

## UNIT 18 - HUBBLE'S LAW

### Introduction

In this unit, you will make an investigation of Hubble's Law, an empirical law which relates the speed with which galaxies recede from us to their distance from us. You will be able to obtain a value for the Hubble Constant, and from that measurement get an estimate of the age of the universe.

The universe contains billions of galaxies, including our own, the Milky Way. With only a few nearby exceptions, these galaxies are receding away from us. The recession speed can be measured using the Doppler Effect, which leads to a change in the observed wavelength of the light detected from a galaxy relative to the wavelength which we know must have been emitted by the stars in that galaxy. Since the galaxies are moving away from us, the light is shifted towards longer wavelengths, or is *red-shifted*. By measuring the Doppler shift of the wavelength, the speed of recession can be calculated using the formula:

$$\frac{\text{Change in wavelength}}{\text{True wavelength}} = \frac{\text{Speed of recession}}{\text{Speed of light}}$$

where the speed of light equals  $3.00 \times 10^8$  meters/sec, or 300,000 km/sec.

Edwin Hubble discovered that when a plot is made of the speed of recession versus distance to a galaxy (see figure-1), there is an unmistakable trend which is expressed by Hubble's Law:

$$v = Hd$$

in which  $v$  is the speed of recession,  $d$  is the distance, and  $H$  is known as the Hubble Constant.

### The Experiment

Select *Galactic Speeds and the Hubble Law* from the *Start Lab* menu. You are given a view of the sky which contains a cluster of ten galaxies. Both spiral galaxies and elliptical galaxies can be observed, with some spiral galaxies seen from a face-on perspective, and others edge-on. The stars which appear in the field of view are relatively nearby stars from our own galaxy that appear in the foreground as we look deeper into space to view the more distant galaxies. The distances to the galaxies are difficult to obtain. Some of the techniques for estimating the distances are covered in other exercises. For the purpose of this exercise, the estimated distances are given to you when you position the cursor over a galaxy, or when you click on a galaxy.

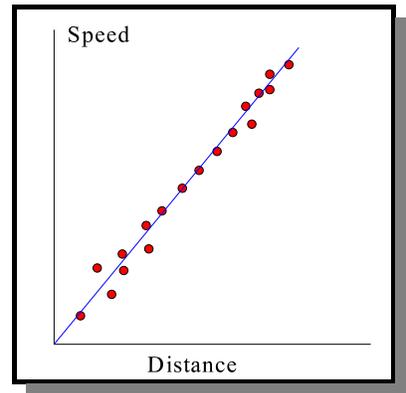


Figure 1

### MEASURING THE DOPPLER SHIFTS

By positioning the cursor directly over any one of the galaxies, the hydrogen spectrum from that galaxy and a reference hydrogen spectrum (as measured in a laboratory) appear below the field of view. You should note that relative to the reference spectrum, the spectrum from the galaxy is shifted towards longer wavelengths (in the direction of the red spectral line). You should also note that the

degree to which the spectrum is red-shifted varies from galaxy to galaxy, indicating varying recessional speeds.

In order to make accurate measurements, it is necessary to expand the view of the spectrum. This can be accomplished by first clicking on the galaxy in which you are interested, this will prevent the spectrum from disappearing when you move the cursor off the galaxy. You can then click on any one of the four hydrogen spectral lines<sup>1</sup>. The view will change to show an expanded region of the spectrum around the line you selected.

The hydrogen spectrum	
Line	Wavelength
Violet	410 nm
Indigo	434 nm
Green	486 nm
Red	656 nm

Table-1

You can now make a measurement of the Doppler shift for that particular spectral line. In order to help you, a grid is superimposed on the spectrum. The major lines on this grid correspond to a wavelength change of 2.5 nanometers (nm), and the finer divisions to a wavelength change of 0.5 nm. Measure the amount by which the spectral line from the galaxy is shifted relative to the true wavelength, then click anywhere in the expanded spectrum view to be returned to the full spectrum. Repeat this procedure for all four lines and record your measurements. (In some cases the speed of the galaxy might be so large that the Doppler shift for the red line is sufficient to cause it to fall beyond the right end of the spectrum. In that case, limit your measurements to the other three lines.)

