightnesses is the same as the difference in magnitudes (just from the usual logarithm laws). If, for example, the magnitude of a star observed through the green filter is V, and its magnitude when observed through a blue filter is B, then its colour could be measured as $B - V$.

- If the object is relatively brighter in green light, compared to blue light, then its $B - V$ will be a positive number. Astronomers would say it had a "red" colour, even though it is actually the blue and green light which is being considered.
- If the object is brighter in blue light than green, its $B - V$ will be negative. It would then have a "blue" colour.

[5]This should be the brightest star **in your image**, which may not necessarily be the brightest star in the whole cluster. Use the DSS image visualisation on the star's Simbad catalogue page to identify it and ask your demonstrator if you are unsure!

For all the objects in your CCD frames, compute colours, and plot these colours against one of the absolute magnitudes (eg. M_V against $B - V$). (You will need to be careful of your axis directions.) This is an HR diagram!

Now, consider the following:

1. Can you see a line of stars; a main sequence? If you see a main sequence, do you see stars in any other regions in the diagram?
2. Compare your diagram to the colour-magnitude diagram in Fig. 6 and see if you can figure out what types of stars are present in this cluster. Note that this HR diagram covers a wider range of absolute magnitude and colour than your plot, so be careful when identifying stars which are off the main sequence.
3. How does your HR diagram compare to the example in Fig. 6? We mentioned that Fig. 6 covers a wider range of colours and magnitudes, can you think of why this might be? Why are you missing especially blue and red stars?
4. Do you have outliers that don't fit in any of the regular regions on the HR diagram? Make a note of these. Outliers can be stars that are too faint in one image, or are so bright that they are saturated and have not had their photometry taken accurately. Or, they could be artifacts in the image that aren't even real! Checking the original images in DS9 will give you an idea of what is happening.
5. Do you get the same or similar HR diagram if you use a different set of magnitudes? (ie. R and I instead of B and V) If there is any discrepancy, can you explain why? You will need to think carefully about this: what exactly does colour measure? If stars are just black-bodies, when would you expect colours to be the same or different?

4.4 How luminous are the stars?

We will now take our photometry measurements and attempt to work out some of the physical properties of the stars in the cluster. To work out how bright our stars really are, we must first convert from magnitudes into energies. The star Vega is apparent magnitude zero in all filters (by definition), so we can use its known brightness at different wavelengths (Table 1) to calibrate our magnitudes to SI units. These *brightnesses* are in units of flux per unit wavelength; ie. the energy hitting a square metre every second with wavelengths in a 1nm range. The units of *luminosity* of a star is just energy per second per unit wavelength; ie. it is the total energy the star radiates at this wavelength, not just the amount that hits a square metre area at the Earth.

A very important note! The standard star in your M93 images **is not** Vega! As mentioned, Vega has an apparent magnitude of zero, whereas the previous standard star has an apparent magnitude around 10 in the different filters. This star is 10,000 times fainter than Vega is! We call it a "standard star" because its flux has already been calibrated to Vega.

Using Table 1 and the definition of magnitudes discussed in the preceding section, work out the flux your stars are producing at the different wavelengths. This tells you how much radiation from the stars are

