

UNIVERSITY COLLEGE LONDON

University Of London Observatory

PHAS1510 – Certificate in Astronomy 1213.01

PHAS1510-01: The Hubble Redshift–Distance Relation

Name: _____

An experienced student should aim to complete this practical in two sessions (and should not spend more than 3 sessions on it).

1 Objectives

The objectives of this experiment are to use a simulated ‘spectrometer’ to acquire spectra and apparent magnitudes of distant galaxies, and then to determine their distances using apparent and absolute magnitudes. Using these distances and the galaxies’ velocities, determined by measuring the Doppler shifts of the ionised calcium (a calcium atom with 1 electron removed) *H* and *K* lines, the rate of expansion of the universe can be calculated, and its age estimated. A secondary objective is to encourage you to consider the *accuracy* of your results, and the corresponding *precision* with which you quote them.

2 Items required

You will need:

- access to a PC running MS-Windows and the CLEA/ULO program ‘The Hubble Redshift Distance Relation’, and a scientific pocket calculator. (Before running the CLEA/ULO program you should ensure that the MS-Windows default printer on the desktop of the ULO computer you are using is set to the ‘ULO-NWcolourprinter’. Ask a demonstrator to make the change for you if you are unsure how to do this. The link to it may be slow but the printer is in your work room and not elsewhere on the ULO site.)

(This practical is also available on the Certificate’s ULO Web site as a downloadable zip file.)

3 Introduction

All of the galaxies in the universe, with the exception of only a few nearby ones, are moving away from the Milky Way. This was first discovered in the early twentieth century by astronomer Vesto Slipher, who noted shifts in absorption lines in the spectra of most spiral galaxies.* Slipher found that these absorption lines had longer wavelengths (i.e., were ‘red shifted’) compared to those observed in the laboratory. Several mechanisms can give rise to redshifts, among which is the Doppler shift: a change in the wavelength of light reaching an observer from a source when the source and the observer have relative motion along the line

*A spectrum is the array of colours or wavelengths obtained when light from a star or galaxy is dispersed, as by a spectroscope. There are small hand spectroscopes in the classroom that can be used to examine the spectra of artificial light sources: please ask a demonstrator to show you where they are and how to use one. Absorption lines are dark lines superimposed on a continuous spectrum, such that colours are ‘missing’ due to the absorption of those colours by atoms.

of sight. Assuming that the wavelength increase was caused by the Doppler shift, Slipher concluded that the distant galaxies are nearly all moving away from us.

In the 1920s, Edwin Hubble measured the distances of the galaxies for the first time, and noticed that further a galaxy was from the Milky Way, the faster it was moving away. Astrophysicists readily interpreted Hubble's relation as evidence of a universal expansion. The distance between all galaxies in the universe is getting bigger with time; thus an observer in *any* galaxy, not just our own, would see all the other galaxies travelling away, with the furthest galaxy travelling the fastest.

The expansion is believed to be a result of a 'Big Bang', which occurred between 10 and 20 thousand million years ago, an interval which can be calculated by making measurements like those by Hubble. The rate of expansion of the universe indicates how long it has been expanding. This rate is determined by plotting the velocities of galaxies against their distances. The slope of the graph, a number called the Hubble Constant, H_0 , represents how fast a galaxy at a given distance is receding from us.[†]

4 Experiment

4.1 Using the 'telescope'

The PC should already be switched on. If the program is not already running, find its icon and double-click the left mouse button to start the program. (In this script an unspecified 'click' means you should use the left mouse button; some of the features of the software require the use of the right mouse button and this will always be specified.) To gain access to the (virtual) telescope click **File|Log In**;[‡] and click 'Okay' twice without filling anything in (i.e., don't bother to "log in"). Then click **File|Run**. The computer should confirm access to the Kitt Peak 0.9-m (36") telescope;[§] click OK.

The screen shows the control panel and view window as found in the 'warm room' at the observatory. The dome is currently closed. Open the dome by clicking **Dome**. The view shown is from the finder scope, which is mounted on the side of the telescope and points in the same direction. The field of view of the finder scope is much larger than the field of view of the main telescope so that it can be used to locate objects easily. A CCD camera attached to the front of the finder scope displays the field of view on the screen.

Note that the stars are drifting westwards in the sky, due to the Earth's rotation; the Right Ascension coördinate, displayed to the left of the view window, is consequently increasing. A tracking motor in the telescope mount is designed to keep it pointed at the same point in the sky as the Earth rotates. Click on **Tracking** to start this motor so that the Right Ascension coördinate stops changing and the field of view remains steady.

