ASTA33:
Galaxies and Cosmology

The Colour-Magnitude Relation for Elliptical Galaxies

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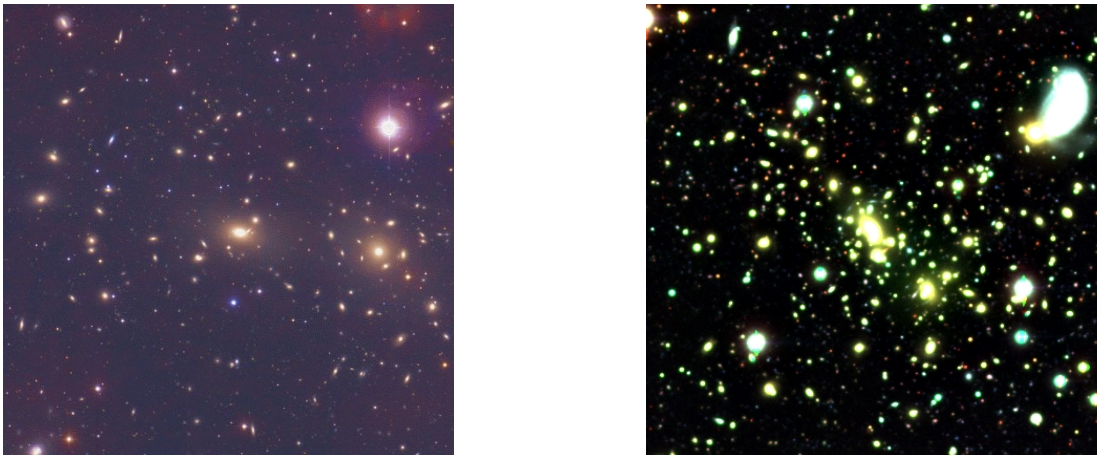


Figure 1: **Left:** Image of the Coma cluster. Notice the two super-massive elliptical galaxies which dominates the central region. **Right:** True colour image of the 1 Mpc central region of a distant rich cluster. Image constructed from individual exposures through blue (B), visual (V) and infrared (I) filters. Images from `http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html`.

1 Introduction

In the following experiment you will be measuring the colours and magnitudes of galaxies in a distant rich cluster from a CCD image taken with Hubble Space Telescope (HST). By plotting this information on a colour-magnitude diagram you can study the properties of the galaxy population in this cluster. By including information about the morphologies of the galaxies (from the high resolution HST image) into this analysis you can measure the relationship between colour and apparent magnitude for early-type (elliptical and S0) galaxies in the cluster. Finally, you can compare the predicted colour of a galaxy with known luminosity from the local Universe, with what you observed in the distant cluster, to estimate how much bluer early-type galaxies were in this distant cluster. Using the theoretical rate of change of colour for a mix of stars as a function of age you can then convert this observed colour difference into an estimate of the lookback-time to the epoch when the cluster is observed. This section starts with a brief overview of the properties of clusters of galaxies, before introducing two concepts which are necessary for completion of the lab: galaxy morphology and colour-magnitude diagrams.

Aims of the experiment

1. To introduce galaxy morphology.
2. To discuss the formation of galaxy clusters.
3. To illustrate measurements of colours and magnitudes of galaxies.
4. To map the relationship between magnitude and colour for galaxies in a rich cluster.
5. To compare the colours of elliptical galaxies in nearby and distant clusters. Then to use the bluing of the distant galaxies, along with the known colour evolution of stellar populations as a function of time, to estimate the lookback time to the distant cluster.

Clusters of Galaxies

Clusters of galaxies are the most massive collapsed structures in the Universe, the largest ones have central masses in excess of 10,000 × the mass of our galaxy. These very rich clusters are intrinsically rare objects, and most galaxies in the Universe inhabit the field, crudely defined as the lower-density regions outside clusters and voids. The most massive nearby cluster is the Coma cluster, see left image in Figure 1. The central regions of the Coma cluster is dominated by two super-massive elliptical galaxies. The extreme conditions found in such rich clusters including very high densities of galaxies, as well as large amounts of very hot gas which emit at X-ray wavelengths, make clusters some of the most luminous X-ray sources in the sky. More detailed information about clusters can be found in Appendix A.

The image to the right in Figure 1 illustrates a view of the central regions, 1 Mpc across, of a distant rich cluster. This is a true colour image, constructed from individual exposures through blue (B), visual (V) and infrared (I) filters. Note that the large numbers of yellow galaxies make up the majority of the luminous cluster galaxies (the large interacting spiral in the upper-right hand corner is foreground of the cluster). The strong central concentration of yellow, elliptical and S0 (see below) galaxies in the cluster can be readily seen, and the cluster centre is further highlighted by the massive dominant elliptical galaxy lying at the bottom of the cluster's potential well.

Galaxy Morphology and Elliptical Galaxies

A galaxy's morphology is a description of its structure, e.g. spiral or elliptical. This is typically estimated by eye from optical images, although modern image recognition techniques has been applied as well. A number of schemes have been constructed to classify galaxy morphology into different classes and in this way to attempt to understand the physical processes which define galaxy morphology and from this gain a deeper understanding of galaxy formation and evolution.