When you have completed making measurements on all four spectral lines, click on the galaxy a final time to “unlock” its spectrum from the display. Move on to the other galaxies and repeat the above measurements. Be sure to record the distance and the identifying number for each galaxy.

### CALCULATING THE SPEEDS

Once you have made all of your measurements and determined the average Doppler shift for each galaxy, you can calculate each recessional speed using equation (1). (You may find it helpful to use the worksheet accompanying this unit.)

### CHECKING YOUR DATA

Select *Check Galactic Data* from the overhead menu. In the window which appears, enter the identification number of the galaxy, one or more Doppler shifts for the spectral lines, and the recessional speed which you have determined for this galaxy. Correct results will be indicated with a check mark, incorrect results should be corrected before proceeding. By identifying each galaxy in turn, you may check your results for as many galaxies as you like.

### Determining the Hubble Constant

The first step in determining the Hubble Constant is to make a plot of the recessional speed vs. distance for the galaxies. Using a sheet of graph paper, plot distance on the horizontal axis and recessional speed on the vertical axis.

---

<sup>1</sup> The true wavelength of the four hydrogen lines are given in Table 1.

Take a ruler and draw on your graph the best straight line which goes through all of the data points. From the Hubble Law (equation 2), the Hubble Constant (H) is just the slope of this line. To get a numerical value, draw a large triangle (see figure- 2) from which you can calculate the rise and run for this line. The slope is then the ratio:

$$\text{Hubble constant} = \text{rise} \div \text{run}$$

Since the distances you have obtained are measured in millions of light years (Mlyr), and the recessional speeds in kilometers per second (km/s), the Hubble Constant has units of km/s/Mlyr.

(Note: The value you obtain for the Hubble Constant is not necessarily equal to that which you might find given in your textbook, although it should be approximately the same.)

### **Estimating the Age of the Universe**

The value of the Hubble Constant can be used to estimate the age of the universe. At some point in the distant past, all objects originated at a single point, an event known as the Big Bang. If a galaxy has been moving with a speed  $v$  since then, and a time  $T$  has elapsed, then we can write:

$$d = vT = (Hd)T$$

where we have substituted for  $v$  using the Hubble Law. Eliminating the distance  $d$ , we get the result for the age of the universe:

$$\text{Age of the universe (T)} = \frac{1}{\text{Hubble Constant (H)}}$$

The only remaining task is to correct the units. Since there are  $9.46 \times 10^{18}$  km in a million light years, and  $3.15 \times 10^7$  seconds in a year, then equation (5) reduces to:

$$\text{Age} = 300.3 \div H$$

where the age is measured in billions of years.

The assumption that the speed of the galaxy has not changed over the life of the universe is not realistic. Because of the gravitational attraction between the galaxies, the speeds must be steadily decreasing. The time that you estimate must therefore be regarded as an upper limit to the age of the universe, the true age will be less than this.

### **CHECKING YOUR RESULT**

Once you have a value for the Hubble Constant and an estimate for the age of the universe, you can check your results by selecting *Check Your Hubble Constant* from the overhead menu.

UNIT 18 APPENDIX: WORKSHEET

Complete a worksheet similar to this for each of the galaxies.

Galaxy identification number \_\_\_\_\_

Wavelength ( $\lambda$ )	Doppler Shift ( $\Delta\lambda$ )	$\Delta\lambda/\lambda$ (divide column 2 by column 1)
Violet line - 410 nm		
Indigo line - 434 nm		
Green line - 486 nm		
Red line - 656 nm		
	Average value =	

Recession speed of galaxy = \_\_\_\_\_ km/s

(Multiply the average fractional Doppler shift from the above table by the speed of light: 300,000 km/s)