The Universe Through Hubble's Eyes

Part 1: Measuring Distance using Cepheid Variable Stars

Aims:

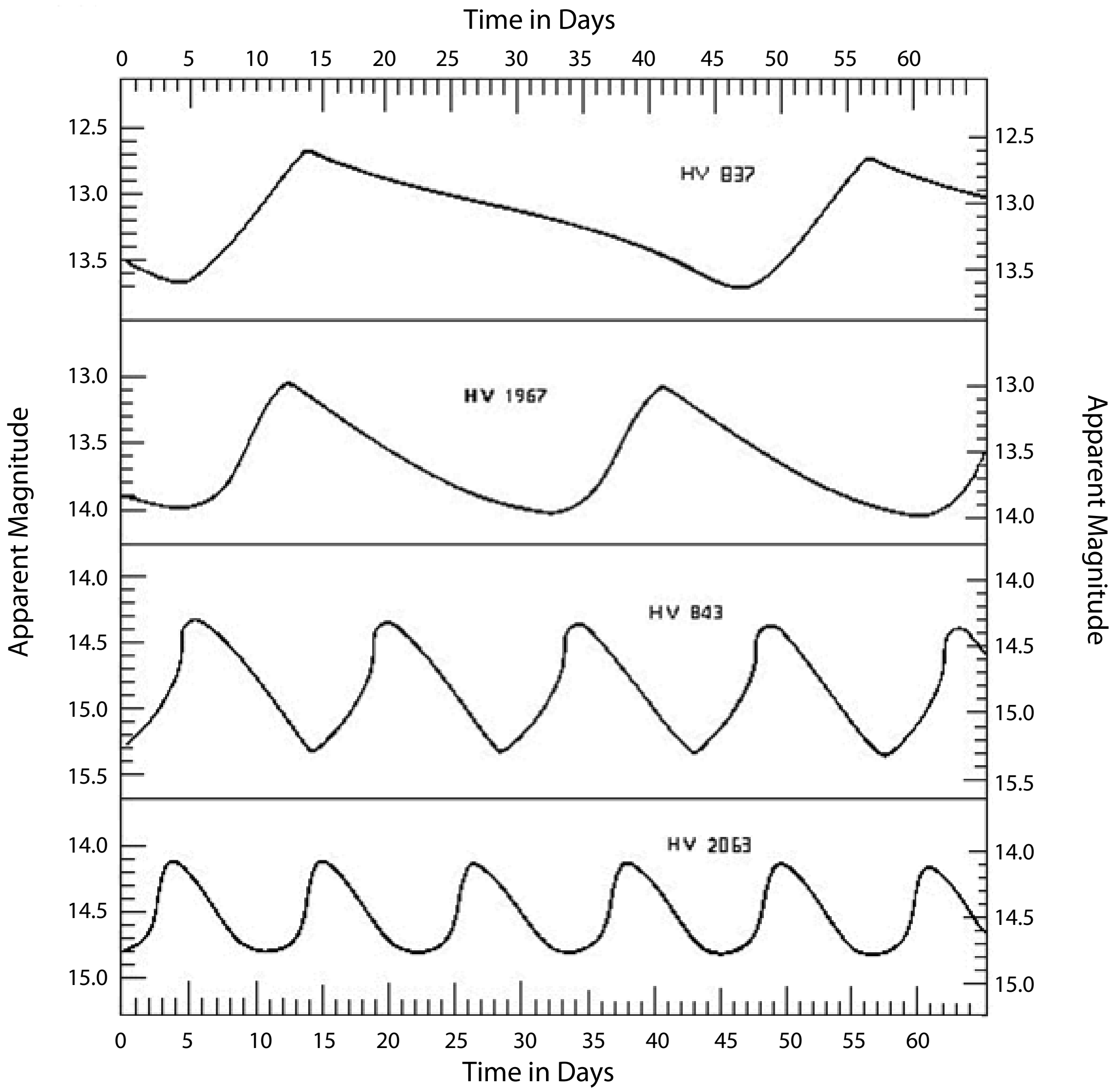
In this project, you are going to use the relationship that Henrietta Leavitt discovered to find out how far away four Cepheid variable stars are from us. There are three steps in the process:

1. Find the apparent luminosity and period of the Cepheids from their light curves (the period is the time between two peaks in the Cepheid's brightness).
2. Find the actual luminosity of the Cepheids from their periods.
3. Find the distance of the Cepheids from the apparent and actual luminosities.

