Name:

Lab 16

Hubble's Law: Finding the Age of the Universe

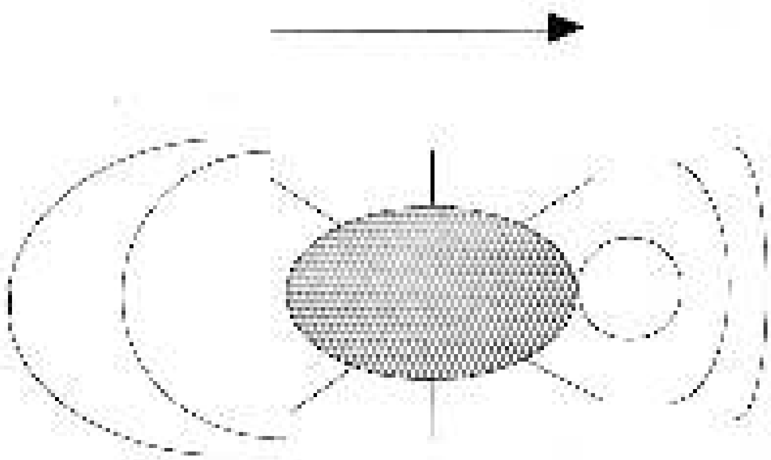
16.1 Introduction

In your lecture sessions (or the lab on spectroscopy), you will find out that an object's spectrum can be used to determine the temperature and chemical composition of that object. A spectrum can also be used to find out how fast an object is moving by measuring the Doppler shift. In this lab you will learn how the velocity of an object can be found from its spectrum, and how Hubble's Law uses the Doppler shift to determine the distance scale of the Universe.

- *Goals:* to discuss Doppler Shift and Hubble's Law, and to use these concepts to determine the age of the Universe
- *Materials:* galaxy spectra, ruler, calculator

16.2 Doppler Shift

You have probably noticed that when an ambulance passes by you, the sound of its siren changes. As it approaches, you hear a high, whining sound which switches to a deeper sound as it passes by. This change in pitch is referred to as the Doppler shift. To understand what is happening, let's consider a waterbug treading water in a pond.



The bug's kicking legs are making waves in the water. The bug is moving forward relative to the water, so the waves in front of him get compressed, and the waves behind him get stretched out. In other words, the frequency of waves increases in front of him, and decreases behind him. In wavelength terms, the wavelength is shorter in front of him, and longer behind him. Sound also travels in waves, so when the ambulance is approaching you, the frequency is shifted higher, so the pitch (not the volume) is higher. After it has passed you, the frequency is Doppler shifted to a lower pitch as the ambulance moves away from you. You hear the pitch change because to your point of view the relative motion of the ambulance has changed. First it was moving toward you, then away from you. The ambulance driver won't hear any change in pitch, because for her the relative motion of the ambulance hasn't changed.

The same thing applies to light waves. When a light source is moving away from you, its wavelength is longer, or the color of the light moves toward the red end of the spectrum. A light source moving toward you shows a ______________________(color) shift.

This means that we can tell if an object is moving toward or away from us by looking at the change in its spectrum. In astronomy we do this by measuring the wavelengths of spectral lines. We've already learned how each element has a unique fingerprint of spectral lines, so if we look for this fingerprint and notice it is displaced slightly from where we expect it to be, we know that the source must be moving to produce this displacement. We can find out how fast the object is moving by using the Doppler shift formula:

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$

where $\Delta\lambda$ is the wavelength shift you measure, λ_o is the rest wavelength[1] (the one you'd expect to find if the source wasn't moving), v is the radial velocity (velocity toward or away from us), and c is the speed of light (3×10^5 km/s).

In order to do this, you just take the spectrum of your object and compare the wavelengths of the lines you see with the rest wavelengths of lines that you know should be there. For example, we would expect to see lines associated with hydrogen so we might use this set of lines to determine the motion of an object. Here is an example:

Excercise 1. *10 points*

If we look at the spectrum of a star, we know that there will probably be hydrogen lines. We also know that one hydrogen line always appears at 6563Å, but we find the line in the star's spectrum at 6570Å. Let's calculate the Doppler shift:

a) First, is the spectrum of the star redshifted or blueshifted (do we observe a longer or shorter wavelength than we would expect)?

b) Calculate the wavelength shift: $\Delta\lambda = (6570\text{Å} - 6563\text{Å})$

$\Delta\lambda =$ ____________________Å

c) What is its radial velocity? Use the Doppler shift formula:

$$\frac{\Delta\lambda}{\lambda_o} = \frac{v}{c}$$

$v =$____________________km/s

[1] For this lab we will be measuring wavelengths in Ångstroms. 1.0 Å= 1.0×10^{-10} m.

