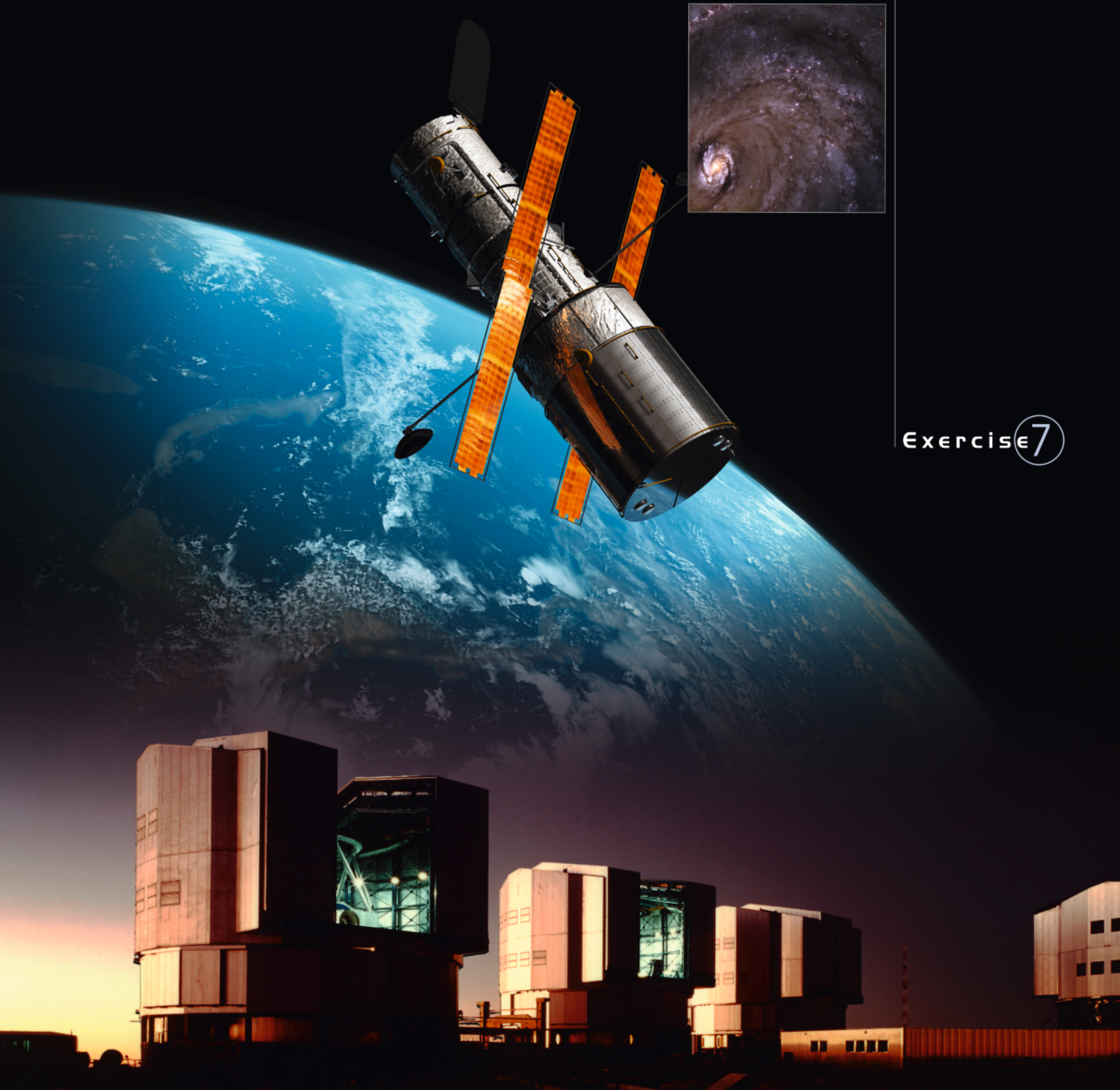
THE ESA/ESO ASTRONOMY EXERCISE SERIES

Student exercises in astronomy using
observations from the
NASA/ESA Hubble Space Telescope
and the ESO telescopes



Exercise 7

The Distance to M100 as Determined by Photometry of Cepheid Variable Stars using the EU-HOU SalsaJ Software

Based on observations with the NASA/ESA Hubble Space Telescope

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The ESA/ESO Astronomy Exercise Series 7

The Distance to M100 as Determined by Photometry of Cepheid Variable Stars performed with the EU-HOU SalsaJ Software

Astronomy is an accessible and visual science, making it ideal for educational purposes. Over the last few years the NASA/ESA Hubble Space Telescope and the ESO telescopes at the La Silla and Paranal Observatories in Chile have presented ever deeper and more spectacular views of the Universe. However, Hubble and the ESO telescopes have not just provided stunning new images, they are also invaluable tools for astronomers. The telescopes have excellent spatial/angular resolution (image sharpness) and allow astronomers to peer further out into the Universe than ever before and answer long-standing unsolved questions.
The analysis of such observations, while often highly sophisticated in detail, is at times sufficiently simple in principle to give secondary-level students the opportunity to repeat it for themselves.

This series of exercises has been produced by the European partner in the Hubble project, ESA (the European Space Agency), which has access to 15% of the observing time with Hubble, together with ESO (the European Southern Observatory).

Figure 1: The NASA/ESA Hubble Space Telescope
The NASA/ESA Hubble Space Telescope has presented spectacular views of the Universe from its orbit above the Earth.

Introduction

Cosmology and distance measurements

How old is the Universe? How fast is it expanding? Will it one day start to contract? These are fundamental cosmological questions that have long awaited satisfactory answers.
The fate of the Universe is closely linked with the future behaviour/evolution of its expansion rate. If the expansion slows down sufficiently then the Universe may one day start to contract again. Observations currently suggest that it is more likely that the Universe will continue to expand forever.
The expansion makes all galaxies recede from a given observer (e.g. on Earth) and the further away they are, the faster they recede. The expression known as Hubble's law (formulated by Edwin Hubble in 1929) describes the relation between the distance of a given object and its recession velocity, v. Hubble's law is:

$$v = H_0 \cdot D$$

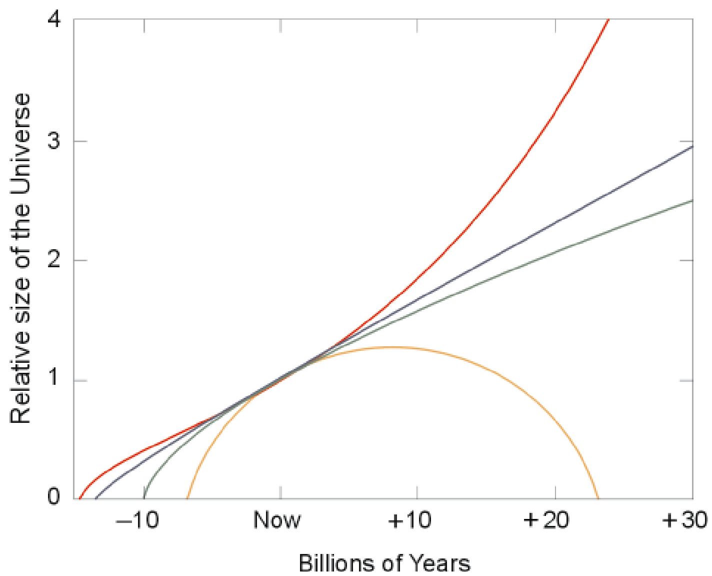

Figure 2: The Fate of the Universe
This graph relates the size of the Universe with time – in other words it shows how it expands and/or contracts with time. The different lines 'in the future' (to the right in the diagram) show different models for the fate of the Universe – an ever-expanding Universe or a contracting Universe.

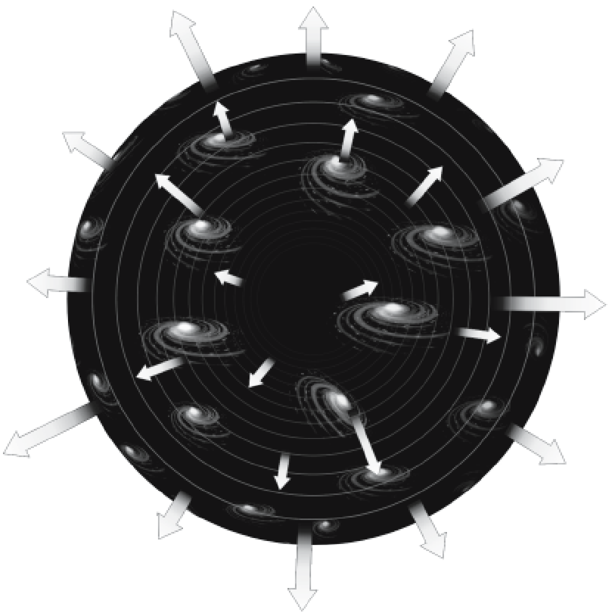

Figure 3: Receding Galaxies
This diagram illustrates how the galaxies recede from each other due to the expansion of the Universe.