The major visible components of giant galaxies are the bulge and disk. The bulge is a roughly spherical cloud of stars in the central parts of the galaxy, this cloud is mostly supported by the random motions of the stars within it. The disk component is a rotationally supported, usually quite thin and extending to larger radii than the bulge component. The disk can also show spiral arms resulting from on-going star-formation in the gas-rich disk material. The bulge and disk are thus the morphological features which are typically used to classify galaxies. More specifically, the relative luminosities of the disk and bulge components, as well as the degree of contrast of the arms in the disk, is used for the aforementioned classification. The presence of a linear bar-like feature in the galaxy is also used to classify galaxies.

Figure 2 shows the classical tuning fork classification diagram of the Hubble galaxy morphology scheme. In the Hubble scheme galaxies are ranked based on the relative strength of the bulge and disk components using the following classes: 1) galaxies with a massive bulge, but no visible disk are termed Elliptical (E); 2) those with large bulges and a small disk void of clear spiral structure are lenticular galaxies (S0); 3) disc galaxies with various sub-types of spiral structure (Sa, Sb, Sc, Sd). The sequence of spiral sub-types has decreasing bulge luminosity compared to the disk light. There is a parallel sequence of barred spiral galaxies, and Elliptical galaxies are further categorised on the basis of their shapes: E0 (circular) to E7 (highly elliptical). The Hubble sequence is sometimes described as one from early- to late-type galaxies, going from ellipticals to spirals. Confusingly, early and late type applies to how the sequence itself is defined and does not have anything to do with galaxy age, in fact, late type galaxies are typically young, whereas early type galaxies are old.

Figure 3 shows a few examples of galaxies on the Hubble classification scheme. The descriptions in the figure caption applies to massive luminous galaxies. There are also a wide range of dwarf galaxies which share some of the same characteristics of the luminous galaxies, as well as classes of low-surface brightness galaxies and other peculiar galaxies, leading to a wide and rich variety of morphological classes. Furthermore, morphologies of galaxies in the distant Universe acquired with the Hubble Space Telescope indicate that an increasing number of galaxies at earlier epochs are hard to place within the confines of the standard Hubble scheme set out above. This implies that a galaxy's morphology

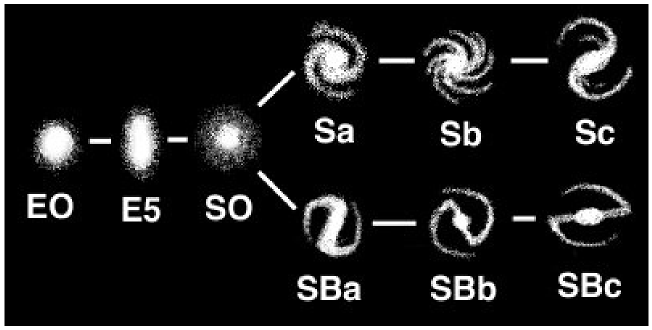
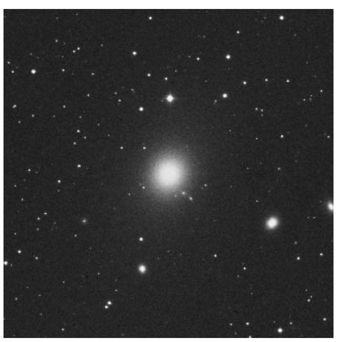
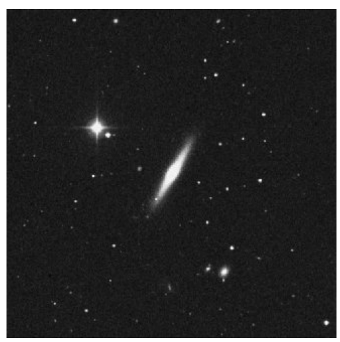


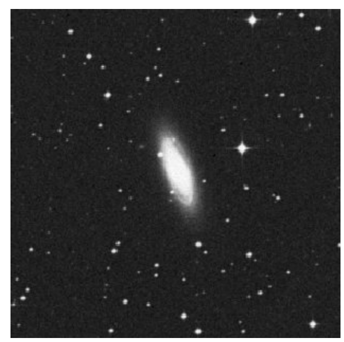
Figure 2: Hubble galaxy morphology scheme (Hubble fork), which is used to classify galaxies. Some observed examples are shown in Figure 3. See original work from Hubble (1926) for more information. Image from `http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html`.



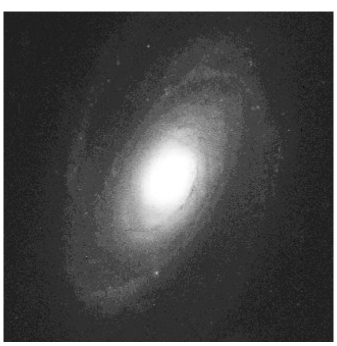
(a) **E**



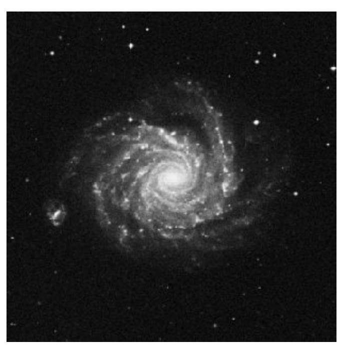
(b) **S0**



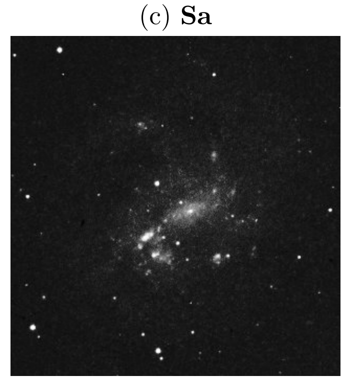
(c) **Sa**



(d) **Sb**



(e) **Sc**



(f) **Sd**

Figure 3: Images of galaxies of different morphological type: a) dominant bulge, no disc (**E**); b) strong bulge, small disc component (**S0**); c) strong bulge and spiral arms difficult to distinguish against the disc (**Sa**); d) spiral arms are obvious and weaker bulge (**Sb**); e) strong spiral pattern, weak bulge component (**Sc**); f) spiral arms break up into floculent structure, minimal bulge (**Sd**). Images from the Sky Scanner (SkyView: `https://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl`).