A way to check your answer is to look at the sign of the velocity. Positive means redshift, and negative means blueshift.

Einstein told us that nothing can go faster than the speed of light. If you have a very high velocity object moving at close to the speed of light, this formula would give you a velocity faster than light! Consequently, this formula is not always correct. For very high velocities you need to use a different formula, the *relativistic* Doppler shift formula, but in this lab we won't need it.

16.3 Hubble's Law

In the 1920's Hubble and Slipher found that there is a relationship between the redshifts of galaxies and how far away they are (don't confuse this with the ways we find distances to stars, which are much closer). This means that the further away a galaxy is, the faster it is moving away from us. This seems like a strange idea, but it makes sense if the Universe is expanding.

The relation between redshift and distance turns out to be very fortunate for astronomers, because it provides a way to find the distances to far away galaxies. The formula we use is known as Hubble's Law:

$$v = H \times d$$

where v is the radial velocity, d is the distance (in Mpc), and H is called the Hubble constant and is expressed in units of km/(s $\times$ Mpc). Hubble's constant is basically the expansion rate of the Universe.

The problem with this formula is that the precise value of H isn't known! If we take galaxies of known distance and try to find H, the values range from 50 to 100 km/(s $\times$ Mpc). By using the incredible power of the Hubble Space Telescope, the current value of the H is near 75 km/(s $\times$ Mpc). Let's do an example illustrating how astronomers are trying to determine H.

Exercise 2. *(15 points)*

In this exercise you will determine a value of the Hubble constant based on direct measurements. The figure at the end of this lab has spectra from five different galaxy clusters. At the top of this figure is the spectrum of the Sun for comparison. For each cluster, the spectrum of the brightest galaxy in the cluster is shown to the right of the image of the cluster (usually dominated by a single, bright galaxy). Above and below these spectra, you'll note five, short vertical lines that look like bar codes you might find on groceries. These are comparison spectra, the spectral lines which are produced for elements here on earth. If you look closely at the galaxy spectra, you can see that there are several dark lines going through each of them. The left-most pair of lines correspond to the "H and K" lines from calcium (for the Sun and for Virgo = Cluster #1, these can be found on the left edge of the spectrum). Are these absorption or emission lines? (Hint: How are they appearing in the galaxies' spectra?)

Now we'll use the shift in the calcium lines to determine the recession velocities of the five galaxies. We do this by measuring the change in position of a line in the galaxy spectrum with respect to that of the comparison spectral lines above and below each galaxy spectrum. For this lab, measure the shift in the "K" line of calcium (the left one of the pair) and write your results in the table below (Column B). At this point you've figured out the shift of the galaxies' lines as they appear in the picture. Could we use this alone to determine the recession velocity? No, we need to determine what shift this corresponds to for actual light. In Column C, convert your measured shifts into Ångstroms by using the conversion factor **19.7 Å/mm** (this factor is called the "plate scale", and is similar to the scale on a map that allows you to convert distances from inches to miles).

Earlier in the lab we learned the formula for the Doppler shift. Your results in Column C represent the values of $\Delta\lambda$. We expect to find the center of the calcium K line at $\lambda_o = \mathbf{3933.0}$ **Å**. Thus, this is our value of λ. Using the formula for the Doppler shift along with your figures in Column C, determine the recession velocity for each galaxy. The speed of light is, $c = \mathbf{3 \times 10^5}$ **km/sec**. Write your results in Column D. For each galaxy, divide the velocity (Column D) by the distances provided in Column E. Enter your results in Column F.