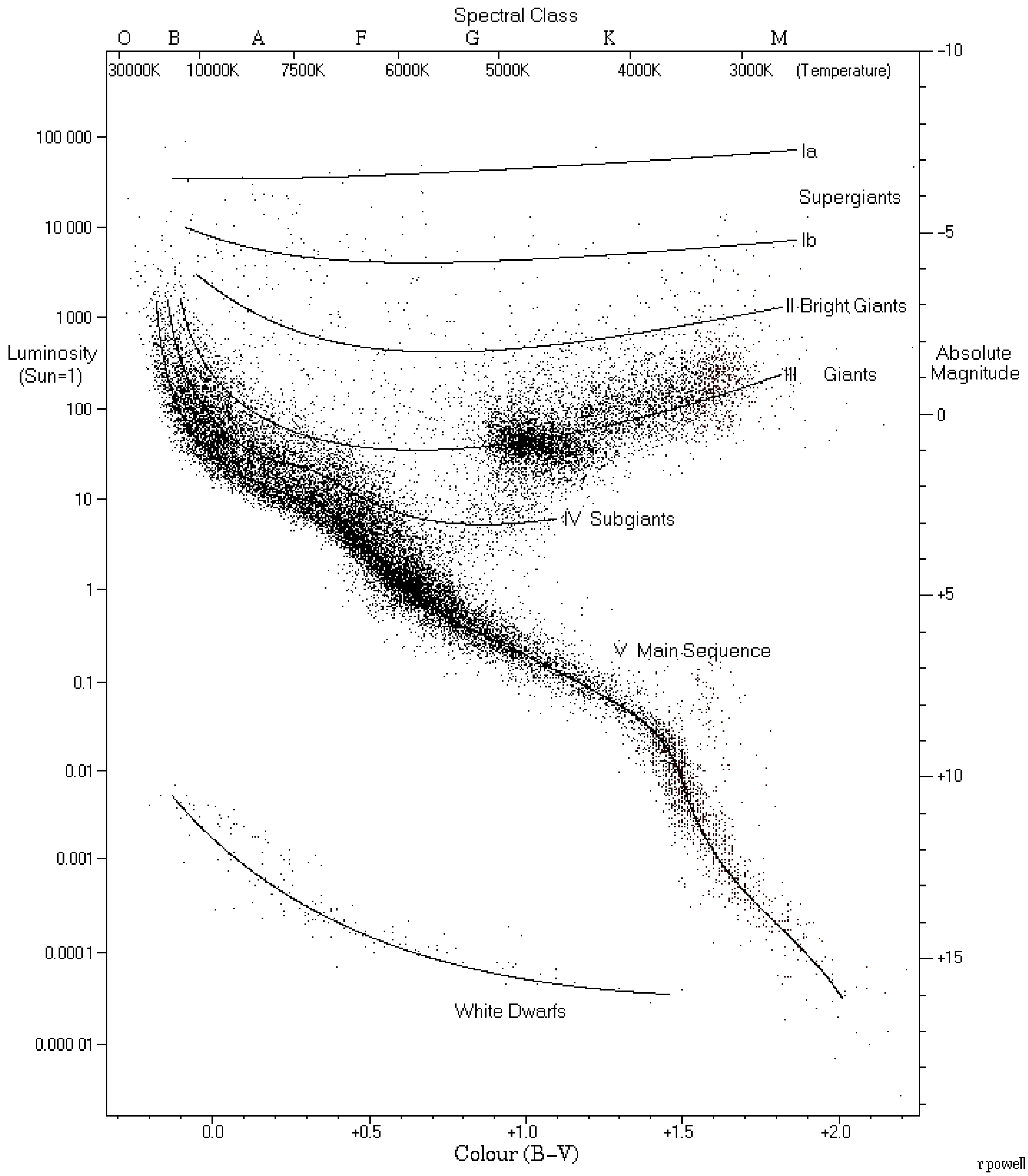

Figure 6: HR diagram. Image source `http://www.atlasoftheuniverse.com/hr.html`.

Filter	Central Wavelength	Flux of Vega	Luminosity of the Sun
B (deep blue)	440nm	$6.3 \times 10^{-11}\mathrm{Wm^{-2}nm^{-1}}$	6×10^{23} W/nm
V (green)	550nm	$3.6 \times 10^{-11}\mathrm{Wm^{-2}nm^{-1}}$	6×10^{23} W/nm
R (dark red)	700nm	$2.2 \times 10^{-11}\mathrm{Wm^{-2}nm^{-1}}$	4.5×10^{23} W/nm
I (infrared)	880nm	$1.1 \times 10^{-11}\mathrm{Wm^{-2}nm^{-1}}$	

Table 1: The four standard filters, and the flux per unit wavelength of Vega when observed through each.

reaching the Earth. Using the distances to the clusters[6] and the inverse square law, work out the total luminosity of the stars. How do they compare with the sun's luminosity? Are these giant stars, or are we seeing things like the Sun? Or are we seeing things fainter still, like brown dwarfs, red dwarfs or white dwarfs?

The very brightest stars known may have luminosities as much as a few thousand times that of the Sun. These are the rare supergiants; some red (very old stars bloating out in their dying moments) and some blue (very young, very hot stars). Do you have any of these? If so, are they red or blue?

4.5 Stellar temperatures and other properties

The radiation from most stars can be approximated as black body radiation. We can use this fact, along with measurements of the stars luminosity through two different filters, to measure the temperature of the stars.

The black body radiation law (Planck function) is

$$F_\lambda = \frac{2\pi c^2 h}{\lambda^5} e^{-\frac{hc}{k\lambda T}} \tag{5}$$

where F_λ is the flux per unit wavelength emitted by a unit area, h is Planck's constant, c the speed of light, k the Boltzmann constant and T the temperature.

Use this equation to derive the ratio in flux at two different wavelengths as a function of T. Hence, with this equation, take the magnitudes measured through two different filters and use this to derive the temperatures of your stars. Repeat the calculation with a different pair of filters. How do the temperatures change?

Now, consider the following:

1. How hot are they? The Sun has a surface temperature of about 6000 K. How do the temperatures compare to that of the Sun? Do they all have similar temperatures or is there a range? Is there a correlation between brightness and temperature?

[6] M93 is at a distance of 1104 pc, and the cluster you observed will likely have distance recorded on its Simbad catalogue page.

