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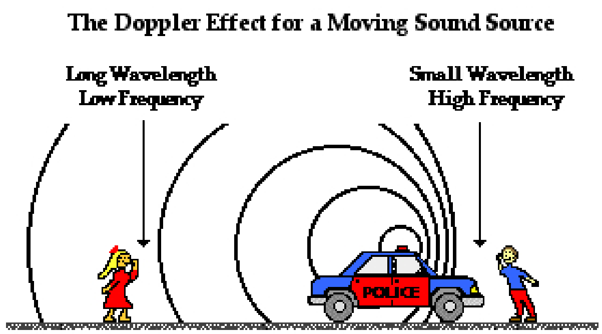
Prelab 8: The Hubble Redshift Distance Relation

The Doppler Effect: When objects are moving, the frequency or "pitch" of waves can change. Think of the noise a car makes when you are standing next to it, a sort of low purr. Now imagine you are standing on a highway and the same car zooms by at a high speed; it makes a different sound when it's behind you than when it's in front of you. You've probably also noticed this effect with ambulances and emergency vehicles as they pass by:



The frequency of a sound wave is simply how often the wave repeats itself. Faster-moving peaks and valleys move at a faster frequency, and hence a higher pitch. The equation that determines how sound changes with motion is called the *Doppler Effect*; below it is written in terms of frequency:

$$f_{observed} = [\frac{v}{v+v_{source}}] \times f_{source} \text{ for a receding source,}$$
$$f_{observed} = [\frac{v}{v-v_{source}}] \times f_{source} \text{ for an approaching source,}$$

where f_{obs} is the observed frequency, f_{source} is the source frequency, v is the velocity of sound in air, and v_{source} is the velocity of the moving object.

1. (1 point) Imagine someone is throwing tennis balls at you, one ball every second. If you run away from that person, would you get hit more or less often?

2. (2 points) If something is emitting sound waves and you moved towards the source, would the waves repeat more or less often? Does it sound higher or lower?

3. (3 points) The speed of sound is about 340 m/s. Imagine a circus performer with a trombone launches himself out of a cannon towards a crowd of elderly people at 150 m/s. He plays a low Eb, which has a frequency of 155 Hz ($1Hz = 1/s$). What frequency do the elderly people here? What frequency does someone standing behind the cannon hear?

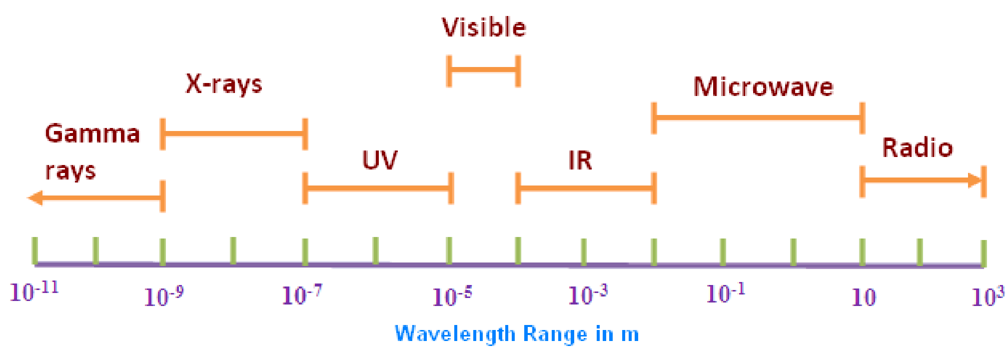
The Wave Nature of Light: Light and sound are distinct phenomena, yet they are both waves. The frequency of light is also affected by movement. The "pitch" of light is what we call color. Just like the pitch of an ambulance is shifted higher when it's moving towards you, light moving towards you would become slightly bluer (*blueshifted*), and light moving away from you would become slightly redder (*redshifted*). Light is not redshifted because of the distance it starts at; rather, it is the motion away from the viewer that causes the effect. The same is true of a blueshift.

Light is also shifted via the doppler effect; another way to write that equation is in terms of wavelength:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0}$$

where $\Delta\lambda$ is the change in wavelength, λ_0 is the source wavelength, λ is the observed wavelength, and c is the speed of light. Note $\lambda = \frac{c}{f}$.

Below is included a diagram of the electromagnetic spectrum for reference:



Electromagnetic Spectrum

4. (2 points) You are moving very quickly towards something that is already very blue/violet in color. You notice it disappears and you can't see it anymore; why is that? In what part of the EM spectrum is the light?

The Stretching of Space and Time: Imagine two ants on a balloon. If you slowly inflated the balloon the ants would move further and further apart. Notice the ants are not moving, but the space between them is expanding. This is one way to understand the expansion of the universe.