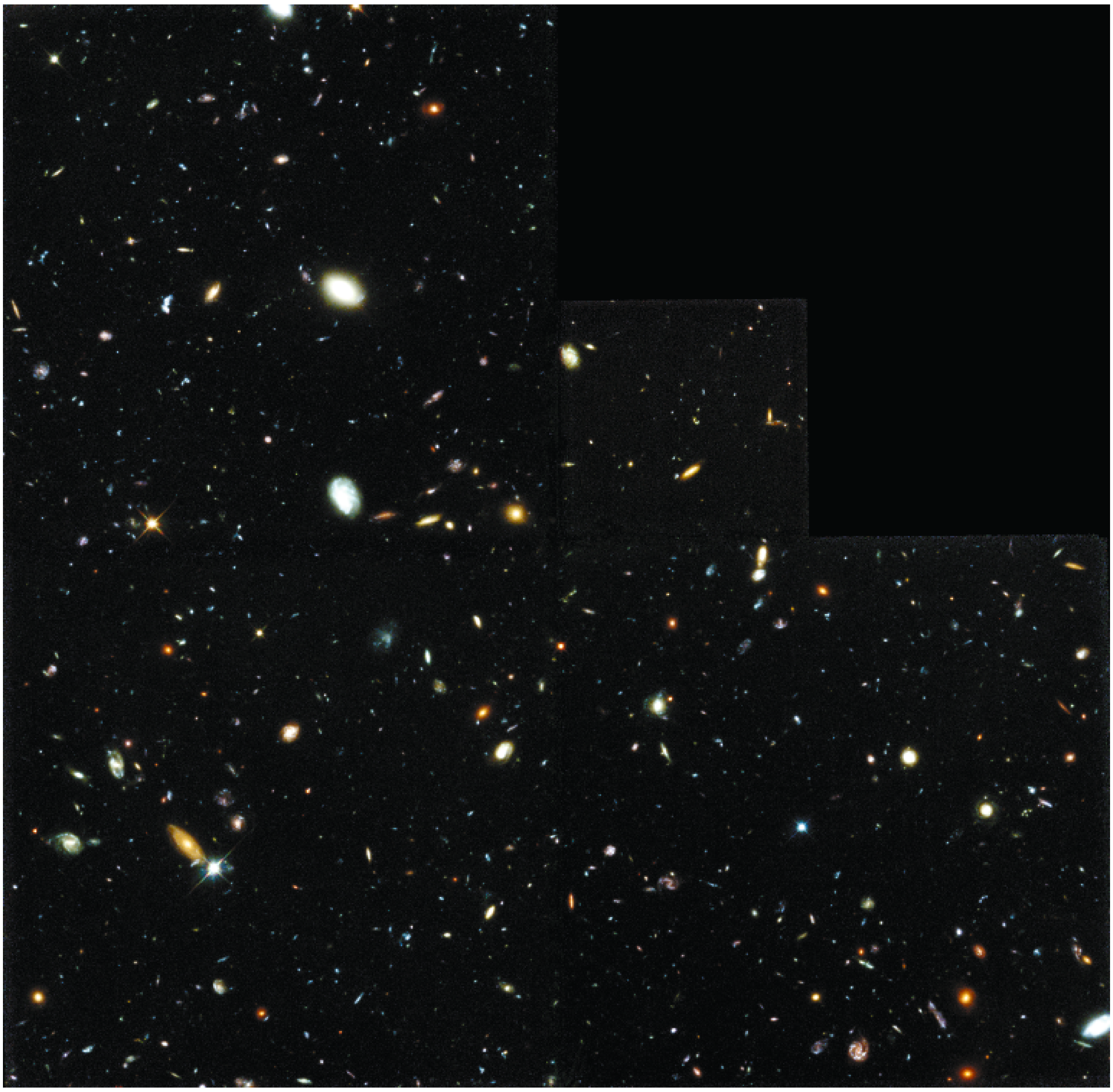

Figure 4: Remote Galaxies with High Redshifts
This image, taken by the Wide-Field and Planetary Camera (WFPC2) of the Hubble Space Telescope, shows many galaxies, billions of light years away. Most of the fuzzy patches are galaxies containing billions of stars. The galaxies in this image are receding from us at high velocities.

It states that the galaxies in our Universe are flying away from each other with a velocity, v, proportional to the distance, D, between them.

H_0 is a fundamental property of the Universe – the Hubble constant – important in many cosmological questions and is a measure of how fast the Universe is expanding today.
The age of the Universe, t, can be approximated by the inverse (or reciprocal) of the Hubble constant H_0:

$$t = \frac{1}{H_0}$$

The value of H_0 has enormous significance for estimates of the age of our Universe. But how do we measure it? To determine H_0, we 'simply' need to measure both the recession velocity, v, and the distance, D, for an object, usually a galaxy, or, even better, for many galaxies and find the average measurement.

The *recession velocity* is relatively easy to determine: we can measure the so-called redshift of the light from the galaxy. Redshift is a direct consequence of an object's motion away from us. It is a Doppler-shift of the light from the

Figure 5: Henrietta Leavitt
The understanding of the relative brightness and variability of stars was revolutionised by the work of Henrietta Swan Leavitt (1868-1921). Working at Harvard College Observatory, Leavitt calibrated the photographic magnitudes of 47 stars precisely to act as standard references or 'candles' for the magnitudes of all other stars. Leavitt discovered and catalogued over 1500 variable stars in the nearby Magellanic Clouds. From this catalogue, she discovered that brighter Cepheid variable stars take longer to vary, a fact used today to calibrate the distance scale of our Universe (Courtesy of AAVSO).

individual galaxies, resulting in a shift of the wavelength of the light from the galaxies towards the red end of the spectrum. As the wavelength of red light is longer than blue light, the wavelength of the light from the galaxies has increased during its journey to the Earth. The fractional change in wavelength due to the Doppler-shift is called the redshift and galaxies with a high redshift have high recession velocities.

Using Cepheids as distance estimators

Measuring the *distance* to an astronomical object is much more difficult and is one of the greatest challenges facing astronomers. Over the years a number of different distance estimators have been found. One of these is a class of stars known as Cepheid variables.

Cepheids are rare and very luminous stars that have a very regularly varying luminosity. They are named after the star δ-Cephei in the constellation of Cepheus, which was the first known example of this particular type of variable star and is an easy naked eye object.

In 1912 the astronomer Henrietta Leavitt (see Fig. 5) observed 20 Cepheid variable stars in the Small Magellanic Cloud (SMC). The small variations in distance to the individual Cepheid variable stars in the Cloud are negligible compared with the much larger distance to the SMC. The brighter stars in this group are indeed intrinsically brighter and not just apparently brighter because they are closer. Henrietta Leavitt uncovered a relation between the intrinsic brightness and the pulsation period of Cepheid variable stars and showed that intrinsically brighter Cepheids have longer periods. By observing the period of any Cepheid, one can deduce its intrinsic brightness and so, by observing its apparent brightness, calculate its distance. In this way Cepheid variable stars can be used as one of the 'standard candles' in the Universe that act either as distance indicators themselves or can be used to calibrate (or set the zero point for) other distance indicators. Cepheid variables can be distinguished from other variable stars by their characteristic light curves (see Fig. 6).

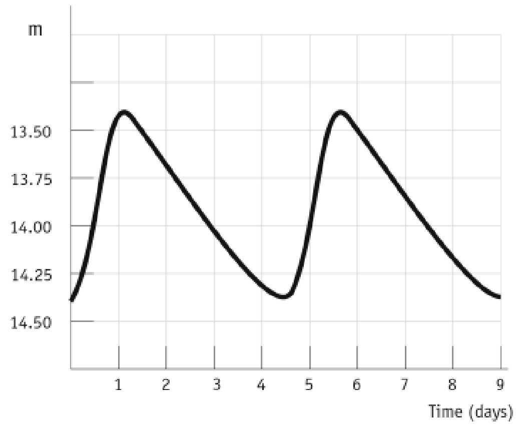

Figure 6: Typical Cepheid light curve
The light curve for a Cepheid variable star has a characteristic shape, with the brightness rising sharply, and then falling off much more gently. The amplitude of the variations is typically 1-2 magnitudes.