[†]Hubble's 'Constant' is constant in space, but not in time. Until recently, it was widely believed that Hubble's Constant was decreasing with time, as the rate of expansion of the universe slowed under the mutual gravitational pull of the galaxies within it. Within the last few years, however, evidence has accumulated which suggests that the rate of expansion is currently *increasing*.

[‡]This means click on the '**File**' menu, then select '**Log In**' from the options offered. In this script, instructions in **this font** always indicate options on the computer screen.

[§]ULO does not have a telescope of this size. The Radcliffe and Allen telescopes each have approximately 24" apertures

The displayed field of view shows the cluster of galaxies in the constellation Coma Berenices. Such clusters are giant systems of up to tens thousands of gravitationally bound galaxies. The red outline of a square in the centre of the field is the instrument field of view. Select a galaxy for measurement by moving the red outline until that the galaxy image sits within the square. To slew (i.e., move) the telescope, click on the appropriate direction buttons North, South, East, West. To move continuously, press and hold down the left mouse button. Notice the red light comes on to indicate the telescope is slewing in that direction. The speed, or slew rate, of the telescope can be adjusted by clicking on the **Slew Rate** button (with 1 being the slowest and 16 the fastest).

4.2 Using the spectrometer

Once a galaxy has been selected, click on **Change View**. The word ‘instrument’ will appear below to indicate that the spectrometer has been selected. The spectrometer is part of the main telescope and so the field of view is of a higher magnification than that of the finder scope. In the centre of the view are two short parallel red lines, which show the position of the *slit* of the spectrometer. A spectrum is produced by collecting light from an object through the slit and then shining it onto a diffraction grating, which disperses the light into its constituent wavelengths onto a CCD detector that can be read out digitally. Slew the telescope so that the slit is positioned over the selected galaxy. Try to position the slit on the brightest portion of the galaxy – the more light that enters the spectrometer, the stronger the signal detected, and the shorter the time required to get a usable spectrum. If the slit is positioned on the fainter parts of the galaxy, a good spectrum can still be obtained, but the exposure time or ‘integration’ required will be much longer. However, if the slit is positioned completely off the galaxy, only a spectrum of the background sky will be obtained, which will mostly be random noise.

You should check that you have indeed observed a galaxy, and not a star. This is straightforward for obviously extended sources, but for point-like sources the easiest way to check is to look at the target brightness (given on the spectrum-integration screen) - pretty much all galaxies are rather faint ($V > 10$), and all the stars in the simulation are rather bright ($V < 6$).

4.3 Obtaining a spectrum

To collect data for the galaxy, click on **Take Reading**. This will open a window showing a plot of intensity versus wavelength in Ångstroms ($1\text{Å} = 10^{-10}$ metres). To initiate the data collection, click on **Start/Resume Count**. The spectrometer will begin to accumulate photons in each wavelength interval across the spectrum. The spectrum will become steadily clearer as more and more photons are collected. The following information appears beneath the plot:

- Object: the ‘name’ of the galaxy.
- Apparent Magnitude: the visual magnitude of the object.
- Right Ascension: the celestial coördinates equivalent of longitude.
- Declination: the celestial coördinate equivalent of latitude.
- Integration (Seconds): the exposure time elapsed.
- Photon Count: the total number of photons collected.

- Avg. per Channel: the average number of photons per pixel.
- Signal/Noise (S/N): a measurement of the quality of the data, which here depends mainly on the number of photons collected. The more photons collected, the less noise in the spectrum, making the absorption lines easier to pick out. You should aim for a S/N of much greater than 10 in each spectrum. The larger the better but you pay the price of longer observing time. Photons are collected one by one and could be of any wavelength. Thus for faint galaxies, it is necessary to integrate for some time. *Important.* Make a record of the (S/N) achieved and the integration time for each of your measurements on a spectrum.

Once a suitable S/N ratio ($\gg 10$) has been obtained, click **Stop count** and check to see if the *H&K* lines are clearly visible.[¶] If it is necessary to integrate for longer, click on **Start/Resume Count** again until the S/N ratio is sufficiently high that the lines stand out clearly. This will normally require around 40,000 photons. The wavelengths of the *H&K* lines will be significantly larger than their laboratory values of 3968.5 and 3933.7 Ångstroms, respectively, because the galaxy is moving away and the lines have been red-shifted.