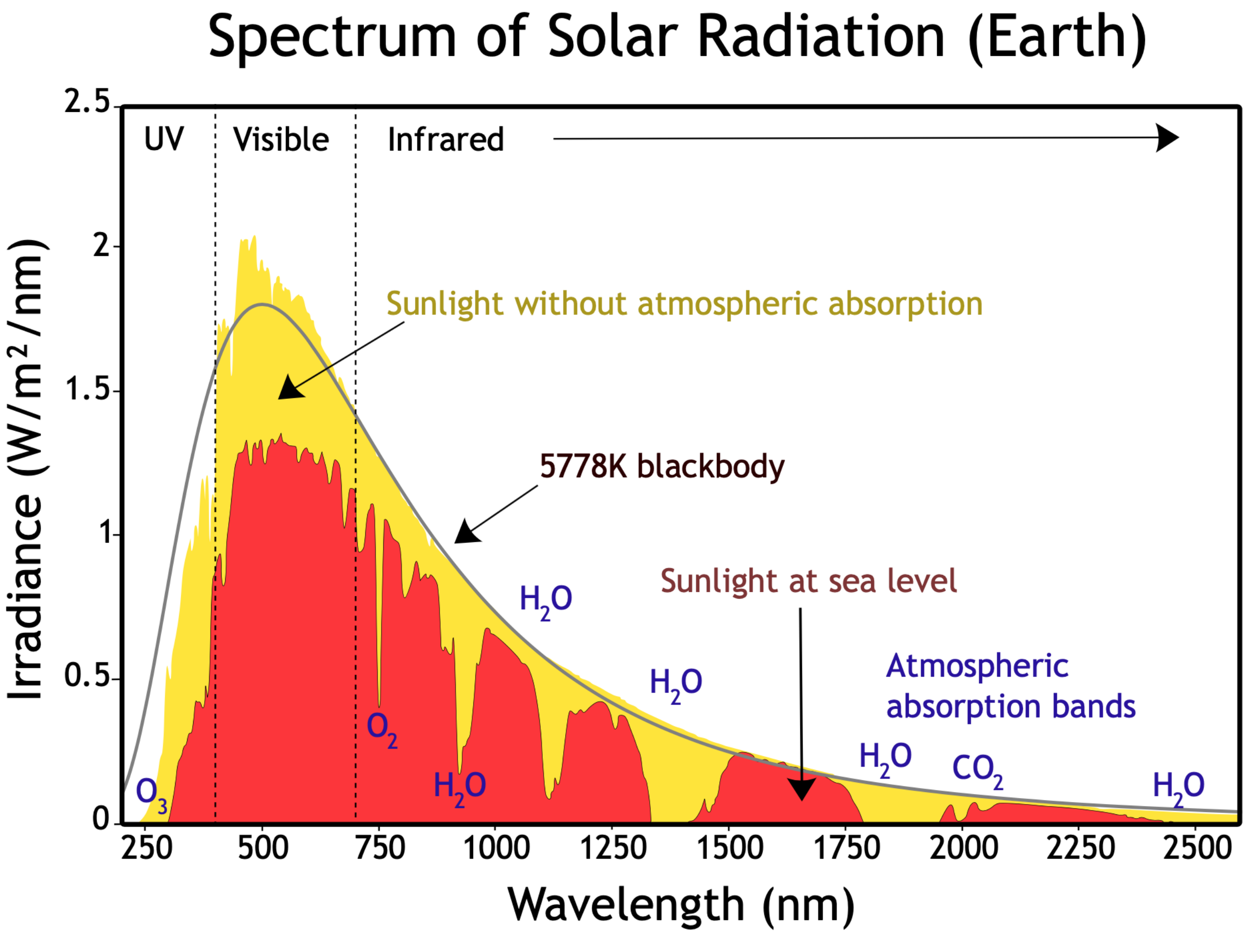

Figure 7: Spectrum of the Sun. Yellow filled spectrum: the spectrum of the Sun, measured from an extraterrestrial telescope, without absorption from the Earth's atmosphere. Red filled spectrum: the yellow spectrum after it has passed through the Earth's atmosphere. Black line: the black-body spectrum that best matches the solar spectrum, giving an effective temperature of 5778 K. (Source: Robert A. Rohde, 2008)

2. Use the Planck function to derive the surface area of your stars and hence their radii (be careful converting units! You will need to do a dimensional analysis). For comparison, the Sun has a radius of 7×10^8 m. How do they compare?

3. Some of your stars are very luminous. The luminosity of a star goes as roughly their mass to the power 2.5 (ie. $L \propto M^{2.5}$) for main sequence stars like the sun and blue supergiants. How massive are these things compared to the Sun? The Sun has an expected lifetime of 10^{10} years: how long will these ones last?

