SECOND YEAR LABORATORY
CEPHEID VARIABLES

1 Aims

To use and understand the method of distance determination to nearby galaxies using Cepheid variable stars.

2 Objectives

1. To construct lightcurves of Cepheid variable stars in NGC4258 from HST data.
2. To understand and use the astronomical magnitude system.
3. To gain experience in fitting non-analytic models to data.
4. To measure the distance to NGC4258 using the photometric lightcurves.

3 Introduction

Cepheid variable stars are blue giant stars which do not have the usual stability against sudden radial expansions and contractions. They pulsate periodically, and vary in brightness over a pulsational period [1]. They give us one of the most powerful methods of distance determination due to the fact that their variations follow a period-luminosity law; the period of the variation is directly proportional to the luminosity of the star [2]. The object of this experiment is to locate Cepheid variable stars in a sequence of Hubble Space Telescope (HST) observations of the nearby spiral galaxy NGC4258 [3], [4] and to measure their brightness variations. From this their luminosity can be calculated, and comparison with their mean apparent brightness gives the distance to the galaxy.

4 Method

If you are in the Schuster building, log on to the computer using the username cepheid and a password which will be given to you by the demonstrator. Otherwise you should download the ds9 software from https://sites.google.com/cfa.harvard.edu/saoimageds9 where versions for Windows, MacOS and Linux are available. See the guide at http://www.jb.man.ac.uk/~gbendo/Sci/Pict/DS9guide.pdf for information on using ds9. If you are not on the Schuster computer, you can get the data in a zip file (92Mb total) from Blackboard.

Study the attached figure from [4] which discussed the results from the HST imaging. The HST instrument used is the WFPC2 (Wide Field & Planetary Camera 2) which has four CCD chips, three large and one small. The observations were taken in the outer regions of the galaxy NGC4258.

The files u01_n.fits up to u12_n.fits contain data taken on different dates in the spring of 1998 from the WFn chip, where n is 2, 3 or 4. The figure from the paper indicates the Cepheid variables identified in the project. For each file, open the file in ds9 and then zoom and pan around as needed to find each Cepheid that you wish to measure.

You will need the date of observation of each file, which you can get using File→ View Header, and then page down to the keyword EXPSTART (in the section 'Exposure information'; units are days since midnight on November 17, 1858).

For each file, use the "region" menu in ds9 to measure the counts in as many Cepheids as possible in each image. To access this menu, go to edit → region, and then pull out the region you want on the main image using the cursor. Next, double-click in the region and go to "analysis" to get the statistics in this window. Record the total signal and number of pixels. You also need to measure the background (brightness away from the star). The easiest way to do this is to use two circular regions around the star, one of which has a relatively small radius around the star but contains all of its emission, and one with a larger radius which includes the star, together with more background (but no other stars). If you want to re-use the regions you have selected, you can use "save regions" under the "region" menu to save to a file, and "load regions" to reload the same region when processing a different image. As well as saving time, this will ensure that you keep exactly the same regions for measurement when processing different images. There may be very slight shifts (one or two pixels) between images.

If you are proficient in Python, you may be able to automate the process. FITS files can be read using the astropy package, by importing the getdata routine (from astropy.io.fits import getdata) and using it to form a numpy array (a = getdata('filename.fits')) of the data. If you are doing this, you can also get a header object using h=getheader('filename.fits') and access the exposure time information by e.g. h['EXPSTART'].

5 Results

Measure the brightness of as many Cepheids as possible for each dataset, plot them appropriately on graphs and deduce the period and luminosity of each Cepheid. You will need to bear in mind the shape of the Cepheid light-curve (e.g. [1], [2]) and think about how to get the best possible fit of such a light-curve to your data for each star. How big do you think the $\chi 2$ of each fit is?

Measure the mean apparent brightness of each Cepheid. The scaling of the HST data is such that a star which gives 1000 counts would have an apparent magnitude of 22.57. You may wish to look up the definitions of absolute and apparent magnitude in PHYS10191 notes or any textbook on introductory astronomy (e.g. [2]). Use your data to calculate the absolute magnitudes of the Cepheids, and hence the distance to NGC4258 with an estimate of the error.