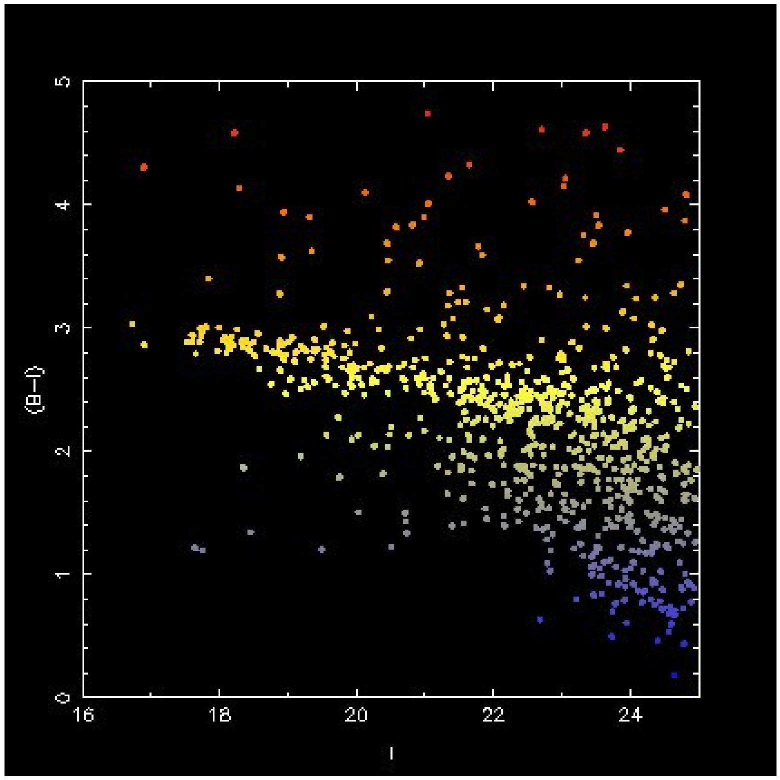


Figure 4: Example of colour-magnitude diagram for galaxies. The plot shows colour (B-I) (i.e. the difference in magnitude in the blue (B) and infrared (I) filter) as function of magnitude (in this case in the I filter) for the galaxies shown in the right image in Figure 1. Image from `http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html`.

can change over the course of its lifetime. Nevertheless, galaxy morphologies remain some of the most basic and most useful information which can be gleaned for a galaxy. The importance of morphology is shown by the good correlation between a galaxy's morphology and the rate of star-formation within the galaxy, with later-type spirals showing stronger star-formation. Another strong morphological correlation is between galaxy morphology and galaxy density - with early-type galaxies (E/S0/Sa) being preferentially found in regions of higher galaxy density (the cores of rich clusters of galaxies) and later-type spiral galaxies inhabiting the lower density surrounding regions (termed the "Field").

Colour-Magnitude Diagrams

The remainder of this lab will concentrate on the properties of the galaxy population of a massive cluster at high redshift. The majority of the bright galaxies in this cluster are early-type galaxies (E/S0). These galaxies show a strong correlation between their colours and their luminosities (or masses), with brighter (more massive) galaxies being redder and fainter/less massive ones bluer. An example of this is shown in Figure 4 which shows the colours and magnitudes of galaxies in a galaxy cluster. The galaxy colours are measured from the apparent magnitudes of the galaxies in two different regions of their spectra: through a filter in the blue (B) around 4500Å and one in the infrared centred close to 8100Å, called the I band. The colour is expressed as simply the difference between the magnitudes in B and I, i.e. (B-I). The strong linear feature between I=18-22 with a colour of around (B-I)=3 is formed by the E and S0 galaxies within the cluster. At fainter magnitudes this relation fades and a population of faint blue galaxies becomes apparent. The linear relation for the brighter