4.4 Measuring wavelengths and magnitudes

Position the cursor over the spectrum and hold down the left-hand mouse button. A red cursor will be visible on the spectrum and a wavelength display will appear above the plot. Move the cursor (keeping the mouse button depressed) to the centre of each of the calcium lines in turn, and read off the wavelength of each line from the display. Measure the *K* line, which is on the left (i.e., at the shorter wavelength). Once the *K* line's wavelength has been measured, its value can be entered in a box provided by clicking **Record Meas.** Now measure and record the wavelength of the *H* line in the same manner. Ignore the Blend (*G*-band) line. The magnitude is recorded automatically.

4.5 Repeating for each galaxy

Once all measurements have been recorded for the galaxy, click **Return** to get back to the telescope window. Click on **Change View** to select the finder scope. To select a new field of view, click **Field** and highlight a new galaxy cluster and then click **OK**. Follow the procedure as described above for ONE galaxy from EACH galaxy cluster on the list, ignore the Sagittarius option. When data from five different galaxies, one from each cluster, have been collected, return once more to the telescope window and click **File|Data|Review**. This allows the measurements to be reviewed. Ensure that for each galaxy the apparent magnitude and red-shifted values of the *H&K* lines are displayed in the window. If everything is there, click **Close** and then go back to **File|Data|Print** to print out the data. Use these in the 'Calculations' section, and remember to attach them to the worksheet at the end of this script to be handed in for marking.

*Note - It may not always be possible to see both the *H&K* lines on every measurement taken, as sometimes the *H* line can be redshifted off the scale used to record measurements. In this case, just the *K* line should be recorded.*

[¶]These lines result from absorption by singly-ionized calcium in the atmospheres of solar-type stars in the galaxy. Although calcium is not a particularly abundant element, these lines happen to be strong in stars across a wide range of temperatures, so they are often the strongest features in the integrated starlight from a galaxy.

5 Calculations

Record each value resulting from the equations below in the appropriate place in the tables provided in the worksheet at the end of this script.

5.1 Redshifts and velocities of galaxies

For every galaxy, compute the redshift (z) for the $H&K$ lines using the equation:

$$z = \frac{\Delta\lambda}{\lambda_0}, \quad (1)$$

where λ_0 is the rest wavelength and $\Delta\lambda$ is the difference between the red-shifted wavelength (the measured value) and the rest wavelength. Hence:

$$\Delta\lambda_K = \lambda_K - \lambda_0(K), \quad (2)$$

and likewise;

$$\Delta\lambda_H = \lambda_H - \lambda_0(H). \quad (3)$$

Average the redshifts for the $H&K$ lines in each galaxy, and compute the velocity of each galaxy from the non-relativistic Doppler formula:

$$v = c \times z, \quad (4)$$

where c is the speed of light (3×10^5 km s⁻¹). (The ‘non-relativistic’ formula is an excellent approximation for velocities much less than the speed of light. You might care to check that it is appropriate for your objects.)

5.2 Distances to galaxies

Determine the distance to each galaxy by assuming its absolute magnitude to be $M = -22$.^{||} If the apparent magnitude of a galaxy is m , then its distance D can then be found from the distance modulus:

$$m - M = 5 \log D - 5, \quad (5)$$

where D is in parsecs (and we have ignored the complicating effect of absorption of light by interstellar dust; this effect is small for our targets). Rearrange equation 5 to make $\log D$ the subject; the anti-log then needs to be calculated. (**N.B.** if your maths is rusty and this is gobbledegook, don’t be afraid to ask a demonstrator for a refresher!.) Convert the distances to units of megaparsecs (1 Mpc \equiv 10^6 pc).

5.3 Plotting the Hubble Diagram

Plot a Hubble Diagram by drawing a graph of the velocities of the galaxies (in km s⁻¹) on the vertical y -axis, against the distances to the galaxies (in Mpc) on the horizontal x -axis. Draw a straight line through the origin, $(x, y) = (0, 0)$, that best fits all the data points.* The slope of the line is the Hubble Constant (H_0). To calculate the slope of the line, measure a

^{||}The absolute magnitude of an object is defined to be the magnitude it would appear to have if it were at a distance of 10 parsecs.

*Of course, the line should pass through $(0, 0)$ because an object at a distance of zero is not receding from the observer – indeed that object *is* the observer!

value of D and v from a somewhere near the upper right end of the line of best fit. (Measure from the line, not one of the plotted data points – in effect, you are averaging the results from all your measurements, and are thereby obtaining a more accurate value.) Label this point on the graph. You may do all this the old fashioned way using a handdrawn graph on paper and measure the slope of the graph by hand or using EXCEL and fitting a straight line to the data, remembering to force it through the origin. Either way supply a copy of your graph and results to be marked. Substitute these values from the graph into the following equation to determine H_0 :

$$H_0 = \frac{v}{D} \quad (6)$$

Record this value on the graph, with its units. Label the axes of the graph, give it a meaningful title and remember to attach it to the worksheet along with the printout at the end of the exercise.