The most accurate measurements of both velocity and distance are naturally obtained for objects that are relatively close to the Milky Way. Before the NASA/ESA Hubble Space Telescope was available, ground-based observatories had detected Cepheid variables in galaxies with distances up to 3.5 Megaparsecs (see the definition of Megaparsecs in the Mathematical Toolkit) from our own Sun. However, at this sort of distance, another velocity effect also comes into play. Galaxies attract each other gravitationally and this introduces a non-uniform component to the motion that affects our measurements of the uniform part of the velocity arising from the expansion of the Universe. This non-uniform part of the velocity is known as the peculiar velocity and its effect is comparable with the expansion velocity in our local part of the Universe. In order to study the overall expansion of the Universe, it is necessary to make reliable distance measurements of more distant galaxies where the expansion velocity is significantly higher than the peculiar velocity. Hubble has measured Cepheid variables in galaxies with distances of up to ~20 Megaparsecs.

Before Hubble made these measurements astronomers argued whether the Universe was 10 or 20 billion years old. Now the agreement is generally much better – the age of the Universe is believed to be somewhere between 12 and 14 billion years.

One of the Hubble's Key Projects had as a long-term goal a more accurate value for the Hubble constant and the age of the Universe. Eighteen galaxies located at different distances have been monitored to reveal any Cepheid variables. One of these galaxies is M100.

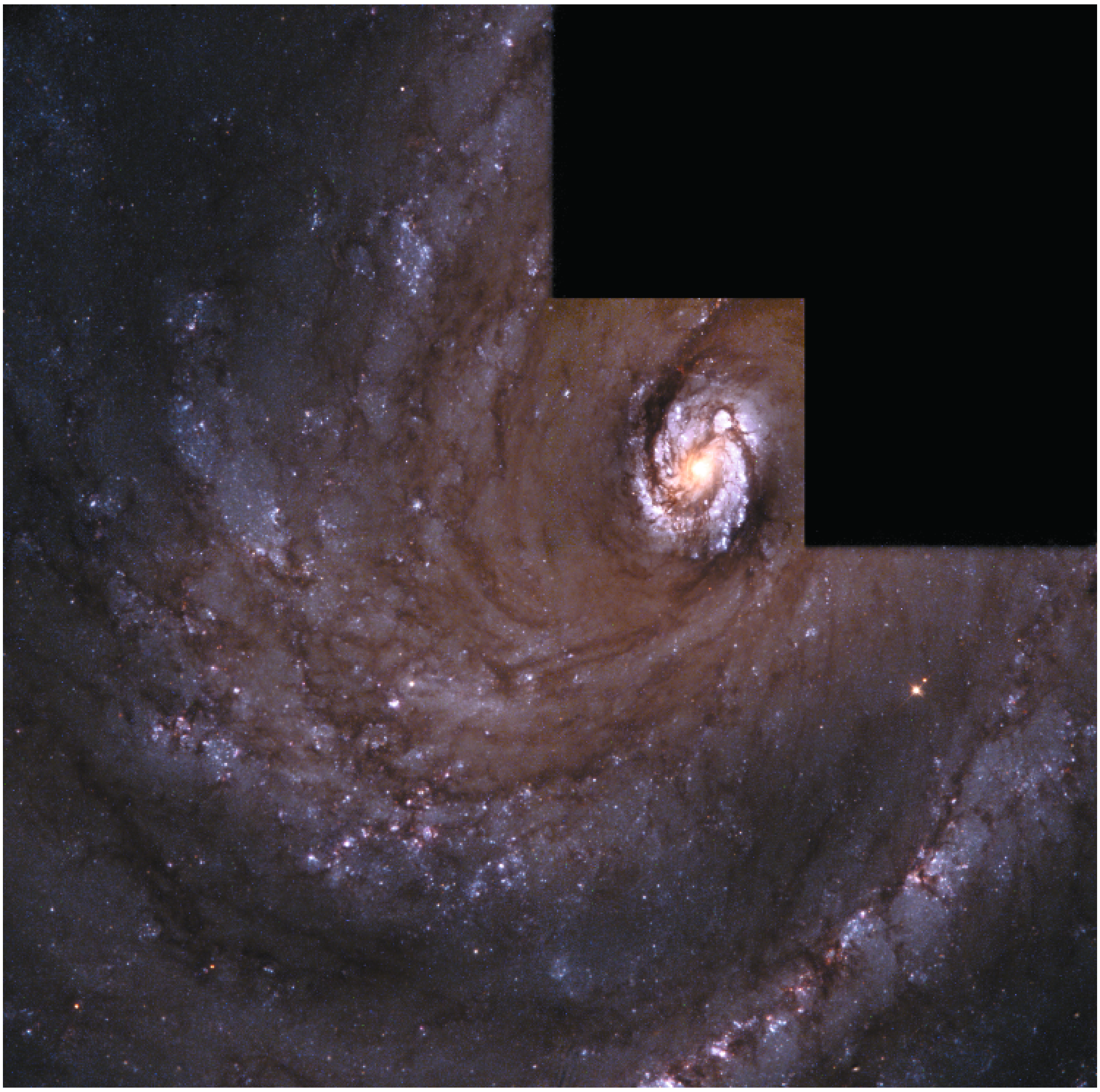

Figure 7: The Spiral Galaxy M100
If we could observe our galaxy, the Milky Way, face on from an extragalactic space vessel, its shape would be similar to the Spiral Galaxy M100. Spiral galaxies are rich in dust and gas. The dust shows up in this image as dark lanes running between the majestic spiral arms. M100 is a popular target for amateur astronomers and is located in the spring sky in the direction of the constellation of Coma Berenices. The image was taken with Hubble's Wide Field and Planetary Camera 2. Blue colours correspond to regions with young hot stars.

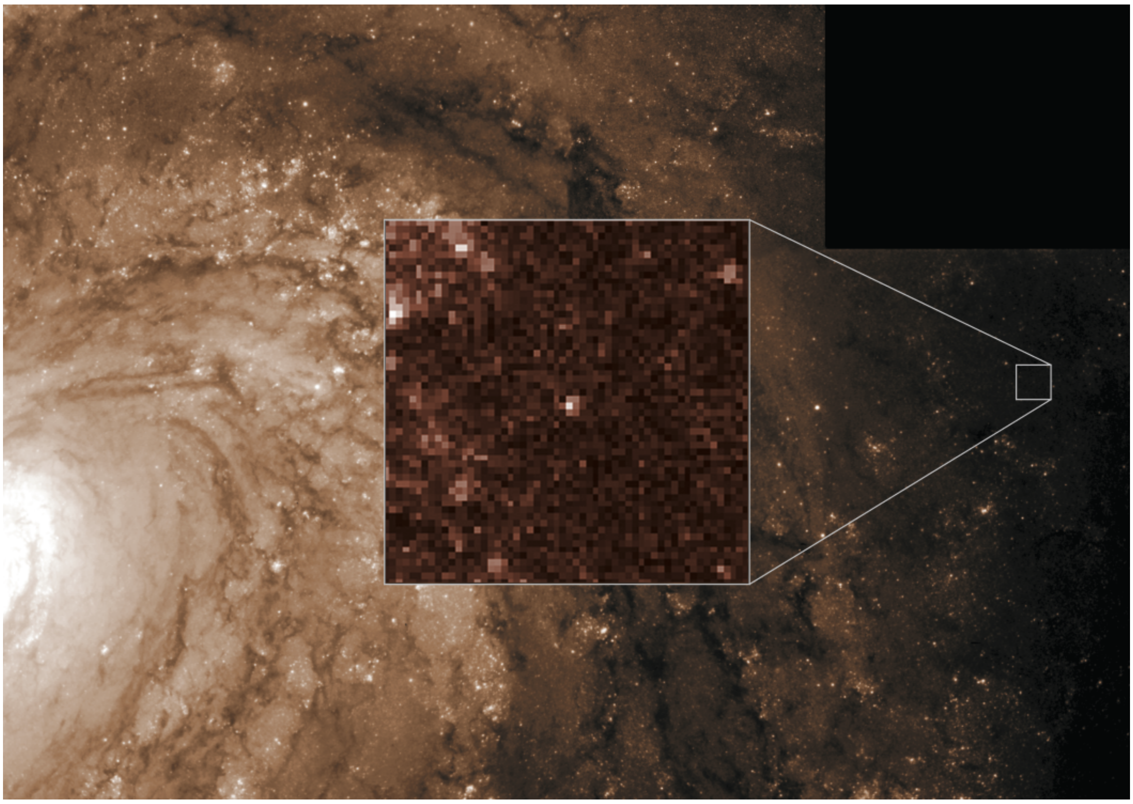

Figure 8: Hubble tracks down Cepheid variable stars in M100
Hubble's high resolution camera detected and picked out one of the Cepheid variable stars used in this exercise. The star is located in a star-forming region in one of the galaxy's spiral arms (the star is at the centre of the box).