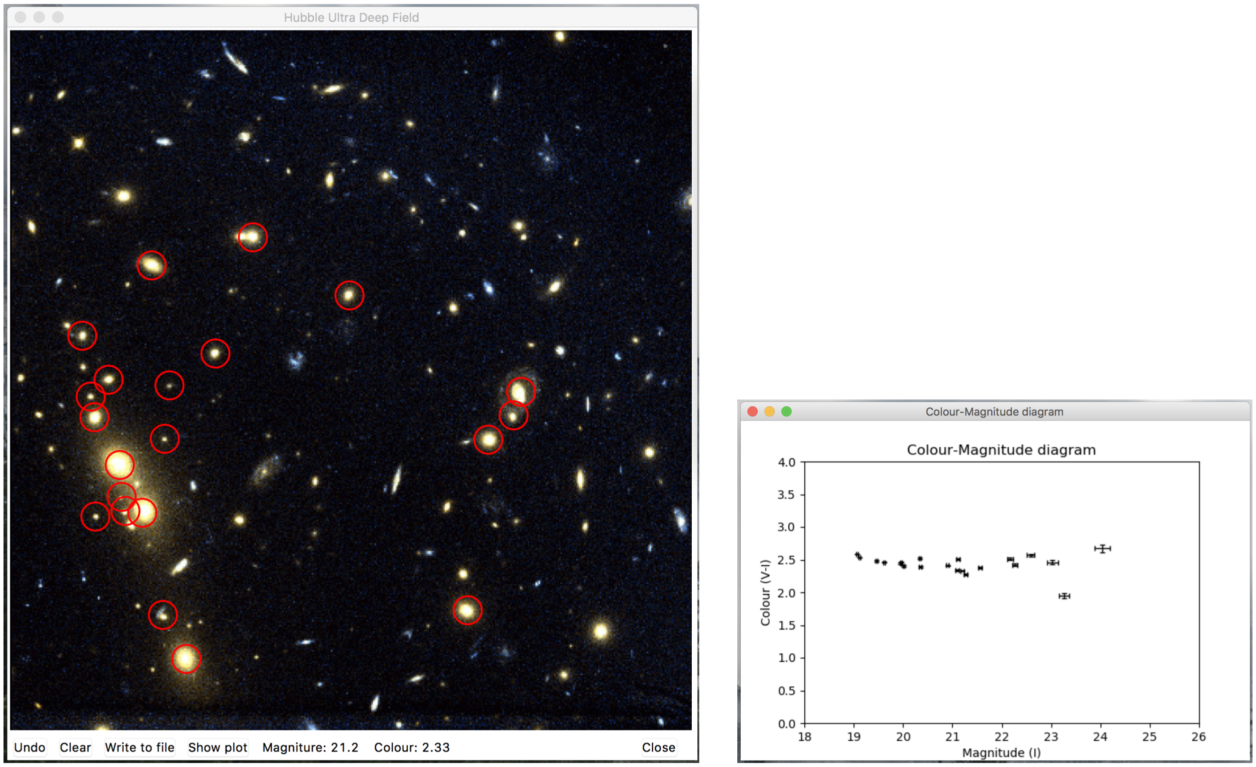


Figure 5: Example showing how the program looks when running.

galaxies indicates that most of the E and S0 galaxies within the cluster were formed via the same mechanism and that this mechanism couples the colour of the stars formed within the galaxy to the final mass of the galaxy.

One mechanism which can produce such an effect is the collapse of a single, massive gas cloud forming all the stars in the galaxy in a short period of time. The first supernovae from the initial burst of star-formation produce large quantities of hot gas which is enriched in heavy elements. The deeper potential wells of the massive galaxies can contain this hot gas and it is therefore incorporated into the next generation of stars which are formed. These stars then have higher metal contents and this tends to make them redder. The hot gas expelled by the supernovae in less massive galaxies can easily escape the galaxy and hence it is not used in the formation of the next generation of stars - which are therefore metal-poor and hence blue in colour.

The same relation between luminosity and colour appears to hold in different clusters at the same epoch. An important feature of the colour-magnitude (C-M) relation of early-type galaxies is thus that in the local Universe a specific luminosity of an early-type galaxy has a well-defined colour. We can use this relation to investigate the change in the colour of early-type galaxies in distant clusters resulting from the younger ages of the stars in these galaxies, which are observed as they were several billion years ago.

2 Experiment

Running the program

For this experiment you are provided with a Python program, `colMag`, which will return the colour and the magnitude of galaxies located in the core of the galaxy cluster C10016+16, see Figure 5 for an example. Make sure that you have Python 3 installed on your computer along with the packages numPy, PIL, tkinter and matplotlib. These are standard packages that should be installed if you have a distribution of Python from for example Anaconda. To install Anaconda visit https://www.anaconda.com/download/ and click Download on Python 3.X. When Anaconda has been successfully installed, download the **colMag** script (including the src folder) from Canvas.

The main script is colMag.py, which requires the data located in the src folder. Make sure to place the colMag.py script, as well as the src folder with its content in the same directory. The easiest way to run the script is to execute the prompt **python3 colMag.py** in a terminal on your computer[1]. For Linux and MacOS[2] this is straight forward since they are distributed with pre-installed terminals. For Windows one can access a terminal via Anaconda, called Anaconda prompt. Note that the program can be executed via Anaconda Spyder, however, the script will open clickable windows on start, which have a tendency to cause the Ipython terminal to crash. If this occurs then restart the kernel after exiting the colMag.py script. It is also possible to run directly from an Ipython terminal using the command %run colMag.py.

When the program is executed it will display an HST/WFPC2 image of the core of Cl0016+16 with 730×750 pixels in size, with each pixel being 0.1 arcsec. The field size corresponds to about 500 kpc in diameter for a Hubble constant of 50 km/sec/Mpc. This is a true colour representation of the cluster made by combining frames taken with V (visual, around 5500Å) and I (near-infrared, centred at 8100Å) filters. When you click the cursor the program will draw a circle on the image around the galaxy you've centred on and output the magnitude and colour of this galaxy. The total magnitude of the galaxy was calculated by integrating the light in the galaxy out to a radius where the brightness of the galaxy falls below the noise in the background sky. A small correction was then applied for the light which would lie outside of this radius. In contrast, the colour of the galaxy is measured within a small aperture (after subtracting the background light from the sky) of the galaxy with both I and V filters. The ratio of the fluxes in these two filters gives the colour of the galaxy.