1. Finding the apparent luminosity:

The graphs below show the light curves for four variable Cepheids over several weeks. Note how regular the variation is for each. The vertical axis gives the **apparent luminosity** of the Cepheids.

a. Start by using the horizontal scale on these graphs to find the **period** of each of these stars.
b. Then use the vertical scale on the graphs to find the **average apparent luminosity**
c. Enter your answers into the table on page 3.



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2. Finding the actual or absolute luminosity:

Next you are going to use the data in the table below to plot a graph of period against absolute (actual) luminosity. There is a problem with this data as it stands – if you plot your graph you will find that the points do not lie on a straight line, however, it is much easier to use a straight-line graph to read off information. Because of this, mathematicians and scientists often use special graph paper, called log-linear graph paper, to convert data points on a curve into data points on a straight line.

Star	Period (days)	$\log_{10}$ (Period/days)	Absolute Luminosity
U Aq1	7		-3.66
Sz Aq1	17.1		-4.78
TT Aq1	13.8		-4.51
FM Aq1	6.1		-3.48
FN Aq1	9.5		-4.04
IU Aq1	22		-5.1
V493 Aq1	3		-2.58
V496 Aq1	6.8		-3.62
V526 Aq1	4.2		-3.02
V800 Aq1	20.1		-4.98
V1162 Aq1	5.4		-3.32
V340 Ara	20.8		-5.03
V475 Ara	1.5		-1.72
RX Aur	11.6		-4.29
SY Aur	10.1		-4.12
YZ Aur	18.2		-4.86
FF Aur	2.1		-2.15
AD Cam	11.3		-4.25
SS CMa	12.4		-4.37
VY Car	18.9		-4.91
WZ Car	23		-5.16
YZ Car	18.2		-4.86
KN Cen	34		-5.65
CP Cep	17.9		-4.84
VX Cyg	20.1		-4.99
V396 Cyg	33.2		-5.62
V609 Cyg	31.1		-5.53
T Mon	27		-5.36
X Pup	26		-5.31

There are two sorts of graph paper provided to plot these points. On page 4 the horizontal axis of the graph paper is the period of the cepheids and the scale is logarithmic. On page 5 the lines on the horizontal axis are equally spaced - to use this graph paper you will need to fill in the blank column above using your calculator to take $\log_{10}\left(\frac{\text{Period}}{\text{days}}\right)$.

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Whichever graph paper you choose, you will need to decide on a scale for the vertical axis and label it appropriately. Once you have plotted your points you should draw a line of best fit though them (alternatively you can look in the spreadsheets and use the tab labelled “Abs Lum vs Period” or “Abs Lum vs Log(Period)”).

When you have your straight line, use it to find the absolute luminosity of the four Cepheids.

3. Finding the distance

Now that you know the apparent and absolute luminosity for the four Cepheids, you can calculate the distance to each of the Cepheids and to galaxies to which they belong.

There is an equation which relates apparent magnitude and absolute magnitude that will provide us with a distance in parsecs.

$$M - m = 5 - 5\log_{10} d \qquad (1)$$

Tips:

1. You may find it easier to rearrange the equation above (1) so that d is the subject of the equation (that is $d =$…..)
2. You can then take each of your values for m and M and put them into the rearranged equation to find d.
3. 1 parsec = 3.26 light years. Use this information to convert the distance in parsecs to a distance in light years.

