Lab 10: Measuring The Hubble Constant

Purpose

This exercise is a computer simulation that is intended to give you a feeling for the operation of a computer-controlled spectrometer attached to a large telescope. It will provide experience in the use of a computer for scientific purposes, and it will familiarize you with the parameters and problems involved in the measurement of one of the most important quantities in all of astrophysics. You, too, can be a cosmologist!

Introduction

In 1931 the American astronomer Edwin Hubble announced what many feel is the greatest discovery in modern astrophysics. Now known as Hubble's Law, the discovery states that the external galaxies are receding from the Earth with speeds that increase with distance; if a galaxy is twice as far from us, it is receding twice as fast. This discovery is the basis for the concept of the expanding Universe, and indeed for all modern cosmology – that is, theories of how the present Universe came into being. To refine such theories, we need to know the Hubble Constant, which is simply the relationship between distance and speed; how fast is a galaxy at a given distance running away from us? The most powerful tool for answering this question is the Doppler shift, the change in the apparent wavelengths of the lines of a spectrum due to the velocity of the source relative to the observer.

In Figure 10.1, we are seeing mock spectra of light which emulate some taken from a spectrograph (see "Astronomical Spectroscopy"). As you learned in Lab 4: Light is A Wave, photons emitted by a source are just electromagnetic waves flying through space at the speed of light. As the light

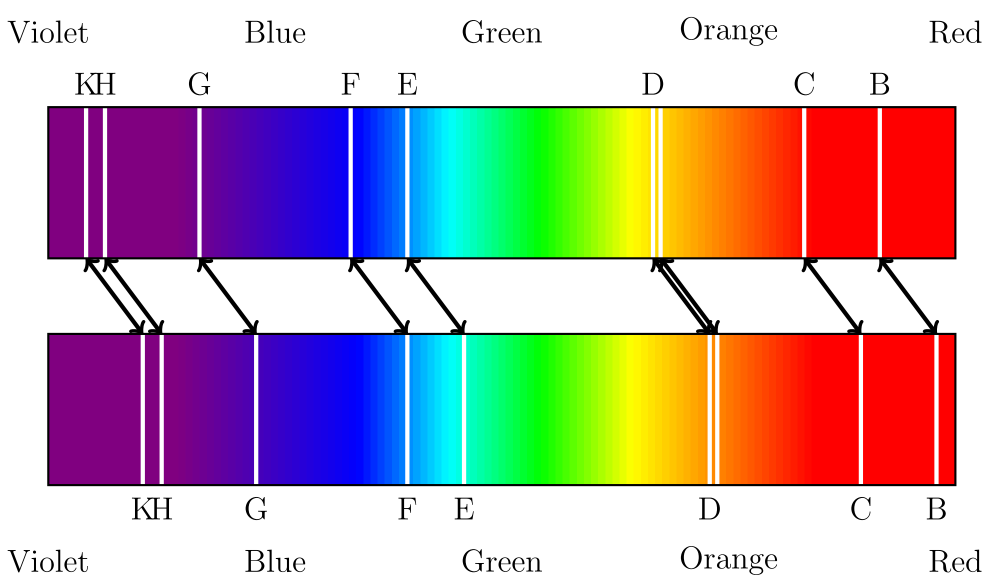


Figure 10.1: Mock Spectrum demonstrating the redshift effect

travels, it encounters many things: dust, gas, nebulae, etc. These structures are cold regions of gas being back-lit by some source.

Once the light encounters cold gas regions these regions, some light corresponding to the specific wavelength is absorbed by the atom (this is because the energy needed to excite atoms is quantized – it must be a specific, discrete value). This is what we see the in the top panel of the diagram. Most of the light that is incident on us from the galaxy has traveled through these regions without being absorbed, but a significant amount that could have been absorbed were. Now, because this physics works in all places of the universe, we can know what wavelength of light is necessary to excite specific atoms through lab tests (extremely similar to what you did in Lab 8: Astronomical Spectroscopy I). Therefore, we can observe spectra from distant galaxies and learn about the chemical composition!

There is a small wrinkle in this whole process though - when we observe distant galaxies, none of the lines are where we would expect them to be. In fact, they have all shifted over by the same amount towards redder frequencies. This is a direct consequence of Hubble's measured expansion of the universe. As the photons travel immense distances throughout space, space itself is expanding causing the wavelengths of the photons to expand as well. This effectively makes the photons appear "redder" than they originally would and causes the effect demonstrated in the bottom panel of Figure 10.1.