M100 – a Grand Spiral

The galaxy M100 is a magnificent spiral galaxy in the large Virgo cluster of galaxies. The Virgo cluster contains 2,500 galaxies. M100 is a rotating system of gas, dust and stars similar to the Milky Way and is viewed face on. The name M100 stems from the fact that it is number 100 in the Messier catalogue of non-stellar objects.

M100 is one of the more distant galaxies where accurate measurements of Cepheid variables have been made. This exercise is based on Hubble's images and data from this galaxy.

The task ahead

The task is to measure the brightness of three different Cepheid variable stars in M100 and to use these measurements to make an estimate of the age of the Universe. The Cepheid variables were observed 12 times over a period of two months. The brightness of each star has to be measured separately in each of the 12 observations so that a curve of the variation in brightness for each star can be constructed to give a measure of their pulsation periods. The measurements are taken using the software package "SalsaJ", which provides a very simple and intuitive interface for handling the astronomical data files also known as "FITS" files. This package can measure the light emitted from a star as seen in a given image using a method known as photometry. A simple and straightforward procedure is used to measure the Cepheids fast and with good precision. When the amount of light emitted by a star is known, it is possible to calculate the standard (apparent) magnitudes using a simple formula. When the apparent magnitudes for each star in each epoch (3 x 12 = 36 measurements) are known, the apparent magnitude can be plotted against the day (i.e. time), giving an estimate for the period (in days) of each Cepheid. This can be converted to an absolute magnitude using the Period-Luminosity relation and the distance to M100 can then be determined using the distance relation. Finally we can calculate a value for the Hubble constant (using a value for the recession velocity of M100 observed by other scientists) and estimate the age of the Universe.

Observations/exposures

Hubble observed M100 12 times during two months in 1994, on the following dates: 23 April, 4 May, 6 May, 9 May, 12 May, 16 May, 20 May, 26 May, 31 May, 7 June, 17 June and 19 June. Each exposure took 1800 seconds (half an hour). This means that the camera collected light for 1800 seconds. We have cut out the relevant areas of the original images, so there are 3 x 12 images – one for each Cepheid in each epoch. Using these smaller images should make the task of identifying the Cepheids easier than searching the entire original image, which can be quite confusing. The three Cepheids are denoted by the original names given by the scientists, namely C22, C25 and C31 respectively. The scientists found 70 Cepheids in Messier 100, but, for the purposes of this exercise, we will limit the measurements to just three of them.
The whole exercise has been broken down into eight tasks, beginning with taking the photometric measurements using the SalsaJ package and ending with an estimate of the age of the Universe based on the measurements taken. Each task begins with a brief checklist of the steps to be completed with more detailed instructions for each step within the task – if appropriate – set out below.

Task 1: Taking the data

Checklist for Task 1:

☐ Load the 12 images for one of the three Cepheids into SalsaJ.

☐ Adjust the brightness settings so you can actually see the stars in the field.

☐ Set up a spreadsheet to enter the data or use Table 1.

☐ Locate the Cepheid using the guide given below.

☐ Measure the photon counts in each of the 12 images and enter the data in a spreadsheet (e.g. Excel) or in Table 1.

☐ Repeat for the remaining two Cepheids.

Loading images into SalsaJ

1) Open SalsaJ – either pre-installed or from http://www.euhou.cicrp.jussieu.fr/euhou/Resources/Soft/index.html

2) Load the 12 images for one Cepheid (e.g. C31) either from your local disk or from by opening the folder containing the files for the Cepheid you are working on.

3) Import the files using the File menu and the sequence File -> Import -> Image Sequence. This loads all twelve images into one window. You can flick from one image to the next using the horizontal slider. As you change images SalsaJ keeps the same location in each image.

Adjust the brightness
1) Adjust the brightness of the images using the Image menu and the sequence Image->Ad-

just->Brightness/Contrast.
2) A pop up appears, click the Set button at the lower left and type in the following values: Minimum Displayed Value: 0. Maximum Displayed Value: 40.

Setting up a spreadsheet – getting ready to collect data

Before you begin to work with the data it is helpful to have a clear way of recording your results. Table 1 below suggests a way of organising the data.

1) Use a spreadsheet if possible. Spreadsheets make performing routine repeated calculations easy, and there are lots of these in this exercise.

2) Make three copies of the table – one for each Cepheid - you will have to fill out the five empty columns in each case – explained fully in the next section – as you begin to collect the data.

3) When you are working with the files, work with one Cepheid at a time and take all the data (location and photometric for that Cepheid for each epoch (date)) before going on to the next epoch.

Locating the Cepheid

It is not trivial at all to locate the Cepheids. In the following three images (one for each Cepheid) each Cepheid is marked by an arrow. This should help you to locate the Cepheids in the remaining 11 epochs / images. If you have the images loaded as a stack the position of the Cepheid changes very little between each image, so once you have found the Cepheid in the top image, you can flick through and see how the Cepheid changes in each successive image.

1) Use the brighter stars in the field to navigate your way to the Cepheid. It can help to pick a couple of bright stars in an image where you are sure you know which the Cepheid is, so that you have the relative positions of the Cepheid and a couple of references. Then in an image where the Cepheid is really faint you can navigate from the stars you have chosen as references to the location of the Cepheid.

Cepheid name

Epoch	Date	Cepheid x-coordinate	Cepheid y-coordinate	Photometric setting y-coordinate	Intensity (SalsaJ)	m (Equation)
0.0	23 April					
10.8	4 May					
13.1	6 May					
16.5	9 May					
19.3	12 May					
23.1	16 May					
27.6	20 May					
32.9	26 May					
37.9	31 May					
44.9	7 June					
55.0	17 June					
57.0	19 June					

Table 1: *Cepheid measurements.*

Tasks

2) Make use of the Zoom-tool in SalsaJ to home in on the star. If you use the Zoom-tool make sure you switch it off before you try to take any photometric measurements.

3) Locate the Cepheid in the image and enter the x and y co-ordinates (shown at the lower left of the main SalsaJ toolbar) into the first two empty columns of your spreadsheet (or Table 1). The Cepheids are at roughly the same position on the different dates, but not exactly so, so expect a few pixels shift between each image.

4) Calculate the Photometric Setting y-coordinate using the equation:

Photometric Setting y-coordinate = 201 – Cepheid y-coordinate

and enter the results in the third empty column. We need this number because sometimes SalsaJ counts its y-coordinate from the bottom of the image upwards (in the main toolbar and the Photometric Results window) and sometimes from the top of the image downwards (in the Photometric Settings window), so we have to be careful we are always talking about the same location in the different windows. The x coordinate is the same throughout.