Star	Average Period (days)	Apparent Luminosity (m)	Absolute Luminosity (M)	Distance (d in parsecs)	Distance (light years)
HV 837					
HV 1967					
HV 843					
HV 2063					

Use the values below also find the distance to these other well known stars:

Object	m	M	Distance (parsecs)	Distance (light years)
Sun	-26.8	4.83		
Sirius	-1.47	1.41		
Vega	0.04	0.5		
Betelgeuse	0.41	-5.6		
Polaris	1.99	-3.2		

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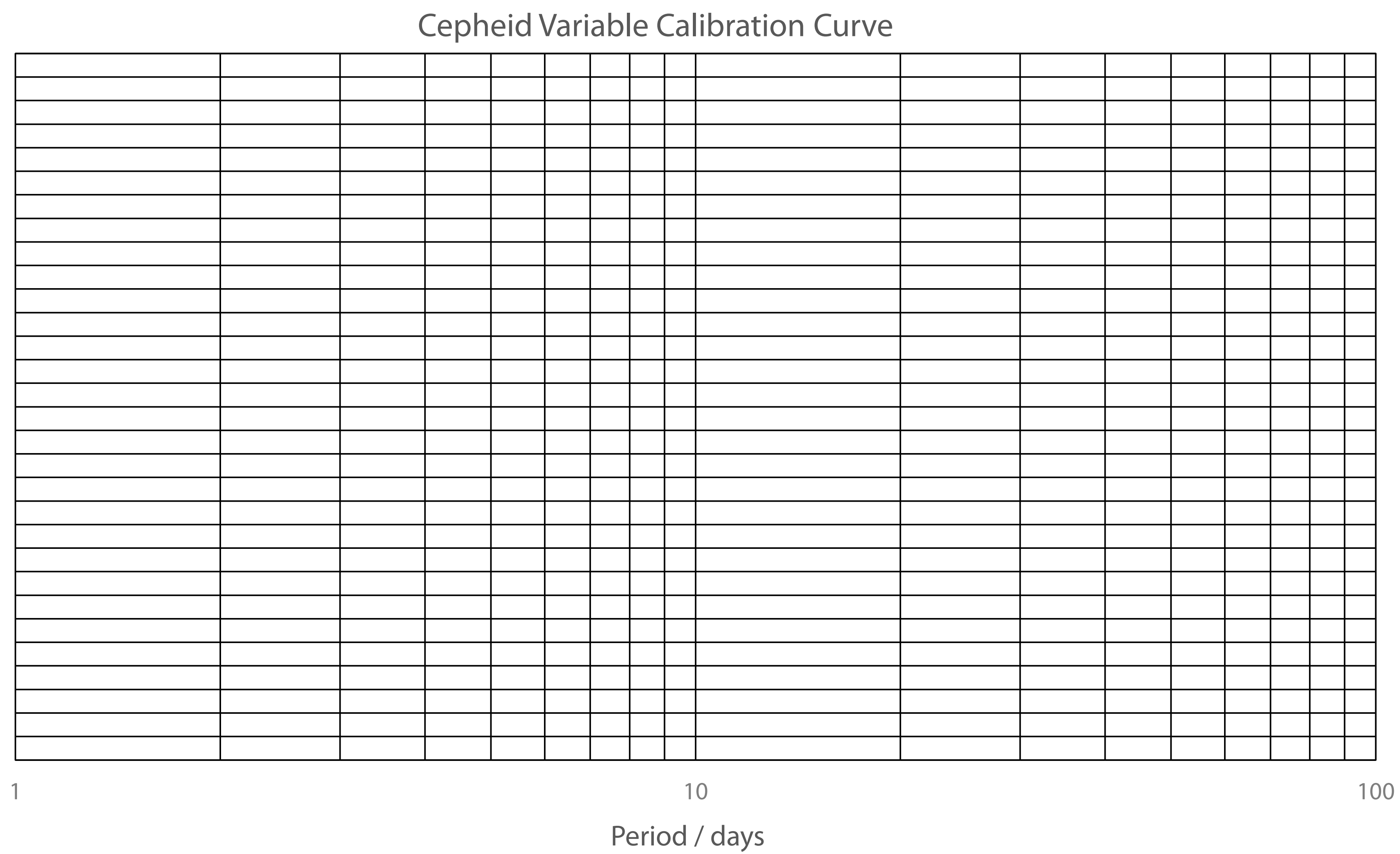