The first galaxy cluster, Virgo, has been done for you. Go through the calculations for Virgo to check and make sure you understand how to procede for the other galaxies. **Show all of your work on a separate piece of paper and turn in that paper with your lab.**

A Galaxy Cluster	B Measured shift (mm)	C Redshift (Angstroms)	D Velocity (km/s)	E Distance (Mpc)	F Value of H (km/s/Mpc)
1. Virgo	*0.9*	*17.7*	*1,352*	20	*67.6*
2. Ursa Major				110	
3. Corona Borealis				180	
4. Bootes				300	
5. Hydra				490	

Now we have five galaxies from which to determine the Hubble constant, H. Are your values for the Hubble constant somewhere between 50 and 100 km/(s $\times$ Mpc)? Why do you think that all of your values are not the same? The answer is simple: *human error*. It is only possible to measure the shift in each picture to a certain accuracy.

For Virgo the shift is only about 1 mm, but it is difficult with a ruler and naked eye to measure such a small length to a high precision. A perfect measurement would give the "correct" answer (but note that there is always another source of uncertainty: the accuracy of the distances used in this calculation!).

16.4 The Age of the Universe

The expansion of the Universe is a result of the Big Bang. Since everything is flying apart, it stands to reason that in the past everything was much closer together. With this idea, we can use the expansion rate to determine how long things have been expanding - in other words, the age of the Universe. As an example, suppose you got in your car and started driving up to Albuquerque. Somewhere around T or C, you look at your watch and wonder what time you left Las Cruces. You know you've driven about 75 miles and have been going 75 miles per hour, so you easily determine you must have left about an hour ago. For the age of the Universe, we essentially do the same thing to figure out how long ago the Universe started. This is assuming that the expansion rate has always been the same, which is probably not true (by analogy, maybe you weren't always driving at 75 mph on your way to T or C). The gravitational force of the galaxies in the Universe pulling on each other would slow the expansion down. However, we can still use this method to get a rough estimate of the age of the Universe.

Exercise 3. *(15 points)*

The Hubble constant is expressed in units of km/(s $\times$ Mpc). Since km and Mpc are both units of distance, we can cancel them out and express H in terms of 1/sec. Simply convert the Mpc into km, and cancel the units of distance. The conversion factor is **1 Mpc = 3.086$\times$10^{19} km**.

a) Add up the five values for the Hubble constant written in the table of Exercise 2, and divide the result by five. This represents the average value of the Hubble constant you have determined.

$H =$ ________________________ $\frac{km}{s \times Mpc}$

b) Convert your value of H into units of 1/s:

$H =$ ________________________ $\frac{1}{s}$

c) Now convert this into seconds by inverting it ($1/H$ from part b):

Age of the Universe = ________________________s

d) How many years is this? (convert from seconds to years by knowing there are 60 seconds in a minute, 60 minutes in an hour, etc.)

Age of the Universe=________________________yrs

16.5 How Do we Measure Distances to Galaxies and Galaxy Clusters?

In exercise #2, we made it easy for you by listing the distances to each of the galaxy clusters. If you know the distance to a galaxy, and its redshift, finding the Hubble constant is easy. But how do astronomers find these distances? In fact, it is a very difficult problem. Why? Because the further away an object is from us, the fainter it appears to be. For example, if we were to move the Sun out to a distance of 20 pc, it would no longer be visible to the naked eye! Note that the closest galaxy cluster is at a distance of 20 Mpc, a million times further than this! Even with the largest telescopes in the world, we could not see the Sun at such a great distance (and Virgo is the closest big cluster of galaxies).

Think about this question: Why do objects appear to get dimmer with distance? What is actually happening? Answer: The light from a source spreads out as it travels. This is shown in Fig. 16.1. If you draw (concentric) spheres around a light source, the amount of energy passing through a square meter drops with distance as $1/R^2$. Why? The area of a sphere is $4\pi R^2$. The innermost sphere in Fig. 16.1 has a radius of "1" m, its area is therefore 4π m^2. If the radius of the next sphere out is

"2" m, then its area is 16π m^2. It has 4× the area of the inner sphere. Since all of the light from the light bulb passes through both spheres, its intensity (energy/area) must drop. The higher the intensity, the brighter an object appears to our eyes. The lower the intensity, the fainter it appears. Again, refer to Fig. 16.1, as shown there, the amount of energy passing through 1 square of the inner sphere passes through 4 squares for the next sphere out, and 9 squares (for R = 3) for the outermost sphere. The light from the light bulb spreads out as it travels, and the intensity drops as $1/R^2$.

