Open Clusters, the HR diagram and Stellar Evolution

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1 Introduction

In this experiment you will use data of a galactic cluster and reduce and analyse the data. We will use data obtained from the internet (from a reliable source). The data analysis procedure would have been very similar to that which you followed in analysing the images to construct the time series of the Cepheid variable in experiment. In view of the fact that you have followed this procedure already, we therefore proceed to give you the reduced and calibrated data and work from there.

The aim of the experiment is that you use B and V magnitudes for as many stars as possible in an open cluster, and then construct the color-magnitude diagram. This diagram can then be used to determine the distance to and the age of the cluster. Of course, these are approximate values only.

2 Preparation

In order to do this experiment successfully you will have to do some reading on your own. You are supposed to already have a lot of physics knowledge at hand and should be able to read some literature independently of your lecturer.

The following points are important:

- As you may know, the intensities or brightness of stars are given in magnitudes. Make sure you know how the magnitude scale is defined.
- You will construct a so-called colour-magnitude diagram. I am not going to show you how to do that or what to plot against what. Make sure you know what a colour-magnitude diagram is and how it relates to the Hertzsprung-Russell diagram. Make sure you understand why the difference between, say, B and V magnitudes of a star, is refered to as a colour and how it relates to the temperature of the star.

- I have refered to open star clusters a couple of times above. Find out what open clusters are, where they form, and why they are so important for studies on stellar evolution.

- Interstellar space is not empty but is a very low density gas that also contains dust particles. The dust particles scatters and absorb light in a frequency dependent way leading to what is known as interstellar reddening or interstellar extinction. I don't expect you to know all the details about interstellar redding but you have to know what it is and what its effect is on the colours of a star. Since you will have to correct for interstellar reddening you must know these things.

- You are going to estimate the distances to an open clusters using the method of main-sequence fitting. In this process you will have to use something that is known as *the distance modulus*. If you don't know what it is, find out.

The following two points are on slightly more advanced topics in stellar evolution. You might have to spend more time understanding them.

- Metallicity: Make sure you know what the term metallicity means in Astronomy. Also read how the initial metallicity of the gas from which stars form determine the evolution of stars.

- Isochrones: To determine the age of star clusters we make use of stellar evolution models. These models predict the position of stars of different masses on the HR diagram at different times in the evolution of a star. In analogy to words like eg *isobar* which means a line connecting points of equal pressure, isochrone denotes a line on the HR diagram for stars of different masses but with the same age.

- Evolutionary tracks: This gives the position of a star of a given mass on the HR diagram at different times. We will not deal with evolutionary tracks but you will come across this term in the literature.

Literature

You can consult the following books on the topics above and on astronomy in general.

1. **An introduction to modern astrophysics**: Carroll & Ostlie
2. **Evolution of stars and stellar systems**: Salaris & Cassisi
3. **Astronomy: A physical perspective**: Kutner
4. **Astrophysics in a nutshell**: Maoz
5. **Astronomy: From Earth to the Universe**: Pasachoff
6. **Astronomy & Astrophysics**: Zelik & Gregory
7. **Introductory Astronomy**: Holiday

3 The experiment

You will be given the B and V **apparent magnitudes** of stars for two open clusters and the observed metallicity of the clusters.

- Construct a colour-magnitude diagram for the clusters. Note that on the y-axis the V magnitude should increase from top to bottom. See examples of colour-magnitude diagrams in the literature.
- Use the CMD 2.2 input form found at

  `http://stev.oapd.inaf.it/cgi-bin/cmd`

  to calculate isochrones. Use the recommended code of Marigo et al (2008). For the photometric system use the UBVRIJHK system. Do not include circumstellar dust and set the interstellar extinction to zero. We will correct for that later. You can ignore the input for the initial mass function.
- Since we work with a cluster of stars that are for all practical purposes of the same age, all the stars should lie on an isochrone - make sure you understand what an isochrone is! We should therefore generate a number of isochrones with the CMD code and compare it with the distribution of stars on the colour-magnitude diagram. If we find a good fit to the observed data for a particular isochrone we also have the age of the cluster.

- At this point it is usefull to generate a number of isochrones with the CMD model and plot it on the same graph as the colour-magnitude diagram for one of the clusters. This is just to give you a feel for what the output from the model looks like and how it compares with the data. I would suggest that you generate single isochrones and not multiple because it becomes a time consuming thing to extract the ones you want if you generated multiple ones. Of course, it is your choice in the end.

- You should also generate an isochrone for the lowest possible age allowed by the models. This will give you the main sequence on the colour-magnitude diagram. It is best to plot this main sequence on each of the color-magnitude diagrams of the two clusters that you are going to analyse since it will give you a reference also for isochrones of larger ages.

- You will see that you have to give a value for the metallicity Z. In reality, Z can be measured observationally. So it is not really an unknown. The metallicities of the two clusters of which the data is supplied to you is: NGC 6231: Use solar metallicity; NGC 2243: -0.44. The latter value is metallicity defined as follows: If the metallicity of the Sun is indicated by $Z_\odot$ and that of an arbitrary star by Z, then the latter two values is defined as $\log_{10}(Z/Z_\odot)$. From this you can calculate the correct number for input in the CMD code.