6 Questions

If the redshift of NGC4258 corresponds to a recession velocity of 440km/s, deduce a value for the Hubble constant. What is the major error likely to be? How is the Hubble constant derived from Cepheid measurements in practice?

It is useful to measure a couple of stars of different brightnesses randomly chosen from the field. Why?

What sort of statistics are obeyed by the photon counts that you have obtained by the photometry? Given that 7 photons are detected per count registered on the CCD, what does this tell you about your photometric accuracy and is this consistent with your results?

Why were the observations taken so far from the centre of NGC4258?

Can the observations be done from a telescope on the ground instead of the HST?

Where do Cepheids lie on the Hertzsprung-Russell diagram?

7 References

[1] Shu, F., The Physical Universe: An Introduction to Astronomy, Mill Valley, California, 1981
[2] Zeilik & Gregory, Introductory Astronomy & Astrophysics, Saunders College Publishing, 1999
[3] Maoz, E., et al., 1999. Nature, vol.401, p.351
[4] Newman, J.A., et al., 2001. Astrophysical Journal, vol. 553, p.562, also available on https://arxiv.org/pdf/astro-ph/0012377.pdf

Neal Jackson, June 2020.

Fig. 1. 13' Digital Sky Survey image of NGC 4258, with the field observed using HST superimposed. North is oriented vertically and east to the left in this image. Reproduced from [4].

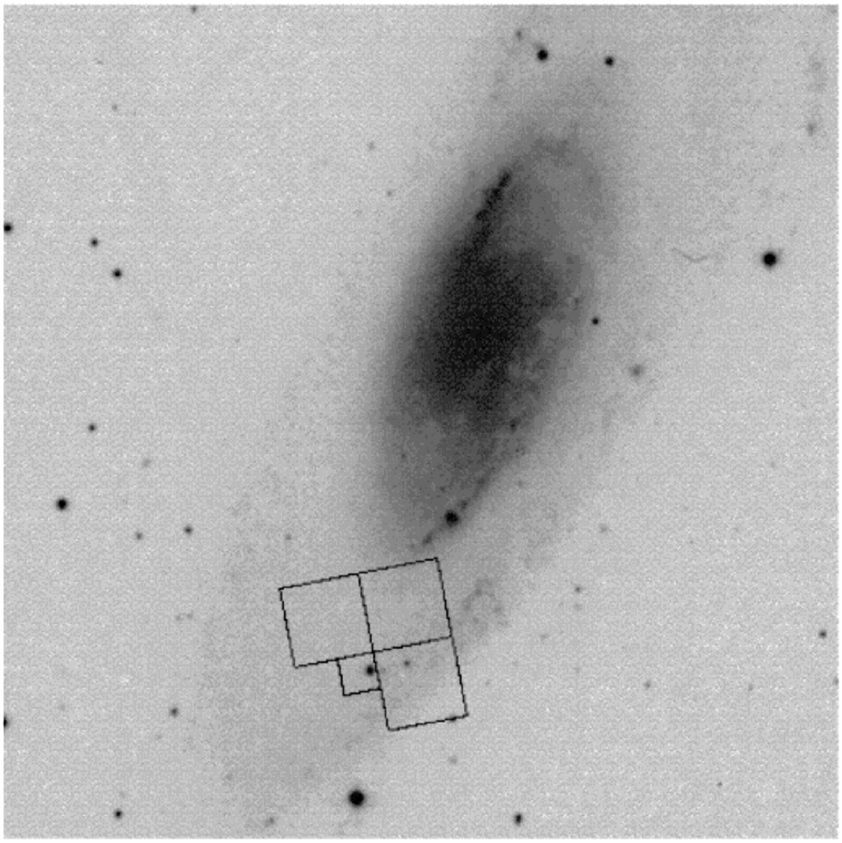
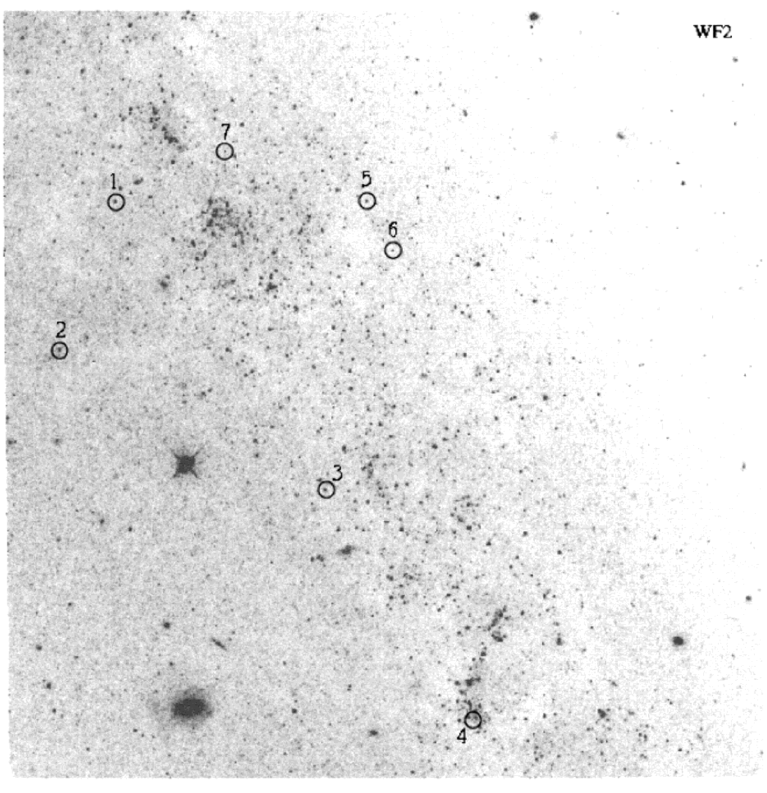