5.4 The Age of the Universe

If you divide the distance to a distant galaxy by its recession velocity, you obtain an estimate of how long it has taken the galaxy to reach that distance from the observer (just as if you divide the distance to, say, Scotland by the speed at which you drive, you get the time taken to get there). The distant galaxy was in the same place as the (putative) observer only in the Big Bang; thus this length of time is, in fact, the age of the Universe (under the assumption that the distant galaxy has always been receding from us at the same velocity[†]).

The Hubble Constant, H_0 , describes the increase in velocity which is observed as one looks towards more distant objects in the Universe, and is usually expressed in units of km s^{-1} per megaparsec. A galaxy at a distance of, say, ' x ' Mpc will therefore have a recession velocity of $x \times H_0 \text{ km s}^{-1}$. Using the argument of the previous paragraph, the time it has taken to reach its observed distance is

$$(\text{distance/velocity}) = x/(x \times H_0) = 1/H_0$$

In other words, an estimate of the age of the Universe is obtained simply by taking the inverse of the Hubble Constant: $1/H_0$. This estimate is called the 'Hubble Time', often written as τ_0 (which would actually *be* the age of the universe if the Hubble Constant were constant with time).

Estimate the age of the Universe, in years, by taking the inverse of your determination of the Hubble Constant. *Pay careful attention to units when making your calculation* – your value of the Hubble constant is in km s^{-1} per megaparsec, which you will need to convert to km s^{-1} per km (i.e., units of s^{-1}). Note that $1 \text{ pc} = 3.1 \times 10^{13} \text{ km}$,[‡] and there are 3.15×10^7 seconds in one year. Show your workings and give the end result for this calculation in an organized manner in the worksheet.

[†]Our galaxy and the distant galaxy have a mutual gravitational attraction, which would suggest that the speed at which they are moving apart must be decreasing with time. This would imply that the velocity of recession of a distant object, averaged over the age of the Universe, must be *larger* than its measured velocity. In that case, simply dividing the distance by the measured velocity *overestimates* the true age of the Universe.

However, recent years have seen growing, if debatable, evidence that the rate of expansion of the universe is *increasing* with time, under the influence of a 'cosmological constant' (or 'dark energy') force. If that is the case, then the age argument is reversed, and simply dividing the distance by the measured velocity *underestimates* the true age of the Universe.

[‡]For 'nearby' – i.e., solar-system – objects, professional astronomers habitually use the Astronomical Unit (approximately the mean Earth–Sun distance) as a measure of distance, while for increasing remote objects they use parsecs, kiloparsecs, or megaparsecs. 'Light-years' are generally used only in popular texts.

6 References and Background Reading

1. Zeilik, M. & Gregory, S. *Introductory Astronomy and Astrophysics*, (4th edition). The 3rd edition, by Zeilik, Gregory & Smith, is very similar.
2. Freedman, R.A. & Kaufmann, W.J., *Universe*, 7th edition; especially §§26–5 & 28–3

1. Attach your printout from Section 4.5
2. Redshifts, velocities, and distance of galaxies: complete the table overleaf. Consider how accurately you can measure line wavelengths – and hence redshifts – and be sure to quote velocities to an appropriate level of precision. (Summarise your reasoning in the space below.)

3. Plot the Hubble Diagram (Section 5.3) – be sure to attach your graph. Show your working, and make a rough estimate of how accurate your result is (and hence quote your result to an appropriate degree of precision). Consult a demonstrator if you are unsure how to set about this.

Value of H_0 = _____

4. Using your value for H_0 , calculate the age of the Universe (Section 5.4).

Age of the Universe = _____

Q2: Redshifts, velocities, distances

Galaxy Cluster:	Com	Uma-I	UMa-II	Boo	CrB
λ_K (Å):					
$\Delta\lambda_K$ (Å): ($\lambda_0 = 3933.7\text{Å}$)					
Redshift, z_K :					
λ_H (Å):					
$\Delta\lambda_H$ (Å): ($\lambda_0 = 3968.5\text{Å}$)					
Redshift, z_H :					
Average redshift, \bar{z} :					
Velocity, \bar{v} (km s ⁻¹):					
Absolute magnitude, M :					
Apparent magnitude, m :					
$\log_{10}(\text{Distance}/\text{pc})$:					
Distance (pc):					
Distance (Mpc):					