Name: ____________________ Date: ____________________
Student ID: ____________________ Section: ____________________

The Hubble Redshift Distance Relation

I. Objective

You will verify the observed fact that all galaxies are moving away from us, and you will use the Doppler shift formula to calculate how fast they are receding and use the magnitudes of galaxies to determine their distances. You will prove for yourself that the nature of their motion means that the Universe is expanding, and you will calculate the age of the Universe.

II. Introduction

During the early part of the twentieth century, an astronomer by the name of Vesto Slipher discovered that the spectra of galaxies indicated that most of them were moving away from our Galaxy. By noting the shift of characteristic lines towards the red end of the spectrum, he surmised that most galaxies were moving away from us, at rather large speeds. In the 1920's, Edwin Hubble measured the distances to many galaxies, and determined an interesting relationship: the farther away the galaxy, the faster it appears to be moving away from us.

If the motions of galaxies are purely do to random motions through our Universe, one would expect to find as many galaxies moving towards us as away from us. The fact that we find most galaxies moving away from us suggests that there is an organized motion to galaxies. In essence, it suggests that the Universe itself is expanding.

At first glance, it may appear that since everything appears to be moving away from us, that we must be located at the center of the Universe, but this is not the case. As we will discover in this lab, we are not in some preferred location in our Universe. In this lab we will also use the fact that galaxies appear to be moving away from us to infer an age for the Universe, based on the amount of time it would take for galaxies to have moved to their current positions, at their current velocities.

III. Gathering Data

- Open up the program titled **"The Hubble Redshift Distance Relation"** which can be found under the appropriate course file (the teaching assistant on duty will help you find the program).
- Click on **File** and then click **Log In**. You will be asked to type in your name and the name of your lab partner (no more than two people in a group, please).
- Once you have entered your names, click **OK**.
- Next, click on **File** and then click **Run**. You are now in control of the KPNO 0.9 (36") Telescope.
- The program begins with the dome closed and the tracking status off. First, click on **Dome** to open the dome. Next, click on **Tracking** so that the telescope automatically moves with the stars over time (so that it will keep pointing at the same object over time).
- After the dome shutters have opened, you will be looking through the finder scope at a field of stars and some galaxies (the finder scope allows you to look at a larger field of view, albeit at a lower brightness, in order to find objects better). All of the stars that you see belong to our Galaxy, the Milky Way. Your goal is to observe the spectra and magnitudes of 5 galaxies, one from each cluster of galaxies.

- The telescope is currently pointed at the Coma Berenices cluster. Use the **"N", "W", "S", "E"** buttons to move the telescope until the central red box is centered on one of the galaxies (you can change how quickly the telescope moves - or slews - by clicking on the **Slew Rate** button). Next, click on **Change View** to change from the finder scope to the spectrometer. You will see an enlarged view of the galaxy. Once again, use the **"N", "W", "S", "E"** buttons to move the telescope until the two central red lines (the spectrometer slit) pass through the center of the galaxy.
- Once you have properly positioned the spectrometer slit, click on **Take Reading**. The screen now displays a graph of the intensity of light as a function of wavelength (in units of Angstroms - which are equal to 10^{-10} meters). Click on **Star/Resume Count** to start observing the spectra of the galaxy. The spectrometer will collect photons of light from the galaxy and record their wavelength. The graph will display the relative intensity of light at each wavelength. A number of other quantities will also be listed:
  - **Object** - the name of the galaxy being observed
  - **Apparent Magnitude (m_V)** - how bright the galaxy appears, as measured in magnitudes.
  - **Right Ascension & Declination** - celestial coordinates of the galaxy.
  - **Integration (Seconds)** - how long you've been observing the galaxy.
  - **Photon Counts** - how many photons the spectrometer has "collected"
  - **Avg. per Channel** - the average number of photons per wavelength.
  - **Signal/Noise** - a measurement of the strength of the signal from the galaxy, relative to background noise. The higher the Signal/Noise, the stronger the signal.