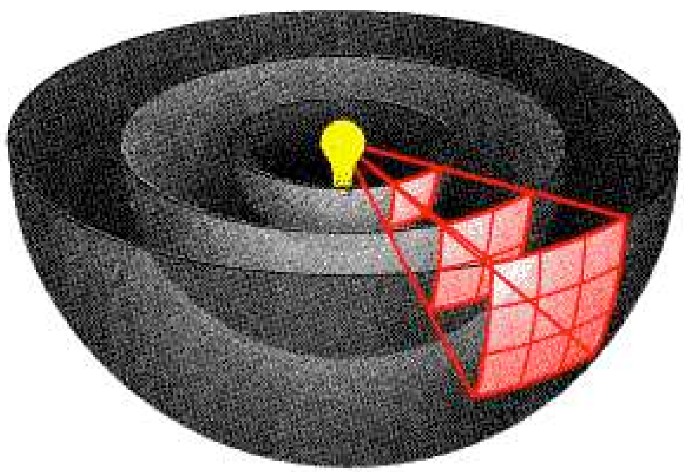


Figure 16.1: If you draw concentric spheres around a light source (we have cut the spheres in half for clarity), you can see how light spreads out as it travels. The light passing through one square on the inner sphere passes through four squares for a sphere that has twice the radius, and nine squares for a sphere that has three times the radius of the innermost sphere. This is because the area of a sphere is $4\pi R^2$.

Exercise 4.

If the apparent brightness (or intensity) of an object is proportional to $1/R^2$ (where R = distance), how much brighter is an object in the Virgo cluster, compared to a similar object in Hydra? [Hint: how many times further is Hydra than Virgo?] *(2 points)*

An object in Hydra is hundreds of times fainter than the same object in Virgo! Obviously, astronomers need to find an object that is very luminous if they are going to measure distances to galaxies that are as far, or even further away than the Hydra cluster. You have probably heard of a supernova. Supernovae (supernovae is the plural of supernova) are tremendous explosions that rip stars apart. There are two types of supernova, Type I is due to the collapse of a white dwarf into neutron star, while a Type II is the explosion of a massive star that often produces a black hole. Astronomers use Type I supernovae to measure distances since their explosions always release the same amount of energy. Type I supernovae have more than one billion times the Sun's luminosity when they explode! Thus, we can see them a long way.

Let's work an example. In 1885 a supernova erupted in the nearby Andromeda galaxy. Andromeda is a spiral galaxy that is similar in size to our Milky Way located at a distance of about 1 Mpc. The 1885 supernova was just barely visible to the naked eye, but would have been easy to see with a small telescope (or even binoculars). Astronomers use telescopes to collect light, and see fainter objects better. The largest telescopes in the world are the Keck telescopes in Hawaii. These telescopes have diameters of 10 meters, and collect 6 million times as much light as the naked eye (thus, if you used an eyepiece on a Keck telescope, you could "see" objects that are 6 million times fainter than those visible to your naked eye).

Using the fact that brightness decreases as $1/R^2$, how far away (in Mpc) could the Keck telescope see a supernova like the one that blew up in the Andromeda galaxy? *(2 points).* [Hint: here we reverse the equation. You are given the brightness ratio, 6 million, and must solve for the distance ratio, remembering that Andromeda has a distance of 1 Mpc!]

Could the Keck telescopes see a supernova in Hydra? *(1 point)*

16.6 Questions

1. Explain how the Doppler shift works. *(5 points)*

2. In the waterbug analogy, we know what happens to waves in front of and behind the bug, but what happens to the waves directly on his left and right (hint: is the bug's motion compressing these waves, stretching them out, or not affecting them at all)? With this in mind, what can the Doppler shift tell us about the motion of a star which is moving only at a right angle to our line of sight? *(5 points)*

3. Why did we use an average value for the Hubble constant, determined from five separate galaxies, in our age of the Universe calculation? What other important factor in our determination of the age of the Universe did we overlook? (Hint:

It was mentioned in the lab) *(3 points)*

4. Does the age of the Universe seem reasonable? Check your textbook or the World Wide Web for the ages estimated for globular clusters, some of the oldest known objects in the Universe. How does our result compare? Can any object in the Universe be older than the Universe itself? *(5 points)*

16.7 Summary

(35 points) Summarize what you learned from this lab. Your summary should include:

- An explanation of how light is used to find the distance to a galaxy
- From the knowledge you have gained from the last several labs, list and explain *all* of the information that can be found in an object's spectrum.