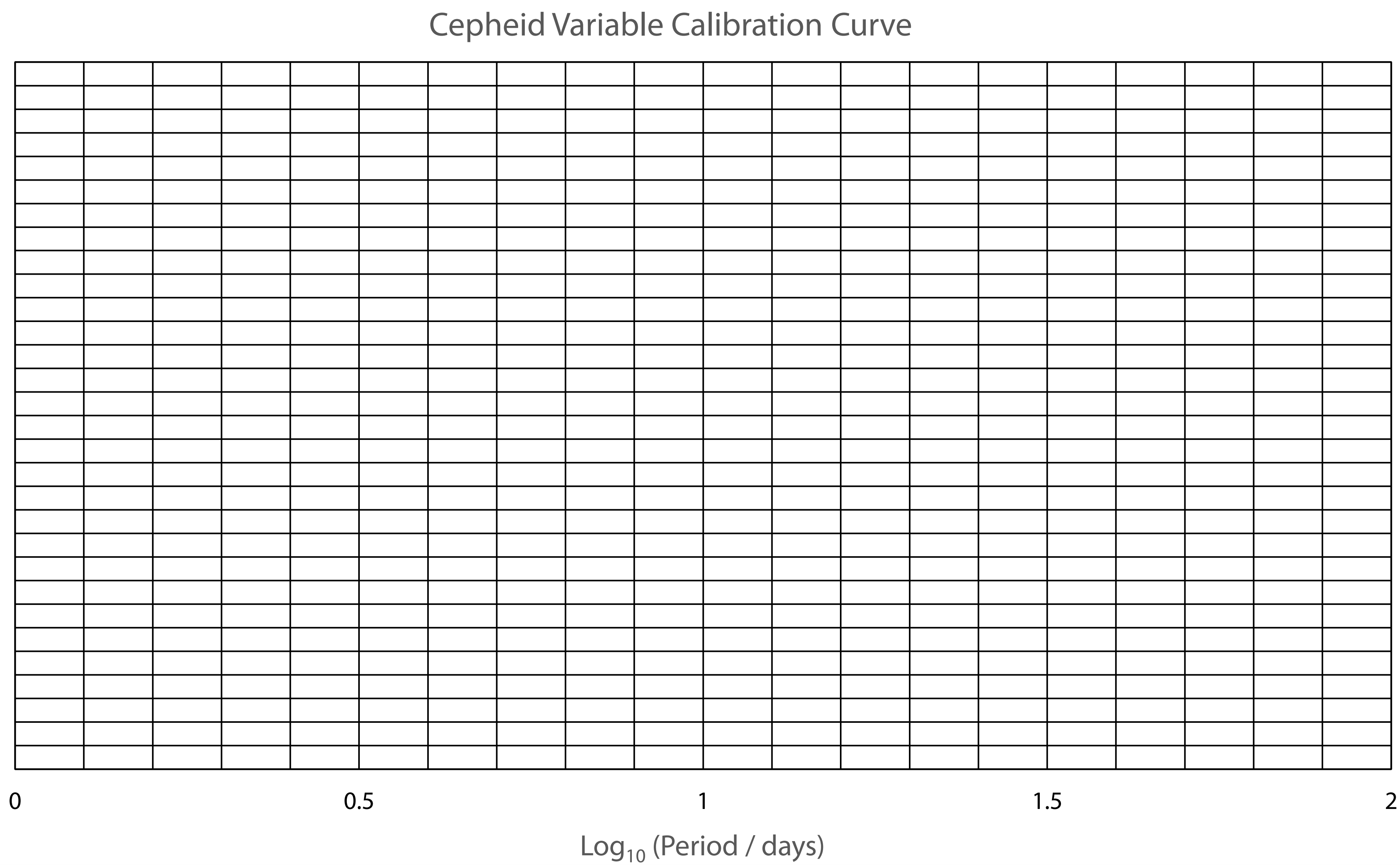

Cepheid Variable Calibration Curve
1
10
100
Period / days



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Part 2: Measuring The Age of the Universe

Aims:

Using images and spectra of a number of galaxies you will determine their distance from us and their velocity away from us. From these distances and velocities we will calculate an approximate age of the Universe.