4. Do you think your stars are perfect black bodies? What sorts of things could affect the actual spectra of stars? Consider both inherent to the stars, and also observational effects. Figure 7 may help with this.

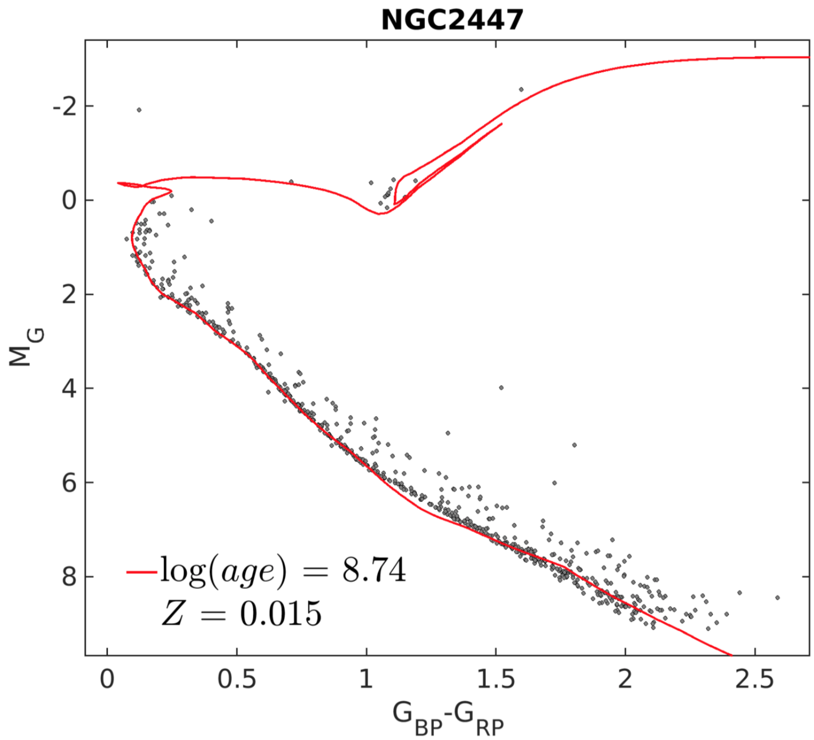

Figure 8: HR diagram of M93 from *Gaia*. (Gaia Collaboration, 2018)

4.6 The *Gaia* HR diagrams

M93 is just one star cluster out of many we have discovered in the Milky Way. As we have discovered, star clusters are very useful in working out the properties of stars, given our assumptions that they are all the same distance from us and that they formed at the same time. By making HR diagrams of many star clusters, we can see how stars evolve. Calculating the ages of stars is very difficult, so we will just do a quick comparison here.

The *Gaia* satellite is a telescope that is currently observing all of the stars in the Milky Way, in order to get very precise distances to these stars. As part of this, it has measured many star clusters, including M93. By looking at the HR diagrams of many different clusters of different ages, we can see how the positions of stars on the HR diagram change as they age.

Open up the link `https://sci.esa.int/gaia-stellar-family-portrait/` and scroll down to the HR diagrams. The default view will be "All 47 clusters". Click on each of the clusters in turn and observe how the main sequence changes for each of the clusters. Which do you think is the oldest and the youngest? Where does your main sequence for M93 fall?[7] Can we tell how old M93 is from this data?

Figure 8 shows the HR diagram for M93 from the second *Gaia* data release. The authors have fitted an isochrone (the red line) to this HR diagram, where an isochrone is a line where stars are all the same age but vary in mass. This line is increased in age until it fits the main sequence at the red end of the main

[7] *Gaia* uses different filters to our data, so the main sequences will likely not fit exactly.

sequence and also any red giants present. The isochrone that fits the data best has $\log(age(\text{years})) = 8.74$. Convert this number to years. Does this age for the cluster match up with the lifetimes of stars you calculated earlier? How much longer do you expect the cluster to last for?

5 References and further reading

- Bessell, M S (2005) "Standard Photometric Systems", *Annual Reviews of Astronomy and Astrophysics*, vol 43, issue 1
- Gaia Collaboration (2018) "*Gaia* Data Release 2: Observational Hertzsprung-Russell diagrams", *Astronomy & Astrophysics*, vol 616, A10
- Hogg, D W (2022) "Magnitudes, distance moduli, bolometric corrections, and so much more", `https://arxiv.org/abs/2206.00989`

5.1 Software information

- AstroPy: `https://www.astropy.org`
- `ccdproc`: `https://ccdproc.readthedocs.io`
- `photutils`: `https://photutils.readthedocs.io/en/stable/`
- SAOImage DS9: `https://sites.google.com/cfa.harvard.edu/saoimageds9`

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