Hubble’s Law

PHYS 1301
Adapted from
http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/hubbles_law_preselected.html

Introduction

In the 1920's, Edwin P. Hubble discovered a relationship that is now known as Hubble's Law. It states that the recessional velocity of a galaxy (how fast it is moving away from us) is proportional to its distance from us:

$$v = H_o d \tag{1}$$

where v is the galaxy's velocity (in km/sec), d is the distance to the galaxy (in megaparsecs Mpc; 1 Mpc = 1 million parsecs, 1 parsec = 3.26 light years), and H_o is the proportionality constant called **"**The Hubble Constant**".** Hubble's Law implies that a galaxy moving away from us twice as fast as another galaxy is twice as far away. In order to precisely determine the value of H_o, we must determine the velocities and distances to many galaxies, preferably those extremely far away. In this lab you will analyze light from a few actual galaxies, to determine a rough value for Hubble's constant. If the universe has been expanding at a constant speed since its beginning, comparing equation (1) to speed = distance/time, we see that the universe's age would simply be $t = 1/H_o$. This will allow you to estimate the age of the universe.

Velocity ***v :*** This can be calculated using the Doppler effect. This effect means that electromagnetic waves received from a source moving away from the observer are shifted to lower frequency f compared to those coming from the same source if it were at rest relative to the observer. Because the speed of light $c = 3 \times 10^5$ km/s is constant, this means that the *wavelength* of the wave (it’s color) defined by $\lambda = c/f$ is shifted to a longer (redder) wavelength. The ratio of this shift to the true `rest’ wavelength is called the *redshift*

$$z = (\lambda_{measured} - \lambda_{true}) / \lambda_{true} \tag{2}$$

λ_{true} is the wavelength of light as emitted from a certain source (usually hot gas) in a lab on Earth, while $\lambda_{measured}$ is the wavelength received at a telescope from the same kind of source in a fast-moving galaxy. The theory of the Doppler Effect then shows that the recessional velocity of a galaxy is

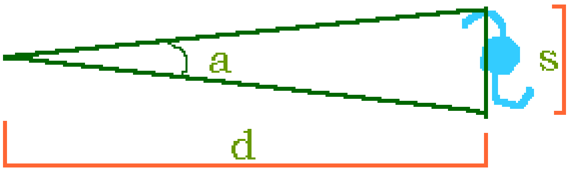
$$v = c\, z \tag{3}$$

Galaxies emit light of many different wavelengths, but certain wavelengths, called emission and absorption lines, tend to be very prominent and can be used to easily determine the redshift due to motion of the source.

> Example: An absorption line is measured in the lab at 5000 Å (1 Ångstrom (Å) = 10^{-10}m). When analyzing the electromagnetic spectrum of a certain galaxy, the same line is found at 5050 Å. Knowing the speed of light, we calculate that this galaxy is receding at $v = (50/5000) \times c$ or approximately 3000 km/s.

Distance *d* : We will assume that all galaxies of the same type are the same physical size *s*, no matter where in the Universe they are. Since objects further away look smaller – they have a smaller angular size *a* when viewed through a telecsope – this can be used to calculate the distance *d* to the galaxy from the geometrical formula

$$d = s / a \tag{4}$$



The typical size *s* has been determined (using other methods) with nearby spiral galaxies such as Andromeda, Triangulum, Messier 81, etc. and is on average

s = 22 kiloparsecs (22 kpc or 22,000 parsecs or about 72,000 light years)

We will assume this is the typical size of all spiral galaxies, measure their angular size *a* from telescope images, then calculate their distance *d* from us using equation (4).

Procedure

Go to the Galaxy List at

http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/galaxies.html

First you will measure angular size and calculate the distance to several galaxies.

1. Choose a galaxy from the list.
    - The images are negatives, so that bright objects, such as stars and galaxies, appear dark.
    - There may be more than one galaxy in the image; the galaxy of interest is always the one closest to the center.
    - To measure the angular size *a*, click on opposite ends of the galaxy, at either end of the longest diameter. **Be sure to measure all the way to the faint outer edges, otherwise you will dramatically underestimate the size of the galaxy, and introduce a systematic error.** The computer will automatically calculate the angular diameter in milli-radians (you can ignore pixel coordinates x1,y1, x2, y2).
2. Repeat step 1 for another four galaxies and record your results for *a* in a data table

3. Calculate the distance to each of the galaxies in Mpc (Megaparsecs) using equation (4) with milli-radians units for *a*

$$d \text{ [Mpc]} = s \text{ [kpc]} / a \text{ [milli-rad]}.$$

Now you will measure the redshift and calculate the velocity of your chosen galaxies.

Click on a galaxy's spectrum link and you will see a graph of the full visible light spectrum of the galaxy at the top of the page. This shows how the intensity (brightness) of the light seen from the galaxy depends on the wavelength (color) of the light. Below it are enlarged portions of the same spectrum, in the vicinity of some prominent spectral features. For each galaxy you will use three well-known sources of light, called CaK, CaH, and Hα, to get three independent estimates of the galaxy's velocity. CaK and CaH are "absorption lines", meaning their intensity is exceptionally low, while Hα is an "emission line", meaning the intensity is exceptionally high.

4. The rest wavelengths of CaK, CaH, and Hα are given in the header caption of the graphs. Record the λ_{true} values of these wavelengths.

The small vertical bars near the lower left corners of the graphs mark the values of these rest wavelengths. These wavelengths become shifted to the right (to larger values) in a moving galaxy. They can be located by searching the graphs for nearby prominent dips in the intensity in the case of CaK and CaH, while for Hα the feature will be a nearby prominent peak in the intensity. Ask the instructor if you are not sure what to look for.

5. For each galaxy in your table, measure the shifted wavelength $\lambda_{measured}$ for each of the 3 spectral lines by clicking at the middle of the corresponding feature (dip or peak) in the graphs.

6. For each galaxy, use equation (2) to calculate the *z* values from each of the different spectral lines. **If they seem compatible**, for each galaxy average your *z* values. If your *z* values for a galaxy are not compatible re-check your calculation or re-measure the wavelengths (you may have picked the wrong feature).

7. Using equation (3) and your average *z* values, calculate the recessional velocity of each galaxy in km/s.

Graph your results for *v* and *d* to find the Hubble constant by following these steps:

1. Plot your data for each galaxy with distance (in Mpc) on the x-axis, and velocity (in km/s) on the y-axis.
2. Draw the steepest reasonable line and the shallowest reasonable line on the graph that seems to fit the points on the graph. These lines must both pass through the origin (0,0) (why?) A good fit will have points scattered either side of the line.
3. Measure the slopes of these lines (rise/run); these slopes are your upper and lower bounds on the value of the Hubble constant H_o.

Age of the Universe

Your H_o has been measured in funny units Mpc/km/s that astronomers use, so to find the age of the universe in years, we must cancel the distance units (1 Mpc = 3.09×10^{19} km) and convert seconds to years (1 yr = 3.16×10^{7} s) so that

$$\text{Age [years]} = 3.09 \times 10^{19} / (3.16 \times 10^{7}\, H_o)$$

Calculate an upper and lower bound on the age of the universe from your values of H_o.

Conclusions