The colour and magnitude is written both at the bottom of the image (for the current galaxy), as well as stored in the program. Additionally, the point will be plotted on a colour-magnitude diagram. To view this plot simply click the "Show plot" button on the bottom of the window, which will display the plot in a separate window. Note that this plot is updated as you click more galaxies. If you click a galaxy that you do not want, then click "Undo". When you have selected a few galaxies you can click "Write to file", which will ask for a prompt where you give the filename to which the selected galaxies will be saved. The program will save the galaxy Id number, the magnitude, the colour and the errors. Note that by default the data is saved in the same folder as the colMag.py script as a .dat file. Play around with the program and see if you make any interesting observations[3]. Try to figure out which galaxies appear to have early-type morphology (E or S0) and which have late-type morphologies (spiral and irregular galaxies), as well as where they appear on the colour-magnitude diagram. Note that some of the galaxies in the frame are too faint for the program to centroid on.

Collecting data

Before starting your measurements read through the list of aims given below, keep these in mind while you select and measure colours and magnitudes for galaxies on the CCD image. When you decide you

[1]Note that most terminals will start in the /usr/home/ directory. You can check the current directory using the command pwd. In order to navigate between folders in the terminal use the command cd. To navigate to a parent folder (i.e. backwards) use cd ../. If you place the the script in a folder ColMag in you home directory you can go to it by typing cd ∼/ColMag/, followed by python3 colMag.py to start the program.

[2]MacOS sometimes break the link between tkinter and the monitor making the program unable to run on such systems. If this is the case for you (that is, the computer restarts when running the script) then contact me.

[3]There are a few buggs in the program. Sometimes the red circles shown in left image of Figure 5 are filled. It's annoying but the program still works with the circles filled. If you find more buggs please report them to eric@astro.lu.se.

have a sufficient number of measurements to answer the questions save the data to a file. It is useful to collect several data sets for different types of galaxies and save them to different files.

By selecting galaxies from this true colour image of a small region in the distant rich cluster of galaxies Cl0016+16 (see picture below), the name gives a crude identification of the position of the cluster on the sky. You can investigate the structure of the cluster's colour-magnitude (C-M) diagram as a function of galaxy morphology and hence the colour-magnitude relation of early-type galaxies. The aim is to populate the C-M diagram sufficiently to tackle the following questions:

1. As you select galaxies note down their morphologies - a crude estimate, i.e. late-type or early-type, will be sufficient. You will need this information to complete your analysis. You should also note down any stars you might find. How faint (i.e up to what magnitude) do you feel you can reliably classify the galaxies into early- or late-type?

2. Notice the way in which the structure builds up in the C-M diagram as you select more galaxies. Can you identify any structure in the plot, what do such structures say about the properties of the galaxies in this distant cluster? Try selecting galaxies with similar colours, or with similar brightness, or all the galaxies with early-type morphologies. Which of these techniques gives the 'fairest' representation of the total cluster galaxy population? Which is the most efficient for defining the colour-magnitude relation for the early-type members of the cluster?

3. Estimate what proportion of galaxies in Cl0016+16 are early-type galaxies. What is a good way of defining this number: in terms of galaxies brighter than a given magnitude, or the fraction of the total number of galaxies in the cluster, or as a fraction of the galaxies within some area of the cluster? How did you go about measuring this?

4. The analysis section of this lab contains a number of measurements for you to perform using the fit to the C-M relation in Cl0016+16.

3 Analysis

Having completed your catalogue of galaxies in Cl0016+16, we now wish to fit to the colour-magnitude relation of the early-type cluster members - the strong ridge-feature which is apparent in your colour-magnitude diagram. We list below the main steps you'll have to complete to derive the relationship between colour and magnitude for the early-type galaxies.

1. Use a program of your choice to load the data that you collected. I encourage the use of Python and provide some simple scripts for loading the data, fitting a line, as well as producing a very basic plots of the data[4] in Appendix B.

2. Select a magnitude limit for your analysis. This should take into account both the observational errors on the colours measured from the CCD frame, and your estimate of the limit of your ability to distinguish early- and late-type galaxies. Remove all those galaxies fainter than this limit from your catalogue.

3. Next, we wish to fit to the colour-magnitude relation of early-type galaxies in the cluster. You should therefore use your the data selected with early-type galaxies, thus not accounting for any late-type galaxies.

[4] This laboratory exercise is primarily to investigate a galaxy group and not to sit and program. If you have any troubles with programming please do not hesitate to contact me (eric@astro.lu.se)

4. Fit the catalogue using linear fitting functions. You should take account of the errors on the individual measurements when you undertake your fitting.

Now, we compare the predicted colour of a galaxy with an apparent magnitude of I=21 from your linear fit to the C-M relation with that observed for a galaxy with this luminosity in the local Universe. We take into account just the shifts in the filter passbands for observations of galaxies at high redshift. This predicts that an early-type galaxy with an apparent magnitude of I=21 in Cl0016+16 should have a colour of (V-I)=2.68±0.03. What is the difference between this colour and that derived from your fit? Are your observations bluer or redder than the prediction and what might be the cause of this? Remember that you are observing the galaxies in Cl0016+16 at high redshift and hence seeing them as they appeared at substantially earlier epochs, due to the finite travel time for light, and that younger stellar populations tend to be bluer (as they have more young, massive blue stars in them).