5. (2 points) If one ant on the inflating balloon has a blue light and shines it towards the other ant (who is moving away from him), what kind/color of light would the other ant see? What happens if the ants move farther apart (*hint: think spatially/geometrically*)?

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Lab 8: The Hubble Redshift Distance Relation

Figure 1: Two colliding spiral galaxies, NGC 2207 and IC 2163, taken with the Hubble Space Telescope. Picture credits below.

1 Introductions

The purpose of this lab is to determine the relationship between the redshift in spectra of distant galaxies and the rate of the expansion of the universe.

The late biologist J.B.S. Haldane once wrote: "The universe is not only queerer than we suppose, but queerer than we can suppose." One of the strangest things about the universe is that virtually all the galaxies in it (with the exception of a few nearby ones) are moving away from our Milky Way. This curious fact was first discovered in the early 20th century by astronomer Vesto Slipher, who noted that absorption lines in the spectra of most spiral galaxies had longer wavelengths (were "redder") than those observed from stationary objects. Assuming that the redshift was caused by the Doppler shift, Slipher concluded that the red-shifted galaxies were all moving away from us.

The increase of galaxy speed with distance was first noted by astronomer Edwin Hubble in the 1920's who measured the distances of nearby galaxies from the brightness of the Cepheid variable stars he could see in them. He measured the speeds (technically called the *radial velocities*) of the galaxies by measuring the wavelengths of absorption lines in their spectra. Due to the Doppler effect, the wavelengths of absorption lines are longer (shifted in toward the red end of the spectrum), the faster the galaxy is moving away from the observer. Astrophysicists readily interpreted Hubble's relation as evidence of a universal expansion, meaning the distance between all galaxies in the universe is getting bigger with time. An observer in any galaxy, not just our own, would see all the other galaxies traveling away, with the furthest galaxies traveling the fastest.

This was a remarkable discovery. The expansion is believed today to be a result of the Big Bang which occurred between 10 and 20 billion years ago, a date which we can calculate by making measurements like those of Hubble. The rate of expansion of the universe tells us how long it has been expanding. We determine the rate by plotting the velocities of galaxies against their distances, and determining the slope of the graph, a number called the Hubble Parameter (H_0), which tells us how fast a galaxy at a given distance is receding from us. Hubble's discovery of the correlation between velocity and distance is fundamental in reckoning the history of the universe.

The Spectra of Galaxies:

Suppose a distant object emits light at a known frequency (color). If we observe the light at a different color we could figure out how fast the object is moving away from us. Galaxies are made up of billions of stars, and the spectrum of an entire galaxy is a sort of average over what stars and dust look like. Many galaxies have three features in their spectra, two Calcium absorption lines and another "blended" line. If we take the spectra of a normal galaxy we should see these three lines, which appear at specific frequencies (colors). We can also assume that all galaxies are about the same brightness. These observations yield two important pieces of information: first, from the observed brightness, we can estimate the distance of the galaxy. Second, from measuring the frequency of the Calcium absorption lines, we can calculate how fast the galaxy is moving towards or away from us. This in turn yields information about the expansion rate of the universe!

Mapping the Universe:

Consider how hard it is to determine the shape and extent of a forest when one is tied to a tree standing in the middle of it, unable to budge from that spot. That's the problem earthbound observers face when surveying the universe; all our mapping of galaxies must proceed from a single spot (our solar system), located about $\frac{2}{3}$ of the way between the center of the Milky Way and its edge.

Two of the three dimensions required to map the positions of galaxies in the universe are the two celestial coordinates, *right ascension* and *declination*, that tell us the location of a galaxy on the celestial sphere. These two celestial coordinates tell us in what direction to look. Hubble's redshift-distance relation gives us the key to the third dimension. Since the radial velocity of a galaxy is proportional to its distance, we can simply take a spectrum of it, measure the amount the spectral lines are redshifted, and use that as a measure of distance. We plot the position of galaxies in three dimensions, two being the Right ascension and declination of the star, and the third being the redshift (or velocity, or distance), to create a three-dimensional map of the universe which, hopefully, will reveal the size and scope of its major structures. Today, only a tiny fraction (about one hundredth of one percent) of the visible universe has been mapped.

2 Instructions

1. Open the CLEA lab entitled "VIREO." Click File, Log-In. There is no need to enter any information.

2. Click File, Run Exercise, "Hubble Redshift Distance Relation." On screen should appear a simulation of the Kitt Peak 0.9m Telescope. Click Telescopes, Optical, Access 1.0 Meter. Click "Open" underneath "Dome" to view the sky.

3. Click "Telescope Control Panel." Another dialogue box will open; there, on the left-hand side of the scren, click "Tracking" to turn tracking on (in real life, this means the telescope corrects for the motion of the Earth while you are making observations).