Fig. 2. Image of the field covered by WF2 obtained by co-adding all images. The candidate Cepheids found on WF2 are circled and labelled. Reproduced from [4].



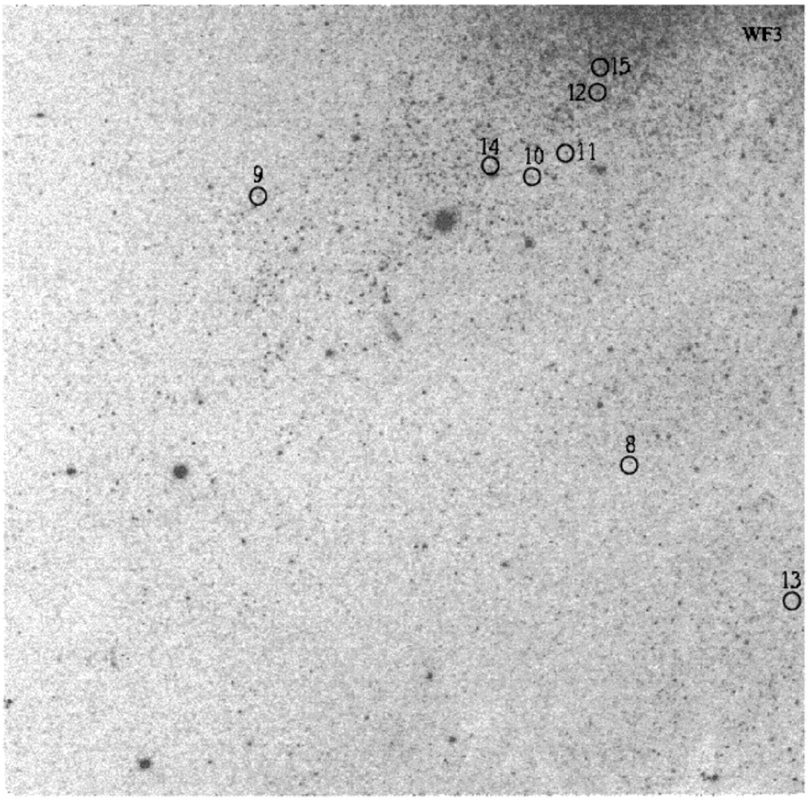


Fig. 3. As Fig. 2, but for WF3.