  To understand the effect of Z on the isochrones you should now conduct a small study within the experiment. For this generate a number of isochrones with different values of Z. For example, for a fixed age of 10^6 years, generate isochrones with Z = 0.03, 0.019, 0.010, 0.005, 0.001 and plot them on the same graph. Then change the age to 10^7 years and do the same. Also do for ages 10^8 and 10^9 years.

  This small study will then generate a number of graphs. Use these graphs to understand what the effect of Z is. **BUT** I would like you to think about what the physical reason is behind the observed behaviour of the isochrones as a function of Z! (This is what a physicist does - try to understand the fundamental reason for why we see certain behaviour) In your report you should describe the dependence on Z as seen in the four graphs and also give your explanation of why you think this is so.

- Having a feel for what the effect of Z is, the next thing to do is to fit an isochrone to the data. You will see (if you have the y-axis correct) that the isochrones lie way above the data and that to fit the data either the data has to be shifted up or the isochrone have to be shifted down. **Why is there this offset between the data and the model**

results? I am not going to give the answer to this but would suggest that the data be moved up. If you shift the data up, make a note by how much, in magnitudes, you had to shift it.

- You will also see that in order to get a good fit (we will define later what we mean by a good fit) it also might be necessary to move the data horizontally, ie. add or subtract something to the observed B-V values. Also in this case I am not going to tell you why you have to shift the data horizontally! If you shift the data to the left or to the right make a note by how much! I want to make the statement that the data has to be shifted to the left and not to the right. **WHY?** You have to give the answer in your report and justify it!!

- So what do we mean by a good fit? You will notice that while the isochrone is a line, the data for the clusters do not lie on a thin line. The main-sequence as seen in the data is NOT a thin line - there is a spread in both V and in B-V. (Note that we have not included errors here). While it certainly is possible to apply a least squares fit of an isochrone to the data, we will not embark on such an effort here. What I would suggest is that you try to find as good a fit as possible by simple visual inspection. I realize that there is some subjectiveness in this but lets do it like that for now. Using a bit of common sense will tell you what a good fit is. And we can discuss it as well so don't worry too much.

4 The report

Here are some specific tips for your report:

The Introduction should include a logic development to the point where you define the aim of the work. You should thus start off with discussing things like the question about how stars evolve (do they evolve at all?), why star clusters are important etc. At the end of the discussion the reader should know exactly why you want to do this work and what it is you are going to do. The Introduction should not be shorter than one A4 page (11pt font)!!!

You have not conducted an experiment in the strict sense of the word, ie. by actually using equipment. This does not mean you have nothing to say about the methods you used.

The results section should contain the graphs showing the colour-magnitude diagrams of the two clusters. Describe to the reader what you see and what should be looked for.

As said in the manual, the discussion section is where YOU have to demonstrate that you understand the problem. Here you should put in the graphs about the effect of Z and discuss it. Note that these are not part of the results. Of course you have to tell the reader why you did it. It must form an integral part of the discussion. You can then show graphs for the relation between the original data (not shifted) and some isochrones for the observed metallicity and point out to the reader that they are offset - here you should tell me why you think they are offset, not only in V but also in B-V!! **I want to see this in the report.** Finally you can show two graphs showing the final fit of the isochrones to the data.

As I have pointed out above, shifting the data in V and in B-V have physical meaning. What do you derive from the shifts in V and B-V. The quantities have specific meaning. How do you get to the distance to the cluster - show the reader. How do you determine the interstellar reddening to the source and what value does it have? What is the age estimate for the cluster? Can you perhaps assign an error to the age? Is there only one isochrone that explain the data? Would you expect a relation between age and metallicity? Explain.

For the NGC 6231 it is also known that this cluster has β Cepheid stars. Find out what these stars are. Is the age that you estimated for this cluster in agreement that this cluster still has β Cepheid stars?

Also compare the outcomes for the two clusters. Do they have different ages? Is it significantly different? What does this difference tell you about star formation in the Galaxy - is it an ongoing process? Justify your answers. Compare the distances and the interstellar reddening of the two clusters. Is it necessarily so that the cluster that is at the further distance have a larger reddening. If it is not so what do you conclude? As you can see there are numerous questions that can be asked. I would say that the discussion part (including figures) should be a couple of pages.

The figures should be part of the text and be properly numbered. They should therefore not be appended at the end of the report. Figures should be clear and meet all the requirements that you have learned since the first year.

Finally, make some conclusions - remember this has to link to what you said towards the end of the Introduction. And make a bibliography list according to the guidelines given in the manual.

This is not a group project which means that each of you have to submit his/her own report. Note that a cross check between different reports will be made and that you may be seriously penalized if there is evidence that two or more of you have copied from each other. This does not mean that you cannot discuss your work with other people. Your report, however, should be your own work.

The following is more or less the weight of each section.

- **Titel/Title:** 2%

- **Opsomming/Summary/Abstract:** 5%
- **Inleiding/Introduction:** 15%
- **Metodes/Methods:** 10%
- **Resultate/Results:** 10%
- **Bespreking/Discussion:** 30%
- **Gevolgtrekkings/Conclusions:** 15%
- **Bibliografie/Bibliography** 3%
- **Neatness, use of language, figures, tables, general impression** 10%