Background:

In the 1920's Edwin P Hubble discovered a relationship that is now known as Hubble's Law. This law states that the velocity of a galaxy is proportional to its distance from us:

$$\boldsymbol{v = H_0 d}$$

where v is the velocity of the galaxy (in $\mathrm{km/s}$), d is its distance (in megaparsecs, Mpc; $1\mathrm{Mpc} = 3.086 \times 10^{19}\ \mathrm{km}$) and H_0 is Hubble's constant.

So, for example, a galaxy that is moving away from us at twice the speed of another galaxy is twice as far away. The exact value of Hubble's constant is still uncertain in astrophysics today, and during this practical we are going to begin to understand why.

To calculate the value of Hubble's constant we need to

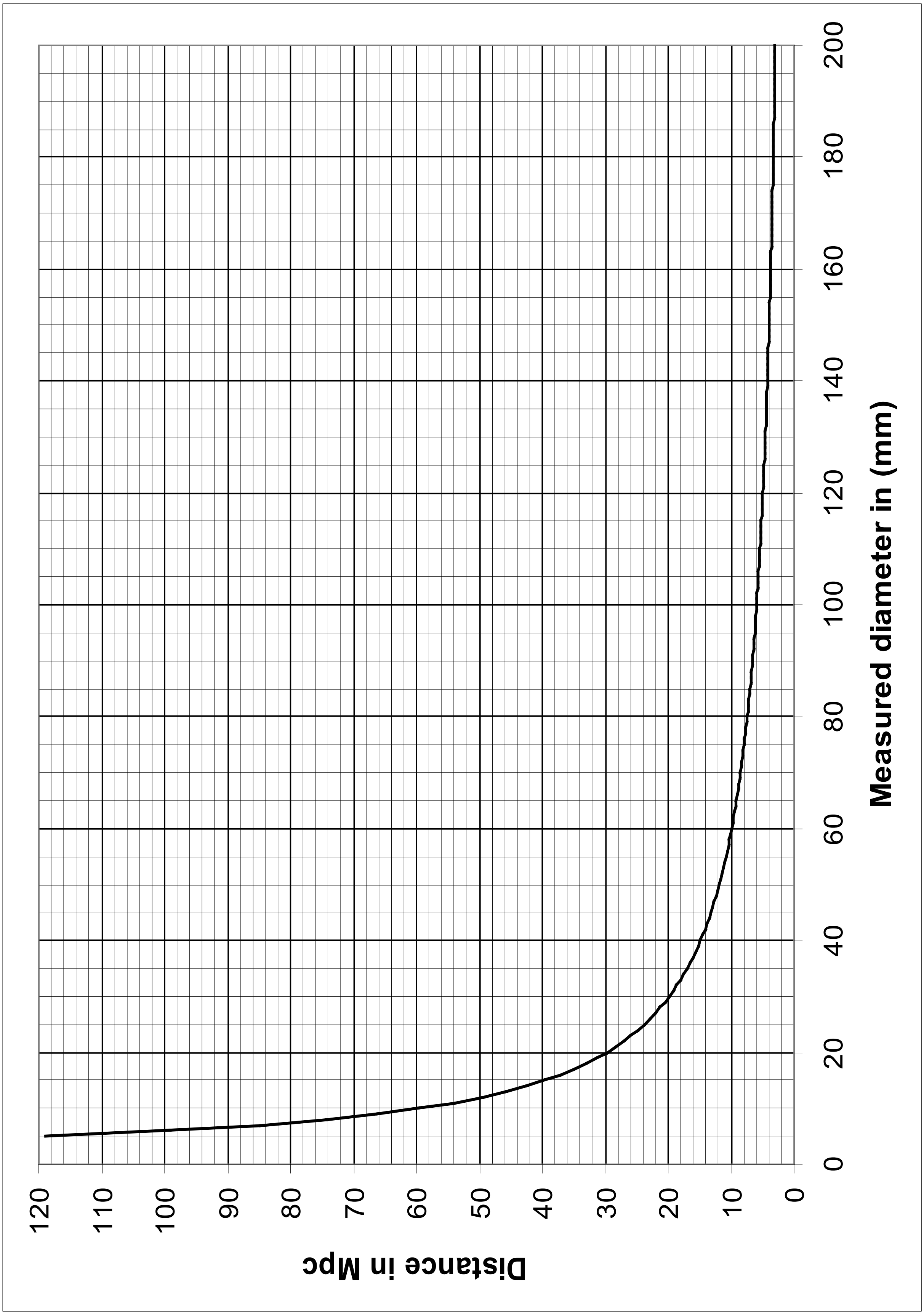
1. Measure the distance of galaxies

2. Measure the velocity of galaxies.

Task 1: Measuring Distance (an alternative method):

- In the handout you will find a number of black and white images of galaxies. By measuring the sizes of the galaxies in these images with a ruler we are going to estimate their distances.
- We have to assume that all galaxies of the same shape are approximately the same size – this allows us to produce a graph of their size in millimetres against their distance from us. This graph has been plotted for you and is **Graph 1** on page 7 of your handout.
- Using a ruler, measure in millimetres the size of each of the galaxies in the black and white images. Enter your results in the table provided
- Convert each of your measurements in millimetres to a distance in megaparsecs (Mpc) using Graph 1 and enter it into the table.
- This completes part one of our practical. Now we need to measure the galaxy velocities!

Graph 1