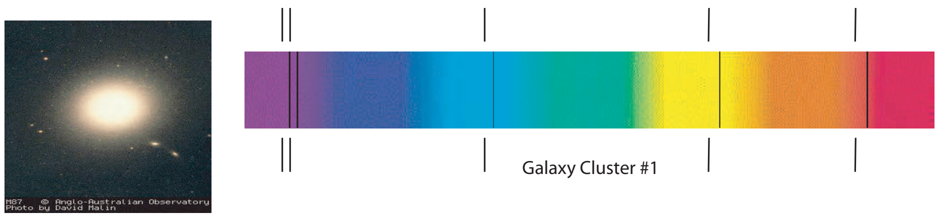
Use complete sentences, and proofread your summary before handing in the lab.

16.8 Extra Credit

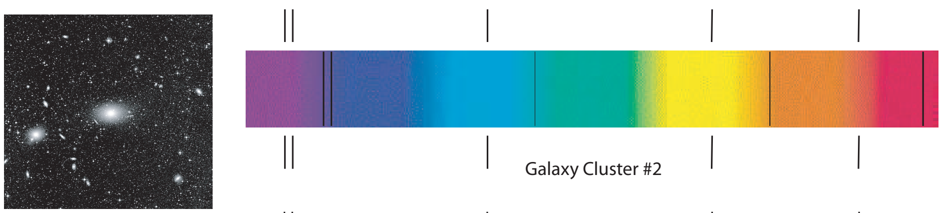
Recently, it has been discovered that the rate of expansion of the Universe appears to be accelerating. This means that the Hubble "constant" is not really constant! Using the world wide web, or recent magazine articles, read about the future of the Universe if this acceleration is truly occurring. Write a short essay summarizing the fate of stars and galaxies in an accelerating Universe. *(4 points)*

Possible Quiz Questions
1) What is a spectrum, and what is meant by wavelength?
2) What is a redshift?
3) What is the Hubble expansion law?

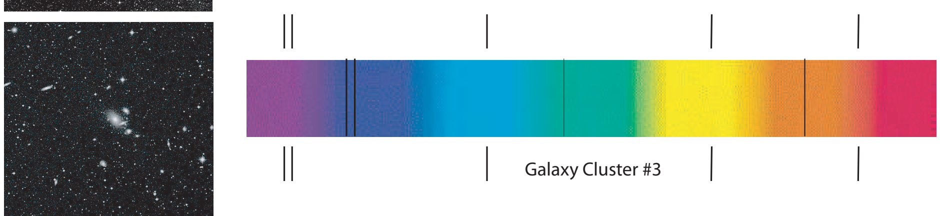
The Spectrum of the Sun



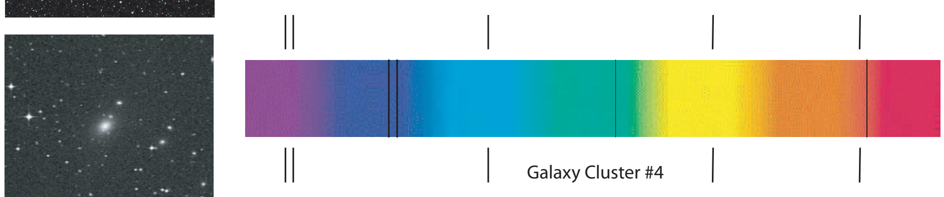
Galaxy Cluster #1



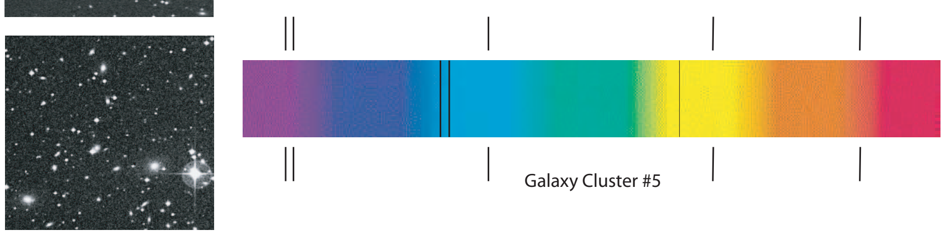
Galaxy Cluster #2



Galaxy Cluster #3



Galaxy Cluster #4



Galaxy Cluster #5