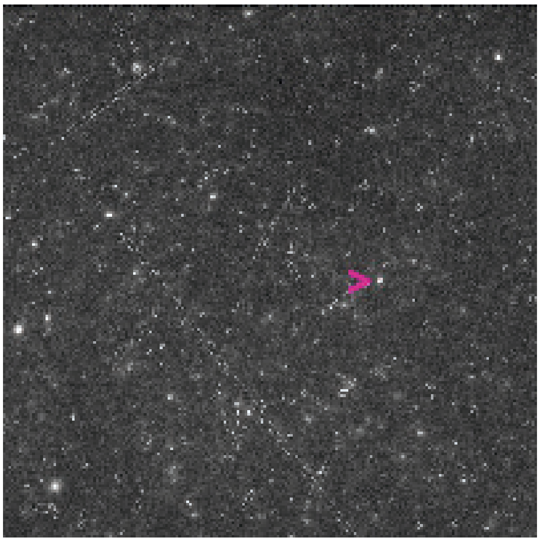

Figure 9: *C22 is here marked with a purple arrow*

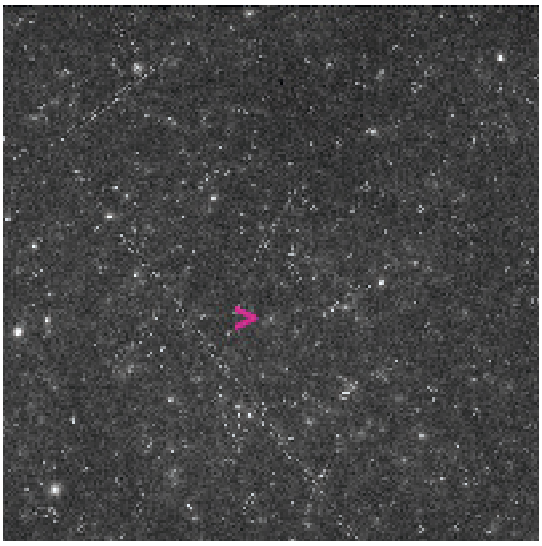

Figure 10: *C25 marked with a purple arrow*

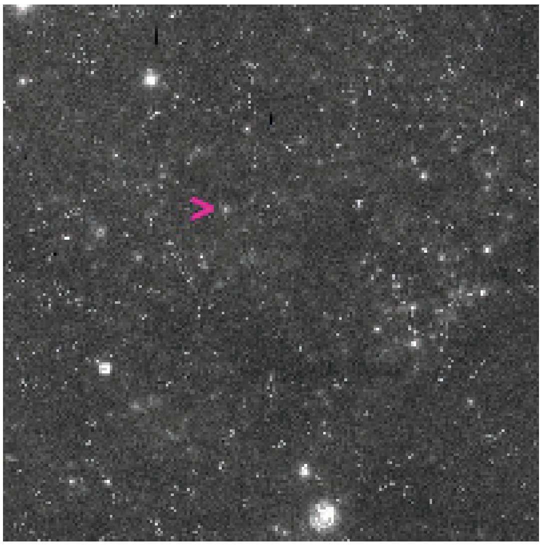

Figure 11: *C31 marked with a purple arrow*

Making photometric measurements

Once the Cepheid has been located we can take the photometric measurements that tell us how much light is coming from each Cepheid on a given date.

1) Start up the photometry by clicking in the Analyse menu using Analyse -> Photometry menu. A new blank window should pop up. This stays blank until you take some data.

2) Now set up the photometry in the Analyse menu using Analyse-> Photometry Settings. A second new window pops up and it looks like this:

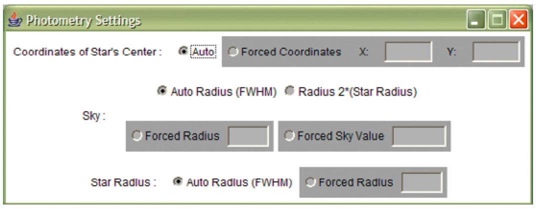

Figure 12: *Screenshot of the photometric settings window in SalsaJ*

a. Since the Cepheid moves a little between images in the stack, use the Forced Co-ordinates option. Select the grey box and enter the x co-ordinate and the SECOND y co-ordinate (the one you calculated and entered in the Photometric Settings y-co-ordinate column).

b. The Sky settings should always be “Auto radius (FWHM)”. The other two sky settings should be left blank.

c. The star radius should be set manually using the “Forced Radius” option while locating the exact centre for the Cepheid (set the Forced value of the radius to e.g. 3). Once the Cepheid is located exactly, use the “Auto Radius (FWHM)” setting to obtain the best estimate of the intensity of the Cepheid.

d. Take a measurement by clicking the image. SalsaJ puts a circle round the star it is measuring so you should be able to see that you have the right co-ordinates.

e. To check that you really have found the centre of the Cepheid try shifting the x and y coordinates by one pixel each way to find the selection with the best fit to the star. It should be the selection with the smallest FWHM circle around it.

f. The “Photometry” window is updated with the x and y co-ordinates, the radius of the measured circle and the photon count (intensity) for the selected area. The x- and y- co-ordinates in this window should match the values in the main SalsaJ application.

3) When you are sure you have the best fit for the centre of the star enter the photon count number (from the Intensity column in the main photometry window) in the “Intensity (SalsaJ)” column in the spreadsheet.

Task 2: Calculate apparent magnitudes

Checklist for Task 2:

☐ Calculate the apparent magnitude for each measurement (for each Cepheid) and write it in your spreadsheet or in Table 1 in the m (Equation) column.

The number you obtained by using the “Photometry” method in SalsaJ on each star (at each epoch!) entered into your spreadsheet in the Intensity (SalsaJ) column is the so-called photon count. It is a direct measure of how much light (i.e. how many photons) were received from the star during the exposure. To calculate the apparent magnitudes use the equation:

$$m = 30.61 - 2.5\log_{10}(DN)$$

The quantity DN is the photon count (the Intensity (SalsaJ) result) . The number 30.61 is a contraction of the numbers m_{ref} and L_{ref} from the equation on p.2 of the Toolkits, which we have simplified to save you having to take further measurements for a reference star.

Task 3: Find the periods of the Cepheid Variables

Checklist for Task 3:

☐ Plot the apparent magnitudes just calculated against the date. An empty graph is given below as well as an example light curve for another Cepheid.

☐ Set up a results table (Table 2) that you can use through the next few tasks to help in the calculation of the distance to M100.

☐ Find the period of the variation in the apparent magnitude from your plot. Enter the results in Table 2.

☐ Repeat for each Cepheid.

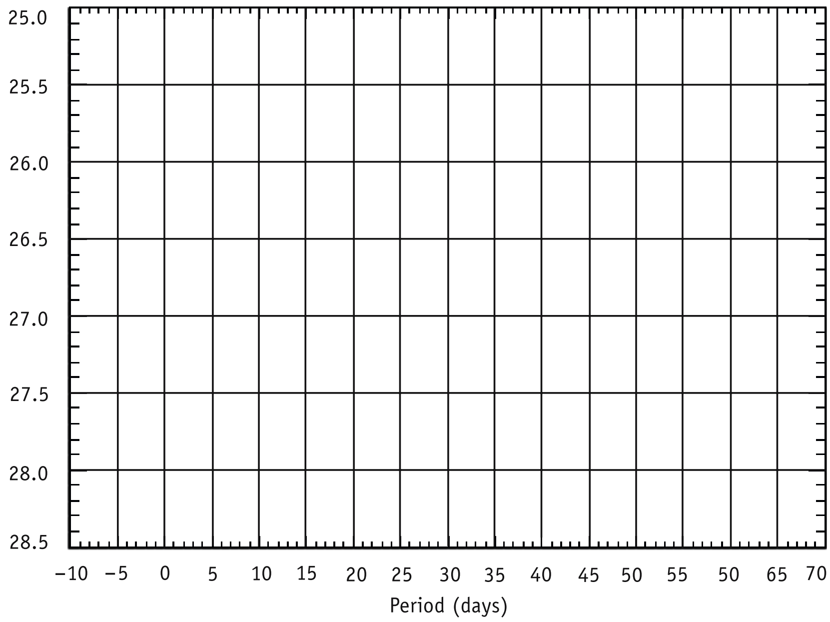

***Figure 13:** Empty graph for Task 3.*

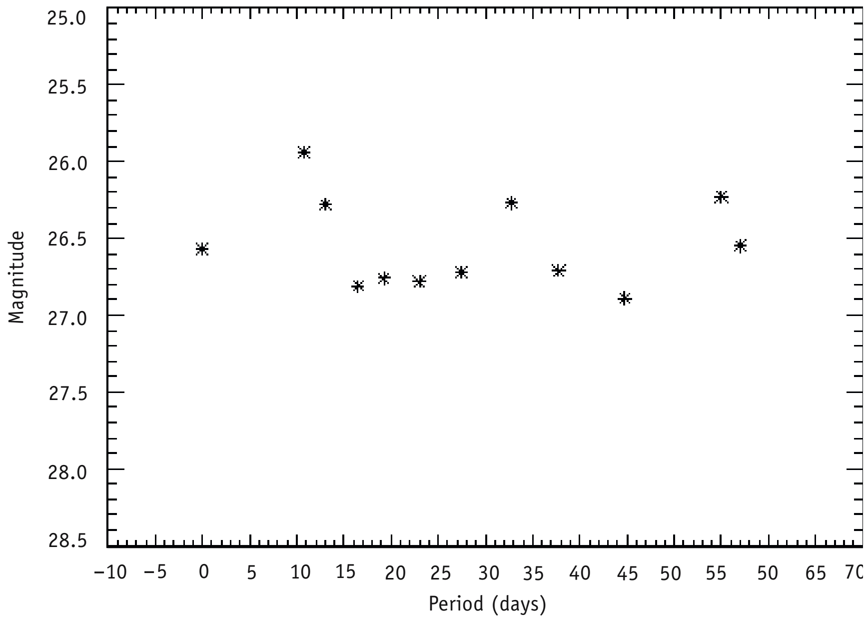

***Figure 14:** Example graph with data from Cepheid C55, which is not a part of this exercise. The distance (D), period (p) and mean apparent magnitude (<m>). In this case D = 20.6 Mpc p = 21.0 days and <m> = 26.5 magnitudes*

Results table for data leading to calculation of the distance to M100

Cepheid Name	Period (days)	Absolute Magnitude M	Average apparent magnitude <m>	Distance in Mpc

Table 2: *Data table for distance calculations*

This table can be used to record the results of the calculations in Tasks 3 – 5.