4. You should be able to see some larger, bright objects along with several fuzzier ones. The larger, brighter, round objects are stars. The smaller, fuzzy, elliptical (oblong) shapes represent celestial bodies, such as galaxies. Go to "Slew," "Observation Hot List," and "View/Select from List." Click on one of the lines of coordinates to select that object (it doesn't matter which one you pick). Click ok twice to direct the telescope to your selected celestial body.

5. Once the telescope has finished slewing, move the red square box to center on the object nearest it on the screen (the red box should not be far off; if not, pick a different set of coordinates). You can move the red box using the N-S-E-W buttons. Set the slew rate to 4 so that the box moves more quickly. Click "Telescope" under "View" to zoom in.

6. Once you have an object selected and have zoomed in, you will want to take a spectral reading of the galaxy. Place the two vertical lines on the center of the galaxy, again using the N-S-E-W buttons to move, and click "Access" under the "Instruments" menu (make sure the small green bar is next to "Spectrometer!"). Next, select "Go" under "Integration" on the bottom right of the screen to start taking data. You should see a spectrum start to take shape; when you start to see large peaks on the graph, you can click "Stop."

7. You should see three lines; the Calcium (Ca) lines are next to each other to the left of the graph; they appear as a doublet, with the Calcium-Potassium (CaK) line on the left of the doublet and the Calcium-Hydrogen (CaH) line on the right of the doublet. You can ignore the other singlet line to the right of the graph. Record the wavelength of the CaK-line on your worksheet in the $\lambda_{observed}$ column (remember, wavelength is measured along the x-axis). Don't forget your units! Also record the "Apparent Magnitude" (here called "V") and the name of the object on your chart in the appropriate column.

8. Fill in the rest of the chart (now or later) with the required calculations.

9. Repeat these steps for five celestial objects total.

10. Once you have collected all your data, complete the rest of the worksheet.

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Lab 8 Worksheet: The Hubble Redshift Distance Relation

You will need the following equations for your calculations:

$$\lambda_{actual} = 3934\mathring{A}, 1\mathring{A} = 10^{-10} meters.$$
$$\text{Doppler Shift: } v = c \times [(\frac{\lambda_{observed}}{\lambda_{actual}}) - 1]$$
$$\text{Speed of Light: } c = 3 \times 10^5 km/sec$$
$$\text{Absolute Magnitude: } M = -21$$
$$Distance = 10^{(m-M+5)/(5)}$$

Note the distance is given in parsecs! Make sure you convert to Mpc for the table.

1. (5 points) Table of Observations

Name	$\lambda_{observed}$	Velocity ($\frac{km}{s}$)	ApparentMagnitude	Distance (Mpc)

2. (4 points) Make a plot of velocity vs. distance, y vs. x. Label your axes! Find the slope of the plot, making sure to include units. Remember that $slope = \frac{rise}{run}$. Your slope should be close to a straight line; if your slope equals 0, use the number 70 as your slope instead. The small slope shows us that the further a galaxy is, the faster away from us it moves. This is the primary piece of evidence we have that the Universe is expanding.

3. (2 points) The Andromeda galaxy is the closest galaxy to the Milky Way. Unlike all of the galaxies here it is blueshifted. Does this mean the Universe is not expanding? Why or why not?

4. (2 points) If we take distance and divide it by speed, we can find how long someone has been travelling ($distance = rate \times time$). For us, this works out to be $1/slope$. Record 1/slope here, remembering units:

   Time: ______________________________

5. (3 points) We need to convert the units in the question above to years; use the below conversion factors for your answer:

$$1Mpc = 3.086 \times 10^{19} km$$
$$3.15 \times 10^{7} sec = 1yr$$

6. (2 points) What is the age of the Universe in years, according to your calculations? How does this compare to the known age of the Universe (13.7 Gyr)?

7. (2 points) Think about our Universe's expansion using the "ants on an expanding balloon" model from the prelab. Where on the balloon (or perhaps when) did the Big Bang happen?

Picture Credits: Prelab, Doppler Effect: `http://www.physicsclassroom.com/Class/sound/u11l3b1.gif`, Prelab, EM Spectrum: `http://images.tutorvista.com/cms/images/83/wavelength-spectrum1.PNG`, Lab, Colliding Galaxies: `http://www.wallpaperish.com/wp-content/uploads/2013/08/Hubble-View-of-NGC-2207-IC-2163-Colliding-Spiral-Galaxies.jpg`

DISCLAIMER: This lab has been edited from the CLEA simulations and student manuals: Lucy Kulbago, ed. Project CLEA Software. Project CLEA. John Carroll University. Web. 15 July 2014. `http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html`.