This effect is known as redshift and is a highly useful tool for astrophysicists in describing how far away distant objects are from our galaxy. In this lab, we will be investigating this very effect and measuring the distance to some real galaxies in a nearby cluster in order to estimate the expansion rate - as well as age - of the universe!

Laboratory Procedure

This exercise is a computer simulation of the operation of a spectrometer attached to a major telescope in taking and measuring the spectra of distant galaxies.

Determining the Recession Speeds of Galaxies

In Figure 10.2, we can see a real spectrum of the galaxy M31 (more commonly known as the Andromeda Galaxy). There are two big dips in the relative intensity at two different wavelengths. The H line is the one on the right and the K line is on the left. You will use the ALEX Labs software to examine these different atomic lines in distant galaxies. When you are performing your analysis, you should notice that these lines are redshifted over by a certain amount! (Note: in Figure 10.2, the lines are actually *blue*-shifted because the Andromeda Galaxy is moving towards us!)

Select three fields from the five listed in Table 10.1 and find the target galaxies in your field. After finding the galaxies, you can take their spectrum (be careful to choose a long enough exposure time!). From the spectra, you will be able to determine the wavelength of the (offset) Fraunhofer H and K lines! The question then becomes: How do you convert these wavelength offsets from rest to recession speeds? The laboratory wavelengths (wavelengths at rest) of the H and K lines are, respectively, 3969 and 3934 Angstroms. Subtracting the laboratory wavelength from your galaxy wavelengths will give you the shift in wavelength, $\Delta\lambda$, of each of the two lines.

With this shift in wavelengths, you can obtain something that looks similar to an error calculation for the wavelengths: $\Delta\lambda/\lambda_{\text{lab}}$. The ratio $\Delta\lambda/\lambda_{\text{lab}}$ is what astronomers refer to as "the redshift". For some reason, this quantity is always designated by the letter z.

To obtain the speed of recession v we use the following relation:

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_{\text{lab}}}$$

where v is the recession speed, c is the speed of light (3×10^5 km/s), $\Delta\lambda$ is the shift in wavelength, and λ_{lab} is the laboratory wavelength. In addition to calculating v, also calculate z for each of your galaxies. At this point, you now have the speeds of recession for the galaxies you measured.

Determining Distances of Galaxies

Determining how distances to far away galaxies represents the greatest uncertainty in determining the Hubble Constant. For this reason, our understanding of the Hubble Constant has changed dramatically over time. In fact, Hubble himself first calculated the value to be around 500 km/s/Mpc, which is almost 10 times as fast as the modern accepted value!