Task 4: Find the absolute magnitudes of the Cepheids

Checklist for Task 4:

☐ Calculate the absolute magnitude M for the three stars using the information in these curves and the Period-Luminosity equation that relates the absolute magnitude of a Cepheid variable to its period. Enter the results in Table 2.

The relationship between period and absolute magnitude was first established by Henrietta Leavitt, but has since been revised many times and today the best estimate of the relation is:

$$M = -2.78 \log(P) - 1.35$$

Here M is the absolute magnitude of the star and P is the period measured in days.

Task 5: Calculate the distance to the Cepheids

Checklist for Task 5:

☐ Look up the distance equation in the Toolkit, p5. Note you need the absolute magnitude, M, and the apparent magnitude, m to calculate the distance, D, to M100.

☐ Think about a method to estimate the apparent magnitude, m, using the curves. Apart from problems in measuring the amount of light received accurately and calibrating the magnitudes that were measured, astronomers have discussed for a hundred years which apparent magnitude, m, to use in the distance equation for a Cepheid that is actually varying in magnitude. At the beginning of the 20th century astronomers measured the minimum apparent magnitude (mmin) and the maximum apparent magnitude (mmax) and then took the average (<m>) of the two.

☐ Find an average apparent magnitude <m> for each Cepheid.

☐ Calculate <m> and D (in Mpc) for each Cepheid and enter the results in Table 2.

Task 6: Assess the calculated results and estimate the distance to M100

Checklist for Task 6:

☐ Consider why the distances to the different Cepheid variables are not exactly the same.

☐ Could the fact that the three stars have different positions in M100 be the reason for the variation in the distances of the three stars?

☐ You have calculated the distance to the three different Cepheid variable stars in M100. Does that give you the distance to M100?

Tasks

- ☐ Find out how large the Milky Way is (you can, for instance, look in an astronomy book or on the Internet). Assume that the size of M100 is of the same order. Now think about the previous question once again.
- ☐ Calculate the mean value of the distances to the three Cepheid stars and take this as the distance to M100.

In the original scientific paper using the Hubble measurements, the distance to M100 was calculated as 17.1 ± 1.8 Megaparsecs. The presence of interstellar dust was taken into account in determining this value.

- ☐ Compare your results with that distance.

Task 7: Estimate the age of the Universe

Checklist for Task 7:

- ☐ Calculate a value for the age of the Universe, assuming that the age of the Universe, t, is given by $t = 1/H_0$. Remember to convert to the correct units. How much older is this than the age of the Earth?

Task 8: Calculate Hubble's constant

Checklist for Task 8:

- ☐ Calculate Hubble's constant.

As you may remember from the introduction (p.5), the recession velocity, v, of a galaxy like M100, together with information about its distance can give you a value for the general expansion velocity of the Universe as described by Hubble's constant, H_0 by using the equation:

$$H_0 = \frac{v}{D}$$

H_0 is expressed in units of km/s/Mpc. The recession velocity of the Virgo Cluster, of which M100 is a member, has been measured to be 1400 km/s (Freedman et al., 1994). Calculate Hubble's constant using this value for the recession velocity as v, and the average of your distance measurements as D.

Further Reading

References

Scientific Papers

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See also the Links on:
http://www.astroex.org/

Colophon

The ESA/ESO Astronomy Exercise Series
Exercise 7: The Distance to M100 as
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Produced by:
the Hubble European Space Agency Information
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ESO

European Organisation
for Astronomical
Research in the
Southern Hemisphere

Hands-On Universe, Europe

Education and Culture

Socrates

Teacher's Guide

Quick Summary

In this exercise we measure the period and apparent magnitudes of Cepheid variables in the galaxy M100. The absolute magnitude is derived using the Period-Luminosity relation and the distance to M100 can then be determined using the distance relation. Finally we calculate a value for the Hubble constant (using a value for the recession velocity of M100 observed by other scientists) and estimate the age of the Universe.

This teachers' guide contains solutions to the problems together with a discussion of the approximations and simplifications made in the exercise.

The hypothesis that the Universe has expanded at a constant rate since the Big Bang is, strictly speaking, only correct in certain cosmological models. Such an expansion is really only possible if the Universe contains very little matter, as all matter, whether visible or dark, interacts gravitationally to slow down the expansion rate. Recent results have led to no firm conclusions concerning the expansion rate of the Universe, and so we can consider the expression used in these tasks as a simple, but reasonable approximation.

Note that, according to recent cosmological models, the Universe underwent a phase of decreasing expansion (due to the gravitational effects of dark and normal matter) that lasted about 5 billion years after the Big Bang. Since then the Universe appears to have entered a period with an accelerating expansion rate where a mysterious 'repulsive gravitation' has taken over. This force is also known by the names 'Dark Energy' or 'quintessence' (the fifth element).

SalsaJ

SalsaJ is an image manipulation and analysis tool for the classroom developed by the European Hands-On Universe Project:
http://www.euhou.net/
The software can be used to do photometry and can be downloaded from the EUHOU website.

The installation is very simple, double-click on the .bat file when you have downloaded an unzipped the software. The software needs Java Run Time Environment (JRE, version 1.5) and Java Media Framework(JMF) as outlined on the pages.

Background for the data

The 3 x 12 FITS images can be downloaded from http://www.astroex.org/data/
The images used in this task came originally from the WFPC2 instrument on Hubble (read more at http://www.spacetelescope.org/about/general/instruments/wfpc2.html). The camera uses an array of 4 CCD detectors, each consisting of 800 x 800 pixels – somewhat smaller than those in modern digital cameras, and optimised for low light levels. More detailed background material on astronomical images is available from http://www.spacetelescope.org/projects/fits_liberator/improc.html and on CCDs in astronomy is from http://www.starlink.rl.ac.uk/star/docs/sc5.htx/node6.html. The images used in this exercise are 201 x 201 pixels in size and have been cut from the original images. Although the images have undergone some pre-processing to remove cosmic rays, students should perhaps be aware of some of the characteristics of CCD images that may affect the quality of the results, including

- Residual cosmic rays, making Cepheid identification harder
- Hot pixels that artificially increase the measured signal if included in the selection for photometry
- Dead pixels that read zero, and so reducing the measured signal if included in the selection for photometry
- Noise – CCD detectors are sensitive enough to count individual incoming photons, but the low pho-

ton counts associated with the faintest Cepheids are just above the background photon levels from the sky, reducing the effective sensitivity of the measurement.
- Undersampling – an inherent feature of the instrument that means essentially there are too few pixels available to define fine features, so that the individual star images (or PSFs) are somewhat 'squared'

As a comparison we include one of the original data images before pre-processing, so that students can appreciate the 'clean up' process that has to occur before analysis can begin. Furthermore we have combined two exposures for each epoch since the observations actually where made in pairs. This increases the signal-to-noise ratio (S/N) and thus gives better results.