The rate of change of (V-I) colour with age can be estimated from theoretical models of the evolution of simple stellar populations (based on observations of globular clusters and models of stellar structure). These indicate that the (V-I) colour of a galaxy (a significant time after the formation of the stars) should become redder at a rate of d(V-I)/dt = 0.05 magnitudes per Gyr. Taking the colour difference which you derived above and this rate of change of colour, estimate the how much younger the stars in Cl0016+16 appear to be compared to those in local Universe. This is the, so called, look-back time to Cl0016+16.

Finally, use your fit to the C-M relation to determine the magnitude of a galaxy which has an apparent colour of (V-I)=2.4. The equivalent rest-frame colour in a local cluster, corrected for the evolutionary effects discussed above, corresponds to an absolute magnitude of -21.3±0.1 in the I-band. Using the apparent (m) and absolute magnitudes ($\mathcal{M}$) of the galaxy estimate the distance modulus (μ) for Cl0016+16 and hence the distance, r, to the cluster in parsecs (for $H_0 = 50\,\mathrm{km/sec/Mpc}$).

$$\mu \equiv m - \mathcal{M} = 5\log(r) - 5 \tag{3.1}$$

The ambitious student might find it interesting to derive this formula from the magnitude formula,

$$m = -2.5\log_{10}\left(\frac{F}{F_0}\right), \tag{3.2}$$

where F_0 is a constant reference flux and

$$F = \frac{L}{4\pi r^2}, \tag{3.3}$$

is the flux given by an object with luminosity L. Note that the absolute magnitude, $\mathcal{M}$, is defined as the apparent magnitude at a distance of 10 pc.

4 Result checklist

At this point you should have noted down the following information:

- An estimate of the proportion of early-type galaxies in Cl0016+16.
- A list of magnitudes, colours and morphologies for the galaxies in Cl0016+16, from which you have calculated a fit to the colour-magnitude relation for early-type galaxies in this cluster.
- Using your fit, you have compared the expected colour of an I=21 early-type galaxy with that observed in the cluster. What is this difference in colours, and what causes this?

- Using the theoretical predictions of the evolution of the colour of an early-type galaxy with age, turn your estimate of the colour difference into a value of the lookback-time to Cl0016+16. What is your best estimate of the error in this measurement?
- Using the apparent magnitude of a galaxy with a given colour and absolute magnitude, you should calculate the distance modulus for Cl0016+16.
- Suggest any shortcomings of using the Colour-Magnitude relationship as a distance indicator.

Use this information to discuss the results that you have gathered.

5 Conclusions

Following is a list of conclusions that can be stated with the information that you have gathered in this experiment. Make sure that these are in agreement with what you have found.

1. Galaxy morphology provides an objective classification of galaxies which provides some insight into the physical processes acting during their formation and evolution.
2. Clusters of galaxies are the most massive collapsed systems in the local Universe. Their luminous galaxy populations are dominated by early-type galaxies.
3. Elliptical galaxies in clusters show a tight correlation between colour and luminosity or mass. These galaxies exhibit remarkably homogeneous stellar populations as expected from simple, single age, single metallicities models of stellar evolution.
4. The Colour-Magnitude diagram provides a powerful tool for investigating the evolution of galaxy populations.

6 Further reading and References

For further reading I point to the course book Extragalactic Astornomy and Cosmology (Schneider, 2006). Furthermore, all images and the vast majority of the text in this exercise originate from `http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html`.

References

Schneider, P. 2006, Extragalactic Astronomy and Cosmology, by Peter Schneider. Berlin: Springer, 2006.,

Hubble, E. 1926, Contributions from the Mount Wilson Observatory / Carnegie Institution of Washington, 324, 1

7 Acknowledgements

This document is a modified version of the exercise previously available on the ASTA33 course website, which in turn originates from the Department of Physics at the University of Durham[5]. Big thanks to the original author of that exercise, whose name does not seem to have made it onto the website.

[5] `http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html`

We can only guess who it might be. At the very least I want to include the acknowledgements that accompanied the original text as these might be a clue to who our mysterious person might be. In fact it rules out all astronomers who does not enjoy good scotch (although I doubt that would be many).

"Thanks to Richard Bower for the original concept for this web lab. Also thanks to the Royal Society and University of New South Wales who paid enough for me to be able to sit and write this listening to the rain in Sydney while drinking good scotch." - Mysterious person