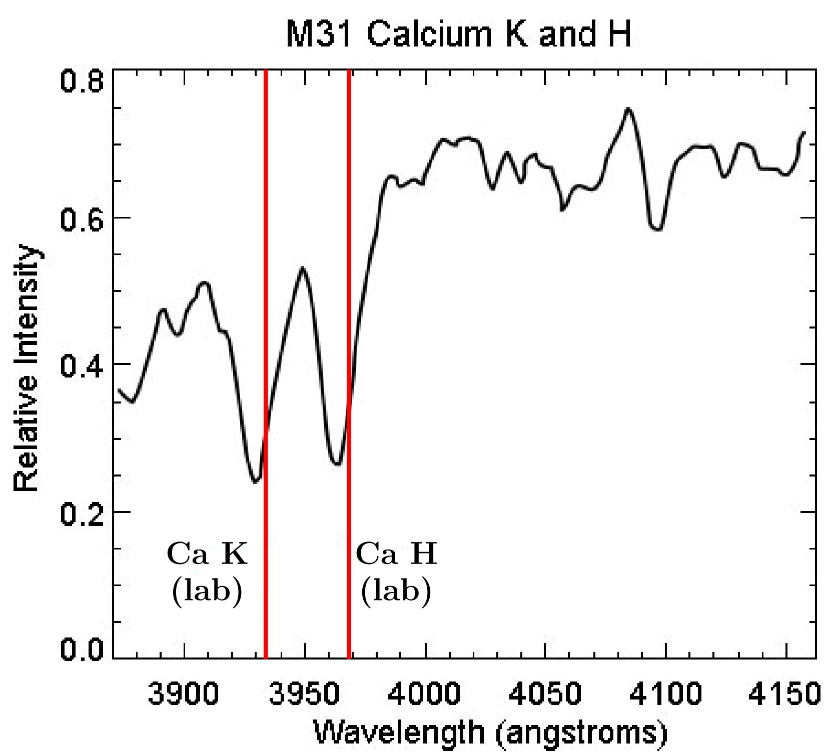


Figure 10.2: Example spectrum of M31 galaxy, courtesy of NASA Goddard Space Flight Center (slightly modified)

Take the absolute magnitude of each galaxy as -20[a]. In the previous step, you were given the apparent magnitude of the galaxy as well. Having both the apparent and absolute magnitude of an object will give you a clue as to its distance. The mathematical relationship (often called the "distance modulus") can be written as

$$\log d = 1 + (m - M)/5$$

where d is the distance in parsecs (one pc = 3.26 light-years, for scale), m is the apparent magnitude, and M is the absolute magnitude. If you have trouble with the log, your instructor will show you how easily it can be handled on a simple hand-held calculator. You now have the distance and speed of recession for each of your galaxies.

Calculation of the Hubble Constant

As we noted earlier, the Hubble Constant H is simply the relationship between speed and distance:

$$H = \frac{v}{d}$$

You measured v in the first part and calculated d in the second part. Perform the necessary division of one by the other, and voila! have a value for the Hubble Constant (note: you should obtain values for each cluster).

Field	**Target Galaxy**
Perseus	NGC1260
Ursa Minor	NGC5452
Ursa Major	M109
Leo Minor	NGC3294
Draco	NGC6143

Table 10.1: The five different fields available as a part of ALEX labs and the associated galaxy targets within those fields.

[a]Note that this is a crude approximation; not all galaxies should be exactly the same brightness

Measuring The Hubble Constant Worksheet

Name: ____________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Through all of these calculations, take the speed of light to be $c = 3 \times 10^5$ km/s.

Observational Data

Data Table 10.1

Name of Galaxy			
Apparent Magnitude m			
λ_K of K line (left line)			
λ_H of H line (right line)			
Integration Time (s)			

Calculation of Velocity

Data Table 10.2

Name of Galaxy			
$\Delta\lambda_K = \lambda_K$-3934			
$\Delta\lambda_H = \lambda_H$-3969			
Redshift K: $z_K = \Delta\lambda_K/3934$			
Redshift H: $z_H = \Delta\lambda_H/3969$			
Velocity K: $v_K = cz_K$			
Velocity H: $v_H = cz_H$			
Avg Velocity: $(v_K + v_H)/2$			