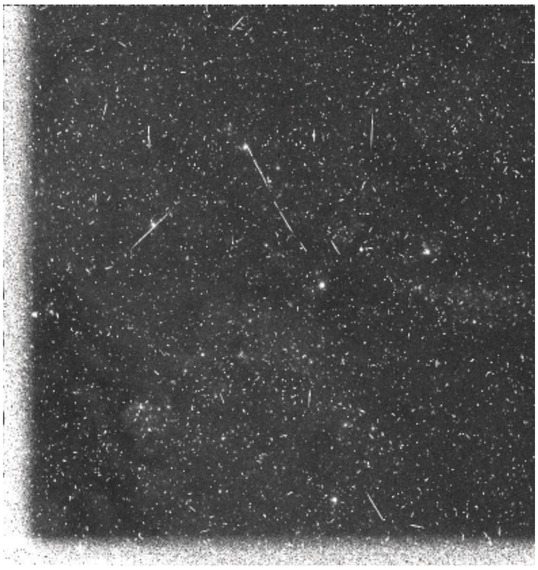

Figure 15: *The exposure from 23 April without removal of cosmics and bad pixels.*

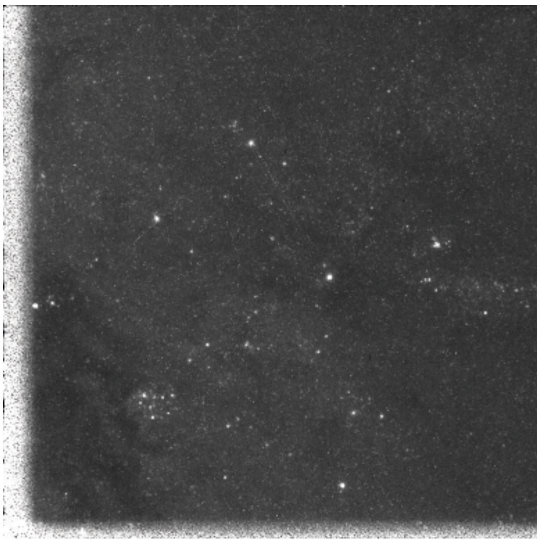

Figure 16: *Exposure from 23 April where the two exposures from that day have been combined and cosmics have been removed.*

Task 1: Taking the data

This is the most difficult and longest part of the exercise. The students are asked to take photometric measurements from some fairly faint objects that are hard to locate in the star field using the SalsaJ package. We have identified three Cepheids to be measured, but careful measurement of each Cepheid is fairly time-consuming and it may be best to allot each student group a single Cepheid to measure, and then pool the class results to obtain an average distance to M100 that can be used to estimate the age of the Universe. Below we discuss the critical points in the process.

Locating the Cepheid in the initial image

Load the data files into SalsaJ as a stack in chronological order. They are labelled with 01_230494, 02040594 and so on up to 12_190694. Make sure you get the right order. The students can then quickly flick through and see how the Cepheid varies through the whole series. It is easiest to make the initial identification of the Cepheid from the original cut-outs before using the Zoom Tool. Encourage the students to write down not only the co-ordinates of the Cepheid, but those of a nearby bright reference star that can be used for orientation in the frames where the Cepheid is faintest.

Photometry measurements in SalsaJ

The students' task is to set the photometry selection carefully so that it best coincides with the Cepheid. This step is probably the most time-consuming in the whole exercise, but without a great deal of care at this stage the best final results will not be achieved.

- Take measurements from a magnified image – 400% is probably the best – as this gives a clear view of the individual pixels without blurring the large scale overview too much.
- Make sure the students understand that there are two y-co-ordinate systems in use, and when to use which one.
- For **Cepheids at their brightest**, the measurement is relatively straightforward. With the
- **Photometry Settings** window set to *Auto,* click on the image near the Cepheid, and SalsaJ will find the Cepheid and mark the selection for photometry with a yellow ring, typically of radius 2 or 3. The results of the photometry are displayed in the main **Photometry** window. It is still worth checking that the selection made by SalsaJ is the best match to the object.
- **When the Cepheid is faint** the **Auto** setting will not find the object, and it is necessary to force the program to use the Cepheid coordinates the students have found as the centre. A shift in one or two pixels can make a major difference in the intensity readings, and students should use their initial coordinates as a starting point, but then step around that point increasing or decreasing coordinates by one each time to find the best match between the centre and the selection around the object. If there are several groups working on the same star it might be interesting to discuss possible strategies to deal with faint objects beforehand and assign a different strategy to each group to see if there is a significant difference in results.

If SalsaJ recognises the object as well-defined it will make a small radius selection that obviously encloses the object and very little background. On occasion the object is so faint that even the smallest Auto Radius selection still includes a fair amount of background, so then it may be necessary then to use the **Forced Radius** option.

- **Illustration of fine tuning the measurements.** The two images in the screen dumps below show the same field and the same exposure (23 April, C31) but with slightly different centres for the star. As the first image suggests the yellow circle (produced by SalsaJ) is small and hence the centre of the star has been found. In the second image the yellow circle is clearly larger than in the first image – this suggests that the centre is not correctly found. The difference in the two images is only one pixel in the x-direction. The coordinates are as follows. Image1: (x, y) = (84, 78), Image2: (x, y) = (84, 79). The photometry of the first set of coordinates yields a photon count of 136 and the second set 144 (because the noise level increases as more background is included). The background value calculated by SalsaJ is more or less the same for both measurements – the only difference is the radius of the circle (which could be thought of as sort of a Point Spread Function (PSF)).

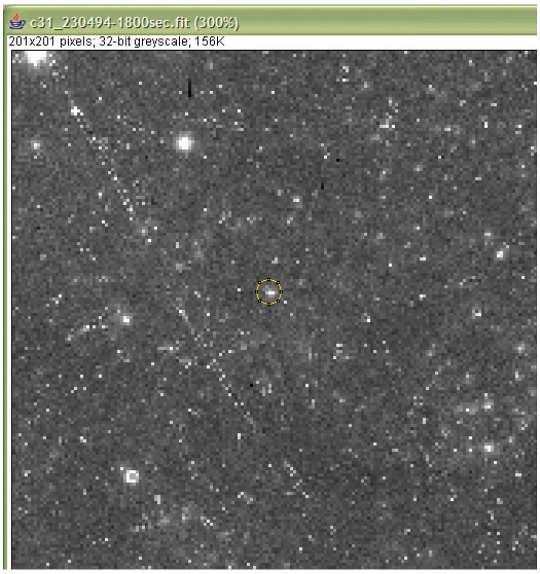

Figure 17: Measuring with a small circle.

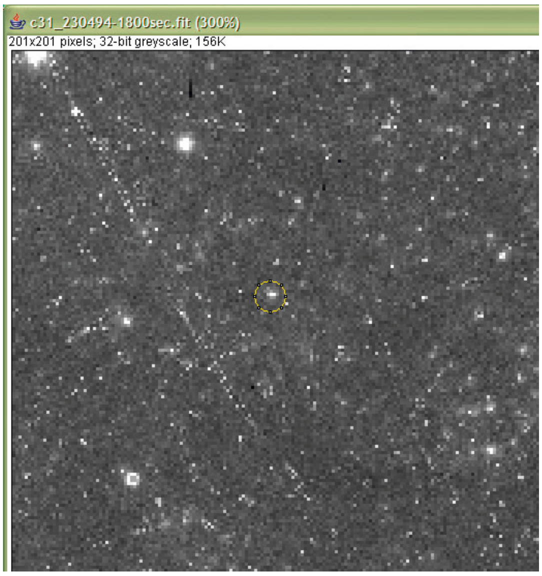

Figure 18: Measuring with a larger circle.

Task 2: Calculate apparent magnitudes

The calculation is straightforward. The formula includes the various constants from the characteristics of the CCD camera, the exposure time etc. It is probably a very good idea to use a spreadsheet – otherwise the students will have to do 36 calculations by hand - and the spreadsheet makes it very easy to plot the data. A template Excel spreadsheet is available for download with these exercises (if you decide to use Excel) from: http://www.astroex.org/data/ .

Task 3: Find the periods of the Cepheid variables

The plots should have the period on the x-axis and the apparent magnitude on the y-axis. It is a good idea to have a table in the spreadsheet with the period of the exposures. This could be done by setting the first exposure (23 April) to be day 0 and the last exposure (19 June) to be day 57. This is probably the easiest way to visualise the magnitudes. Such a plot could look like the one of the following images.