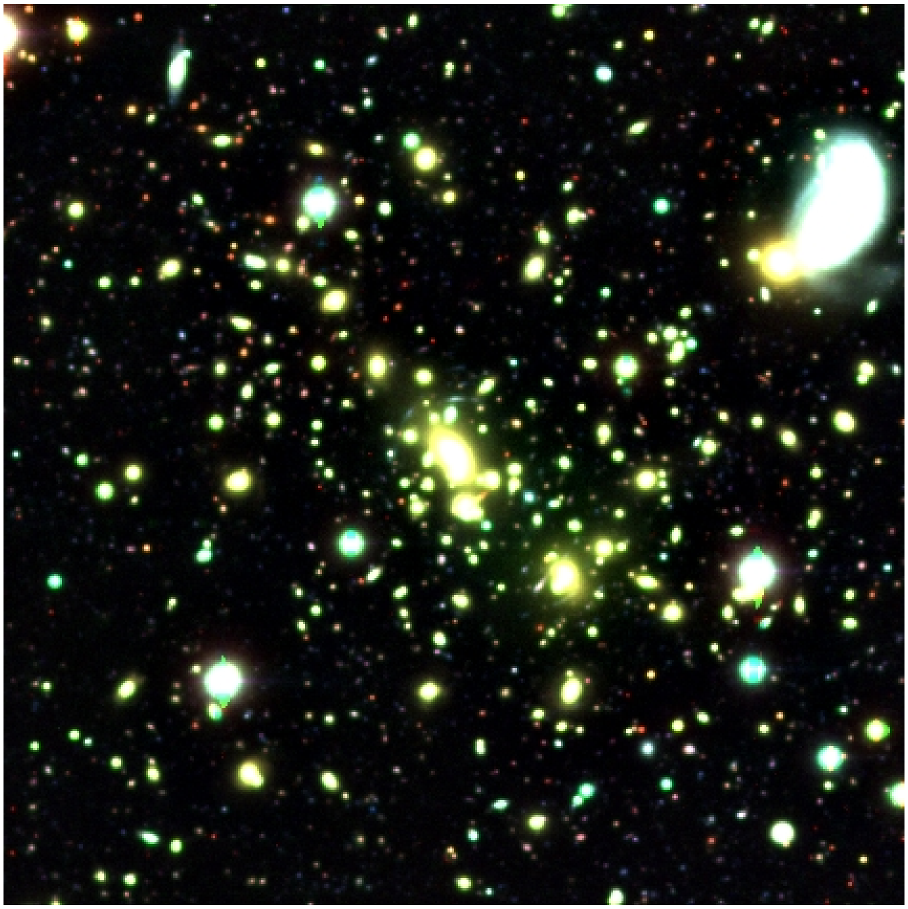


Figure 6: Image of distant galaxy cluster. Same as the right image of Figure 1.

Appendix A

Clusters of galaxies

Rich cluster of galaxies have central masses of 10,000 $\times$ the mass of the Milky Way, and as such are both the most massive collapsed systems and also some of the intrinsically rarest systems in the Universe. Most galaxies inhabit the field, crudely defined as the lower-density regions outside clusters and voids. Although these field galaxies will themselves lie in structures, typically in groups of a few galaxies. The Local Group comprises our Galaxy and Andromeda (M31), as well as a number of smaller galaxies, in a single gravitationally-bound structure. Nevertheless, the Local Group resides on the edge of a moderate-sized cluster in Virgo, and the group is in the process of falling into this cluster. Within the next few billion years the surroundings of our Galaxy will look very different. The most massive nearby cluster is the Coma cluster the central regions of which are dominated by two super-massive elliptical galaxies. The extreme conditions found in such rich clusters including very high densities of galaxies, as well as large amounts of very hot gas which emit at X-ray wavelengths, making clusters some of the most luminous X-ray sources in the sky (see below). In addition to galaxies and hot gas, galaxy clusters contain populations of stars which are not bound to individual galaxies, these have been stripped out of galaxies in the cluster by tidal interactions. As we will see below the vastly different conditions found in the centres of clusters, compared to the lower density field, are associated with differences in the properties of the galaxies in the two environments and in particular with differences in their morphologies.

