Astronomy 150

Exercise 5: Determining the Hubble Constant

Name: ___________________________

Section: ______. Partner: ___________________________

Introduction

Perhaps the most remarkable statement ever made by astronomers about our Universe is that there was a "Beginning". This conclusion is based on observations of the motions of distant galaxies, as first revealed nearly 80 years ago. In this exercise, you will examine the correlation between the distance to a galaxy and its speed of recession. This correlation, known as the HUBBLE LAW, will be used to determine the distances to galaxies using the spectra of these galaxies. The Hubble Law also makes possible an estimation of the age of the Universe.

In 1912, astronomer Vesto Slipher photographed the spectrum of the Andromeda galaxy, only known to be a nebula at the time. Using the best equipment available, it took an exposure of nearly 24 hours over several nights to get an adequate spectrum. He found that the Andromeda nebula was moving towards us at 300 km/s!! By 1917, Slipher had measured the speed of 15 different spiral nebulae, some requiring exposures of 80 hours! All of these nebulae, except for Andromeda and one other, were receding (moving away) from us.

How did Slipher measure the speed of these spiral nebulae? He used their spectra to determine their DOPPLER SHIFT. Remember that an object moving toward us or away from us will have a blueshift or redshift of the absorption and emission lines in its spectrum. This shift is related to the speed of the object which can be determined using the following formula:

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

where $\Delta \lambda$ is the change in wavelength of an absorption or emission line, $\lambda$ is the rest wavelength of the line, $v$ is the speed along the line-of-sight, and $c$ is the speed of light (300,000 km/s). A shift to the red ($\Delta \lambda > 0$) is caused by motion away from the observer and a blue shift ($\Delta \lambda < 0$) means the motion of the object is toward the observer.
Question 1: Both the redshift and interstellar reddening cause the spectrum of an object to be redder than it truly is. How can one tell the difference?

In 1924, the German astronomer Carl Wirtz pointed out that the redshift of a galaxy increased with increasing distance, but nobody noticed! At about the same time, Edwin Hubble was able to photograph individual stars (including a Cepheid variable) in the Andromeda nebula with the then-new 100 inch telescope on Mount Wilson. He was among the first to show that the Andromeda nebula was actually another galaxy beyond the Milky Way. Using the one Cepheid variable, he determined the distance to the Andromeda galaxy to be about 1 million parsecs. While Hubble did not discover the redshift of galaxies and was not the first to suggest that the redshift was proportional to distance, he had the equipment needed for determining the distances to galaxies. By 1929, Hubble had estimated the distances to many of the galaxies that Slipher had already measured speeds.

Part 1: The Hubble Law and Hubble's Constant

The Hubble Law is a relation between the speed of recession of a galaxy and its distance from us and is given by:

\[ V = H D \quad \text{or} \quad H = \frac{V}{D} \]

where \( V \) is the speed a galaxy is moving away from us and \( D \) is the distance to the galaxy. \( H \) is the constant of proportionality and is called the Hubble Constant. Simply put, Hubble's Law states that the greater the speed of recession of a galaxy, the more distant is that galaxy.

Exercise: Attached is a figure which shows the spectra of five galaxies and their estimated distances. All the photographs are on the same scale. The bright lines above and below the galaxy spectra are comparison (rest-frame) spectra. The wavelengths of the three brightest lines are 388.8 nm, 447.1 nm, and 501.5 nm reading from left to right.

Step 1: Using the comparison lines, determine the wavelength scale of the spectra; that is, find out how many nanometers on the spectrum correspond to 1 millimeter on the figure.
Step 2: Calculate the speed of recession for these five galaxies by determining the Doppler shift of the H+K lines (a pair of calcium absorption lines) in each galaxy spectrum, completing the table below.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Arrow Length (mm)</th>
<th>H+K Shift (nm)</th>
<th>H+K rest λ (nm)</th>
<th>Speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgo</td>
<td></td>
<td></td>
<td>395.1</td>
<td></td>
</tr>
<tr>
<td>Ursa Major</td>
<td></td>
<td></td>
<td>395.1</td>
<td></td>
</tr>
<tr>
<td>Corona</td>
<td></td>
<td></td>
<td>395.1</td>
<td></td>
</tr>
<tr>
<td>Bootes</td>
<td></td>
<td></td>
<td>395.1</td>
<td></td>
</tr>
<tr>
<td>Hydra</td>
<td></td>
<td></td>
<td>395.1</td>
<td></td>
</tr>
</tbody>
</table>

Step 3: Plot the speeds you measured versus the distance for these 5 galaxies. Scale the graph so that a maximum distance of 1,000,000,000 pc can be plotted on the x-axis (on the long side of the graph paper) and a maximum speed of 100,000 km/s can be plotted on the y-axis.

Step 4: Draw a straight line of best fit through the 5 points you have plotted.

Step 5: From your graph, determine the Hubble Constant, H. H is usually expressed in units of km per second per million parsecs (km/s/Mpc). So, you can find the Hubble Constant by reading the value of the speed that corresponds to 1,000,000,000 pc (1000 Mpc) and dividing that value by 1000.

\[ H = \frac{\text{Speed}}{1000} \]

Step 6: How does your value compare to the accepted values of between 50 and 100 km/s/Mpc?

Question 2: A galaxy is found to have a recessional speed of 100,000 km/s. How far away is it?
Part 2: Determining the Age of the Universe

We can now use your value of the Hubble Constant to estimate the time since the start of the galaxy recession, the "Age of the Universe".

*Question 3:* If a galaxy is 10,000,000 pc away from us, use the Hubble Law, along with the constant you determined, to calculate the speed the galaxy is receding from us.

   a) Speed of recession = __________ km/s.

   Now, using this distance and speed, find the time at which this galaxy was at a distance of zero. Or, when was this galaxy at the same position as the Milky Way? To do this, remember that distance = (speed x time) and that 1 pc is equal to $3 \times 10^{13}$ km.

   b) Time at zero distance = __________.

      (Be sure to have units of time for this number)

      (There are $3.2 \times 10^7$ seconds in 1 year)

*Question 4:* Now do the same for a galaxy at a distance of 50,000,000 pc.

   a) Speed of recession = __________ km/s.

   b) Time at zero distance = __________.

*Question 5:* What do you notice about these two times?
Simply put, in an expanding universe, the rate of expansion is given by the Hubble Constant. One can use the Hubble Constant to determine how long the expansion has been taking place; or how long ago was it that all the galaxies were at the same position in space. This is what you have just calculated. This time is called the Hubble Time and is a pretty good estimate of how long ago the "Big Bang" took place.

Some Final Questions to Think About Before Answering:

If the Hubble Law is true, then

a) Why is the Andromeda galaxy approaching us?

b) Is everything getting larger? Is the size of the bricks in the Physics building increasing? Why or why not?
### Relation Between Red Shift and Distance for Remote Galaxies

<table>
<thead>
<tr>
<th>Galaxy, Part of Cluster in:</th>
<th>Estimated Distance (megaparsecs)</th>
<th>Red Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgo</td>
<td>15</td>
<td>H + K</td>
</tr>
<tr>
<td>Ursa Major</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Corona Borealis</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>Boötes</td>
<td>490</td>
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<tr>
<td>Hydra</td>
<td>760</td>
<td></td>
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