Measured diameter in (mm)
0
20
40
60
80
100
120
140
160
180
200
Distance in Mpc
120
110
100
90
80
70
60
50
40
30
20
10
0

Galaxy	Size (mm)	**Distance (Mpc)**	CaK		CaH		Average Z	**Velocity (km/s)**
			λ	$z_1 = \frac{(\lambda - 3933.7)}{3933.7}$	λ	$z_2 = \frac{(\lambda - 3968.5)}{3968.5}$	$z = \frac{z_1 + z_2}{2}$	$v = cz$ ($c = 3 \times 10^5$ km/s)
NGC 1357								
NGC 2276								
NGC 2903								
NGC 3627								
NGC 4775								
NGC 6181								
NGC 6643								
NGC 1832								
NGC 5248								
NGC 4631								
NGC 2775								
NGC 3147								

Galaxy	Size (mm)	Distance (Mpc)	CaK		CaH		Average Z	Velocity (km/s)
			λ	$z_1 = \frac{(\lambda - 3933.7)}{3933.7}$	λ	$z_2 = \frac{(\lambda - 3968.5)}{3968.5}$	$z = \frac{z_1 + z_2}{2}$	$v = cz$ ($c = 3 \times 10^5$ km/s)
NGC 3245								
NGC 3368								
NGC 3516								
NGC 4472								
NGC 5548								
NGC 7469								
NGC 3034								
NGC 3227								
NGC 3310								
NGC 3471								

Galaxy	Size (mm)	Distance (Mpc)	CaK		CaH		Average Z	Velocity (km/s)
			λ	$z_1 = \frac{(\lambda - 3933.7)}{3933.7}$	λ	$z_2 = \frac{(\lambda - 3968.5)}{3968.5}$	$z = \frac{z_1 + z_2}{2}$	$v = cz$ ($c = 3 \times 10^5$ km/s)
NGC 3623								
NGC 3941								
NGC 5866								
NGC 6217								
NGC 6764								

Gradient = H_0= ____________________ km/s/Mpc

Age of the Universe = $3.086 \times 10^{19}/H_0$ = ________________seconds

Age of the Universe = ________________sec / ($60 \times 60 \times 24 \times 365.25$)

= _______________ yrs

Task 2: Measuring Velocity:

- The velocity of a galaxy is measured using the Doppler Effect. The electromagnetic radiation coming from a moving object is shifted in wavelength because of its motion:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