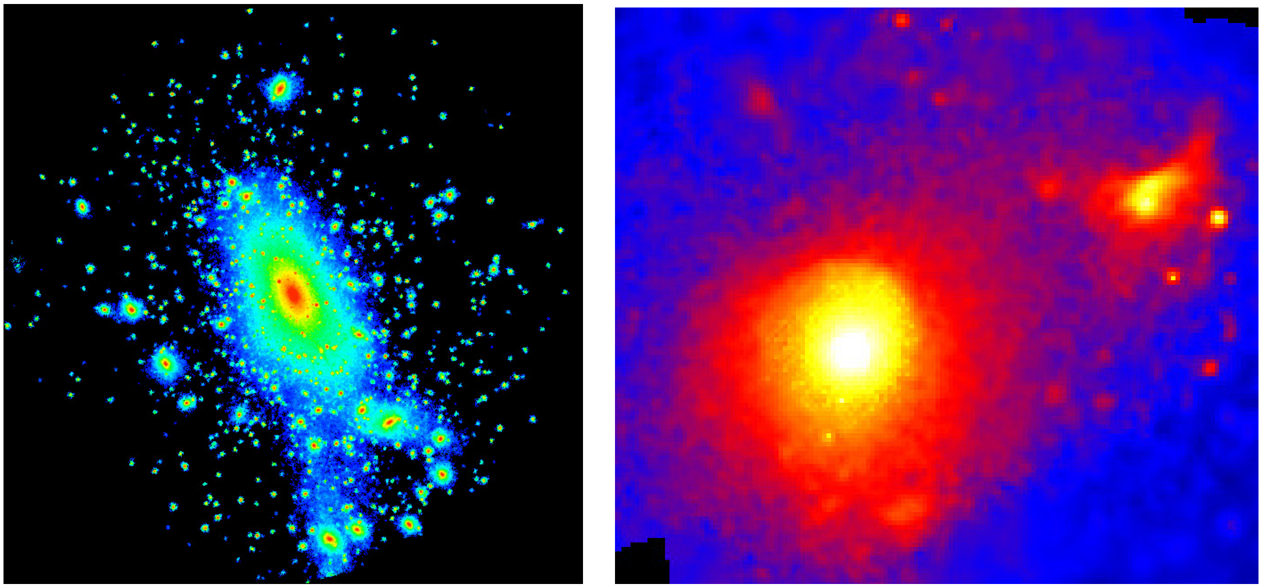


Figure 7: **Left:** Galaxy cluster from a simulation. The colour code shows dark matter density in different regions of the galaxy cluster where red and yellow show high-density regions and blue and black colours shows low-density regions. **Right:** Image of the Virgo cluster in X-ray waveband. The intensity increases in regions containing hot gas. Images from http://community.dur.ac.uk/ian.smail/colMag/colMag_top.html.

The right image in Figure 7 shows a view of the core of the Virgo cluster in the X-ray waveband and illustrates the structure of the hot, gravitationally-bound gas in the cluster's potential well. This potential well is sufficiently deep that the gas between the galaxies within the cluster is compressed and heated to high enough temperature that emits radiation at X-ray wavelengths. Images of this X-ray radiation illustrate the very extended potential well of the cluster, which contains two major peaks, associated with sub-groups of galaxies within the cluster. Nevertheless, the X-ray image still appears much smoother than the distribution of the individual galaxies. Moreover, the temperature and the distribution of the X-ray gas can be used to estimate the mass of the cluster (assuming that the hot X-ray gas behaves as an ideal gas) and in all cases this has been found to significantly exceed the mass contained within the galaxies. These observations are one of the strongest pieces of evidence for dark matter on large scales in the Universe. Observing at X-ray wavelengths requires the use satellites to get above the absorption from the Earth's atmosphere, which is opaque in the X-ray band.

Figure 6 illustrates a view of the central regions of a distant rich cluster, 1 Mpc across. This is a true colour image, constructed from individual exposures through blue (B), visual (V) and infrared (I) filters, and the large numbers of yellow galaxies are the luminous cluster galaxies (the large interacting spiral in the upper-right hand corner is foreground of the cluster). The strong central concentration of galaxies in the cluster can be readily seen, and the cluster centre is further highlighted by the massive dominant galaxy lying at the bottom of the cluster's potential well. This massive elliptical galaxy has accreted an extended envelope of stars stripped from other galaxies passing through the cluster core. The central parts of the cluster are sufficiently massive to bend the space-time, this deflects the paths of photons passing through the core of the cluster in a phenomenon called 'gravitational-lensing'. The deflection means that the images of background galaxies seen through the cluster appear to be distorted into concentric arcs around the cluster. A number of gravitationally-lensed arcs are visible around the central galaxy in this cluster, these are star-forming galaxies at high redshift and are therefore blue, appearing conspicuous against the red, central cluster galaxy. Arcs are also visible around a secondary sub-clump within the cluster below the central galaxy.

Clusters of galaxies are of particular interest for testing models of galaxy evolution in high density regions. The possibility that galaxy properties, such as luminosity or morphology, can be altered by interactions within rich clusters has led to considerable theoretical work on predicting the expected effects of these interactions on model galaxies. Figure 7(left) shows such a simulation, where the motions and interactions of galaxies have been followed through the formation and collapse of a rich cluster. The density of the mass in the cluster is colour coded with the densest regions having red and yellow colours, and less dense regions blue and black. The simulation, although it simply follows Newton's laws, relies on highly sophisticated code running on the most powerful, parallel supercomputers available. Direct comparisons of the observations and simulations of rich clusters of galaxies allow astronomers to test and refine their models of the growth of structure in the Universe.

Appendix B

Python scripts for loading data, line fitting and plotting

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#!/usr/bin/env python3
import numpy as np
import matplotlib.pyplot as plt

### Read in data.
datadir = './data.dat'
data = np.loadtxt(datadir)
mag = data[...,1] # Magnitude.
emag = data[...,2] # Error in magnitude.
col = data[...,3] # Colour.
ecol = data[...,4] # Error in colour.

### Mask data.
mask = (mag < 24) # Remove galaxies dimmer than 24 magnitude.
mag = mag[mask]
emag = emag[mask]
col = col[mask]
ecol = ecol[mask]

### Line fit by least square method.
(p1, p2) = np.polyfit(mag, col, deg=1, full=False) # polynomial coefficients.


### Simple plot.
# Set up figure.
plt.style.use('classic')
fig = plt.figure(figsize=(8,6))
plt.minorticks_on()
plt.gca().tick_params(axis='both', which='both', direction='in', labelsize=14)
plt.ylabel(r'${\rm Colour,}\ (V-I)$', fontsize=18)
plt.xlabel(r'${\rm Magnitude,}\ I$', fontsize=18)
plt.ylim(0,4)
plt.xlim(18,26)

# Plot data-points with errorbars.
plt.errorbar(mag,col,xerr=emag,yerr=ecol,color='r', fmt=' ',
    ecolor='k', elinewidth=1, capsize=2)

# Plot fitted line.
x = np.linspace(min(mag), max(mag)) # To plot fit.
plt.plot(x, p1*x+p2, '-r', lw=2, alpha=0.7)

# Finalise plot.
plt.tight_layout()
plt.show()
```