Calculation of the Hubble Constant

Data Table 10.3

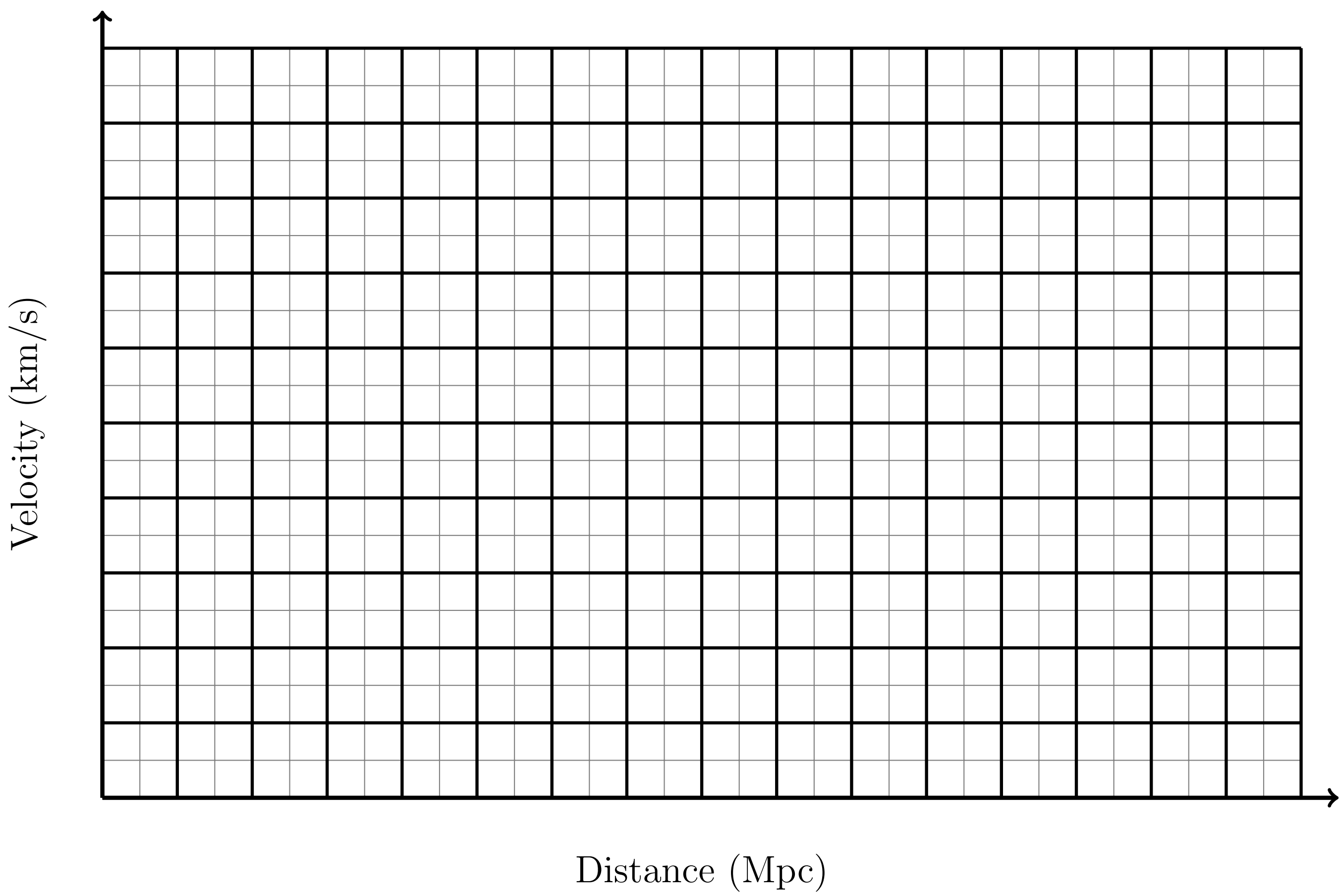
Name of Galaxy			
Apparent Magnitude m			
Absolute Magnitude M	-20	-20	-20
$m - M$			
$\log_{10} d$ [$= 1+(m-M)/5$]			
d in pc			
d in Mpc			
$H = v_{\text{avg}}/d$ (km/s/Mpc)			

H_{avg}	

Discussion Questions

1. In recent years, various astronomers have argued for values of H ranging from 65 to 75 km/s/Mpc. How does your result for H_{avg} compare with these values? Does it lie within this "accepted" range? Assume an "accepted" value of 70 km/s/Mpc and calculate the percentage error of your experimental value of H_{avg}.

2. Create your own Hubble diagram below. Note that for $d = 0$ you can assume $v = 0$. Does your diagram look reasonable? Do your points lie more or less on a straight line? Calculate the numerical value of the slope. How does it compare with the value obtained for H_{avg}?



Graph 10.1

Extra Credit #1: We know how fast the galaxies are receding, and how far apart they are now. If we imagine time running backward, it is evident that at some time in the past all the galaxies must have been jammed together at one location in space. The moment at which the recession began is referred to as the "Big Bang". How long ago was this?

Surprisingly, this age of the Universe is simply equal to the reciprocal of H, or $1/H$! Use your value of H to calculate the age of the Universe in years (Hint: be very careful with units!)

Extra Credit #2: Derive the distance modulus equation. Start with the difference of magnitudes equation from Lab 6: Astronomical Telescope II

$$m_1 - m_2 = 2.5 \log_{10} \left(\frac{b_2}{b_1} \right) \ .$$

From there use the fact that the brightness, b, of an object is its inherent luminosity, L, divided by its distance to us, squared (with some constants)

$$b = \frac{L}{4\pi d^2} \ .$$

Finally, recall both (i) the inherent luminosity, L, will be the same no matter where you observe the object and (ii) absolute magnitudes assume a distance of 10 pc.