- λ_0 is the wavelength in the lab (rest wavelength) and λ is the wavelength of the moving galaxy.
- Wavelengths are usually measured in Angstroms (Å). The speed of light has a constant value of $300{,}000\ \text{km/s}$.
- Astronomers refer to this change in wavelength as a redshift, z:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{v}{c}$$

- So, by measuring the shift in lines in a galaxy's spectrum we are able to measure the speed of the galaxy.
- Underneath each of the black and white images you have been given a spectrum for each of the galaxies. On the spectrum there are two reference lines (rest wavelength, λ_0) labelled close to the axes and two troughs in the plotted line. We need to measure the difference in wavelength between each trough and the marked black line (see figure).
- From each spectrum read off and record your values for λ (wavelength) for the CaK trough and for the CaH trough in the table on page 6 and 7 (or in the excel spreadsheet tab titled "Hubble's Law").
- The columns next to each of your entries for λ then give the formula for you to calculate the redshift according to the CaK troughs and the CaH troughs.
- Using both the CaK and CaH line will give you two values for z so that we may take an average to get our best estimate for the velocity of the galaxy.
- In the final column of the table we use our average value of z to calculate, v, by multiplying z by the speed of light, c.

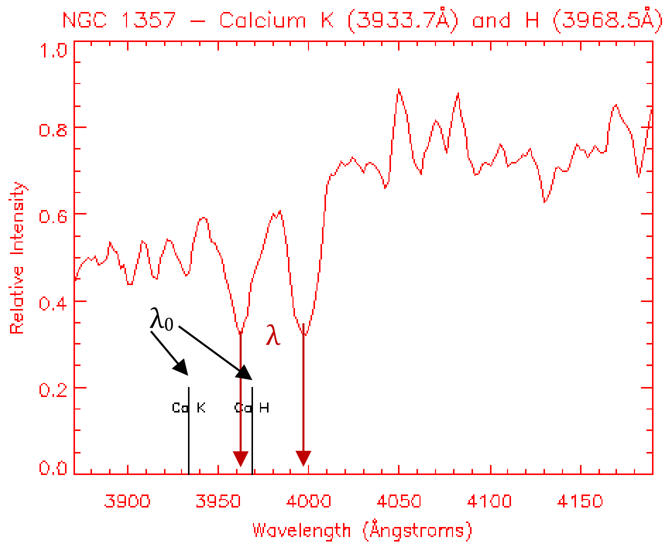


Figure 1: An example of a galaxy spectrum showing the reference laboratory wavelengths for CaK and CaH (in black). The values of the wavelength for these lines is given in the table on pages 8 to 10. The red arrows are the wavelength that you would read off as the wavelength for the moving galaxy for CaK (left red arrow) and CaH (right red arrow).

Tips:

1. Not all troughs in the spectra will stand out as clearly as those shown in the spectrum in **Figure 1**.
2. If you are not sure what troughs to measure the wavelength of, try a value in the table and see whether the redshift from the two different troughs is very different. If it is, look again at the spectrum.
3. Some galaxies may be "blue-shifted" (their velocity is negative). This is OK and you should include them.

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Hubble's Law

Results & Conclusions:

- Now we reconstruct Hubble's Law. In the table two headings are in **bold**. It is these values in the table that we will use to plot our graph of Hubble's Law.
- Using the graph paper titled "Hubble's Law" plot the distances you calculated in task 1 against the velocities you calculated in task 2 for each galaxy.
- Once you have plotted all your values draw a best fit line through the points. Think about whether the line should go through (0,0).
- When you are satisfied with your best fit line you should work out the gradient (or slope) of the line. The gradient you calculate is equal to Hubble's constant and you should fill in your value beneath your table.
- Hubble's constant has the units of 1 over time and is given by

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

  where t is the age of the Universe.

- Beneath the table on page 8, the calculation is explained to convert your gradient, $\boldsymbol{H_0}$, into an age for the Universe.
- How does your value compare with other students' results? Is it the same or very different? Why do you think that might be?

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