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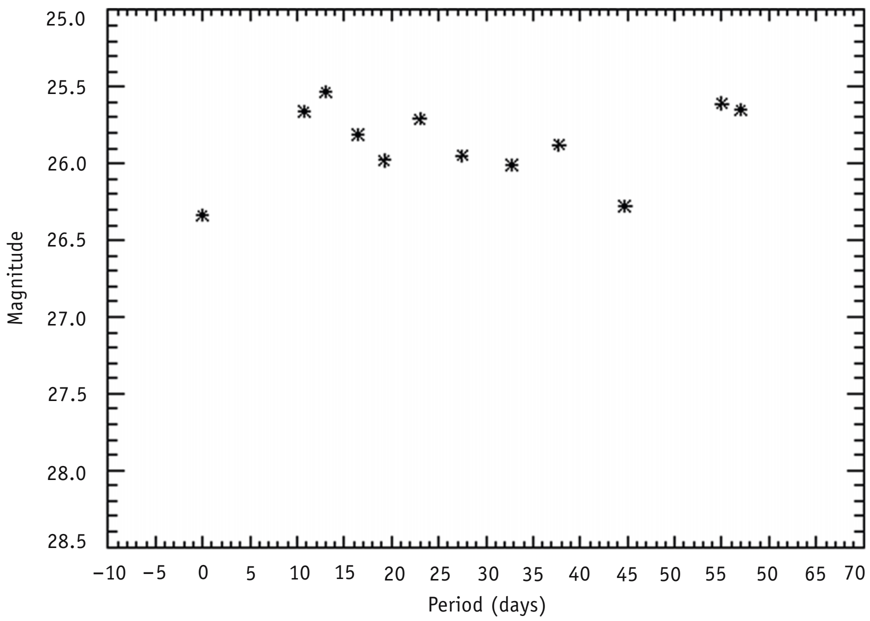

Figure 19: *The graph shows the apparent magnitude of C22 as a function of its period. D = 22.8 Mpc, p = 44.0 days, <m> = 25.9 magnitudes.*

Students should read the period directly from the graphs produced. In the example given above, the period can be seen to be roughly 31 days since the maximum magnitudes are at point number 1 from the left at about 0 days and star number 10 from the left at 44 days, thus producing a period of 44 days.

Example measurements for the two other Cepheids, C25 and C31 are here:

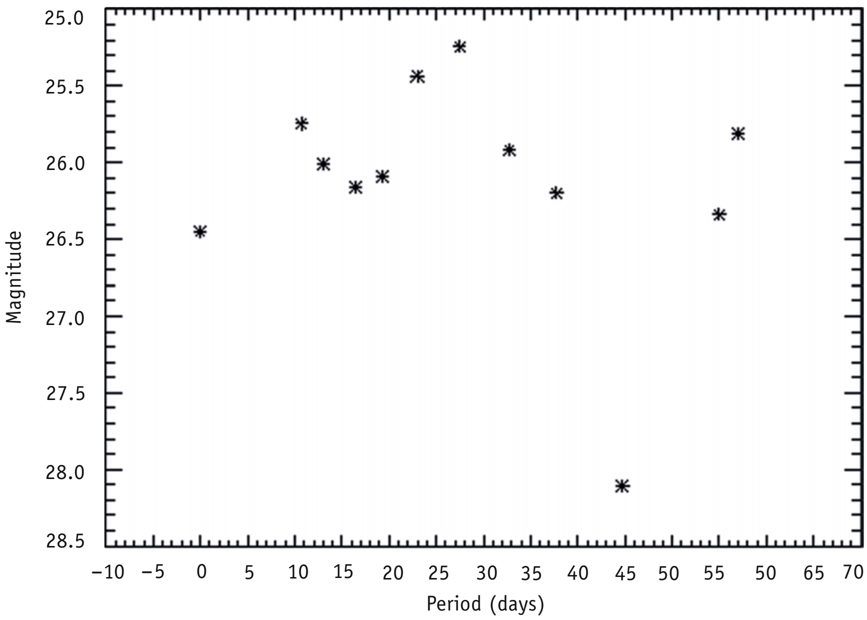

Figure 20: *The graph shows the apparent magnitude of C25 as a function of its period. D = 17.9 Mpc, p = 23.0 days <m> = 26.1 magnitudes.*

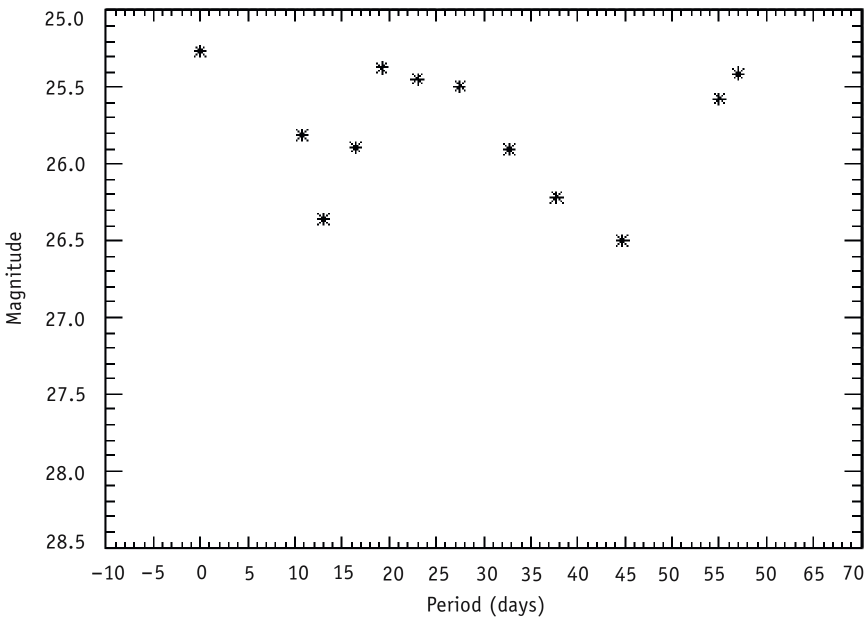

Figure 21: *The graph shows the apparent magnitude of C31 as a function of its period. D = 17.9 Mpc, p = 31.0 days, <m> = 25.5 magnitudes.*

Check that the students understand that a minimum in magnitude corresponds to a maximum in intensity, and discuss whether the students expect any differences in errors between measurements taken on brighter or fainter appearances of the Cepheids. Would that make measuring the period between maxima or minima in magnitude more reliable?

Measurements of this kind, made by hand, are not very precise, so students should not expect identical curves for all the Cepheids. Students should consider all the possible sources of error and inaccuracy in the measurements. Measurements of Cepheid minima where the object brightness is barely above that of the background are obviously particularly sensitive. If the class has used several different strategies in measuring these fainter cases, compare results and assess which appears to be the most effective. The results could then be used as a basis for discussion to see if the students can come up with any further refinements to the measuring process that would improve accuracy.

Alternatively there may be two different classes of Cepheids that have slightly different characteristics. Pool the results from this point to obtain an average for the periods of each of the three Cepheids, and use this combined data to complete the calculations in the later tasks.

Task 4: Find the absolute magnitudes of the Cepheids

This should pose no difficulty. Simply plug and chug with the equation given.

Task 5: Calculate the distance to the Cepheids

Discuss the best method of finding an average apparent magnitude $\langle m \rangle$.

- Is simply taking an arithmetic mean of two logarithmic quantities the best method?
- Should the average be based on a magnitude calculated from the average intensity rather than the average of the magnitudes?
- If you think the measurements on the fainter Cepheids are more inaccurate, should you try some kind of integration over the whole period? For example by finding the total intensity for the twelve frames and averaging that?

If time allows you could see how much variation results from different averaging methods.

Task 6: Assess the calculated results and estimate the distance to M100

Based on the (relatively) large sample of Cepheids, we now have a reasonable estimate for the distance to M100. The Milky Way is approximately 25 kpc in diameter, so no, the size of a galaxy is small compared with the distance to M100 and could not account for the variation in the distance to the Cepheids that we found.

With the crude methods used here distances between 15 and 25 Mpc should be possible to achieve (in our measurements we got **19.7 Mpc**). Compared with the published value of 17.1 ± 1.8 Mpc, this is quite reasonable. Students should be aware that uncertainties are part and parcel of many natural sciences and certainly so in astronomy. Producing the graphs from the original data is not easy and a result calculated from them can be expected to deviate from the published results.

Task 7 Calculate Hubble's constant

Using the measurements above, we get:

$H_0 = v/D = 1400/19.7 =$ **71.77 km/s/Mpc**

This value is very close to the current best known values for H_0. The best estimate currently (with NASA's WMAP satellite) is 70 (km/sec)/Mpc, +2.4/-3.2. Using other methods H_0 is generally considered to lie between 60 and 80 km/s/Mpc.

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Task 8 Estimate the age of the Universe

Using the conversion factor for Mpc to km (3.2426×10^{-20} Mpc/km), we get

$H_0 = 2.326 \times 10^{-18}\ s^{-1}$

$t = 1/H_0 = 4.340 \times 10^{17}$ s = **13.62×10^9 years** (1 year = 31,556,926 seconds)

This is very close to the current best estimate (also from WMAP) for the age of the Universe ($13.7 \pm 0.2) \times 10^9$ years, and is about three times the age of the Earth (~4.6 billion years). This question was posed to try to make students relate the age of the Universe to something they might know beforehand.

www.astroex.org