  Record the relavent data in the chart at the end of the lab.
- Continue collecting photons until you reach a Signal/Noise of at least 10.0. Once you have reached this value, click **Stop Count**. If at any time you need to collect more photons, simply click **Start/Resume Count** until you get to the desired level.
- After you collect enough photons, you will see two dips in intensity in your spectra. These correspond to two absorption lines called the K & H calcium lines. Normally, these lines appear at the following wavelengths when observed in a laboratory (we call these the rest "wavelengths"):

  K line: 3933.67 Angstroms

  H line: 3968.847 Angstroms

  but will appear shifted from these positions due to the radial motion of the galaxies in relation to us. Position the cursor at the lowest point of each absorption line and click on it. This will give you the observed wavelengths of these two calcium lines (the K line will always be shorter than the H line). Record these values in the table on page 58, along with the object name, photon count, and apparent magnitude.
- Once you are done, click **Return**. You will be brought back to the spectrometer view of the galaxy. Click on **Change View** to go back to the Finder scope view.
- Click on **Field** and choose another galaxy cluster. Repeat the above steps for all five clusters of galaxies.

IV. Analyzing the Data

You should have noticed that the K & H calcium lines did not appear in any galaxy at their rest wavelengths.

1. **In each galaxy, was the observed wavelengths of the K & H calcium lines longer or shorter than that observed in a laboratory.**

The "shift" of the pattern is called the *Doppler Effect*, and it is caused by the motion (relative to us, the observers) of the star that is emitting the light. If a star is moving towards us, its light will have a shorter wavelength — the light is *blue-shifted.* If the star is moving away from us, the wavelength of the light is longer — the light is *red-shifted.* It is easiest to detect the change in wavelength of the light from the shift of the spectral lines. (The shift of the line is the difference between the observed wavelength and the rest wavelength.)

2. **Compare the rest wavelength and the observed wavelength of the calcium lines in the previous question. Are the galaxies moving towards us or away from us? How do you know this?**

The shift of the line gets larger as the speed of the light source (relative to us) increases. There is a formula that makes it possible to determine how fast a source is moving by measuring the change in wavelength.

$$\text{Doppler formula :} \qquad \frac{(\lambda_{\text{obs}} - \lambda_{\text{rest}})}{\lambda_{\text{rest}}} = \frac{v}{c}$$

where:

where:	λ_{obs}	is the wavelength we observe,
	λ_{rest}	is the wavelength from an object which is at rest,
	v	is the speed of the object relative to us,
	c	is the speed that the wave travels at.
		A light wave travels at the speed of light, which is 300,000 km/sec.

If the speed of the object is zero, the shift in wavelength will also be zero. For an object that is moving at high speed, v will be large, and the shift in wavelength will also be large.

3. **Use the Doppler formula to determine the speeds of the galaxies. (Show your work below the table on page 58.)**

(We will use the distance modulus formula to determine the distances to the various galaxies. Refer to the Appendix for an explanation of magnitudes.)

The typical galaxy is assumed to have an absolute magnitude of -22. Absolute magnitude is analogous to luminosity, and is an intrinsic property of galaxies. How bright the galaxy appears to us is measured by its apparent magnitude, which is analogous to flux, or brightness. The farther away a galaxy is, the dimmer it will appear, and the larger its apparent magnitude will be in numerical value. A relationship between these two values can therefore give us the distance to each galaxy (just as a relationship between luminosity and flux can be used to determine distances). The distance is given by the formula:

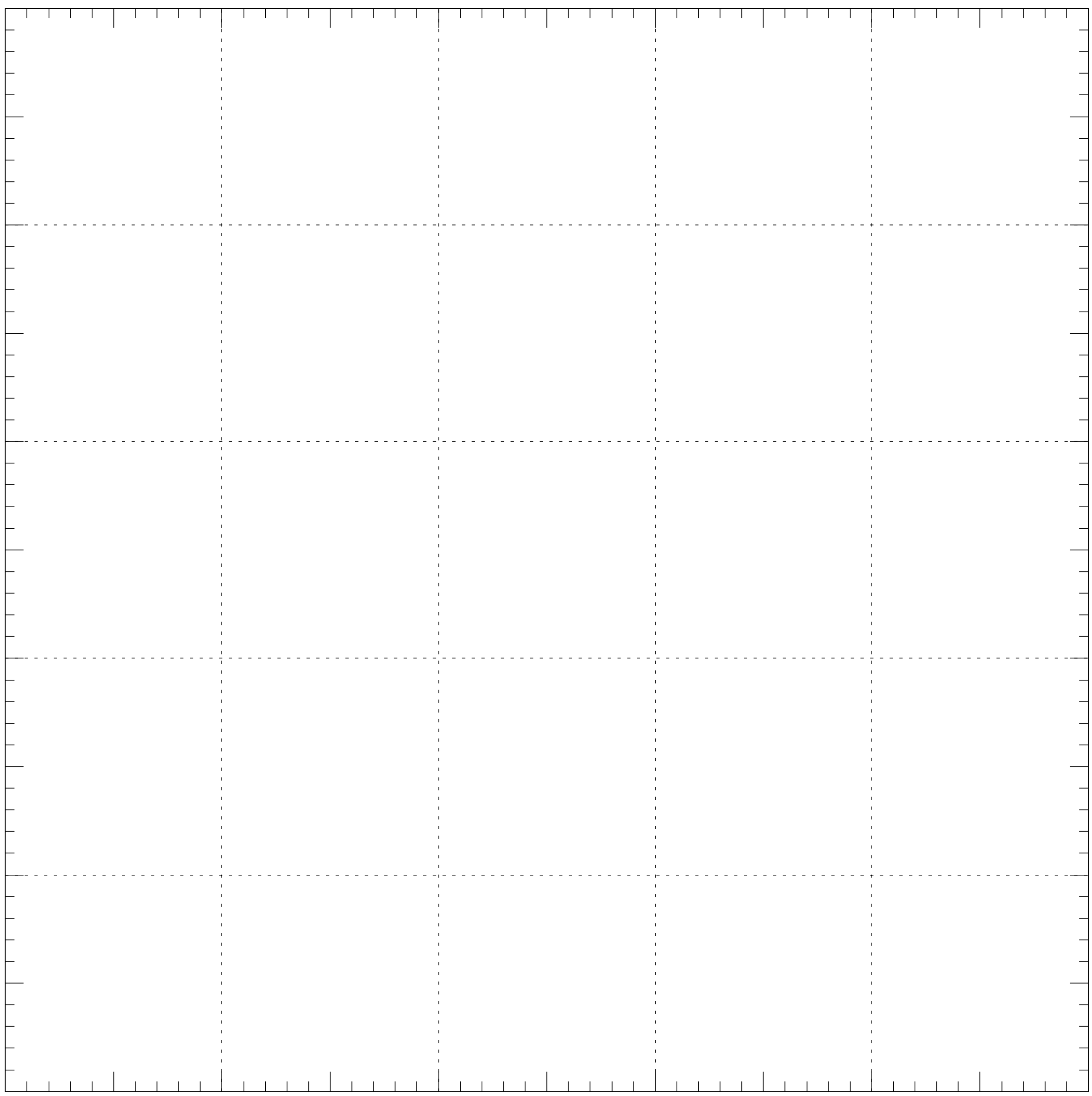
$$\mathrm{m_V} - \mathrm{M_V} = 5\log\frac{\mathrm{d}}{10\ \mathrm{pc}}$$

Where m_V is the apparent magnitude of the star, M_V is the absolute magnitude of the star, and d is the distance to the star. The quantity m_V - M_V is known as the distance modulus, since by knowing this value you can determine the distance of the star.

4. **Use the distance modulus formula to determine the distances to the galaxies. (Show your work here and write your answers in the table on page 58.)**

5. **Compare the distances to the galaxies and the speeds with which the galaxies are moving away from us, and describe their relationship. For each galaxy, plot the recession velocity (y-axis) versus the given distance (x-axis). Draw one straight line which best fits the four data points you have plotted. What is the slope of this "best-fit" line? (What are the units?)**

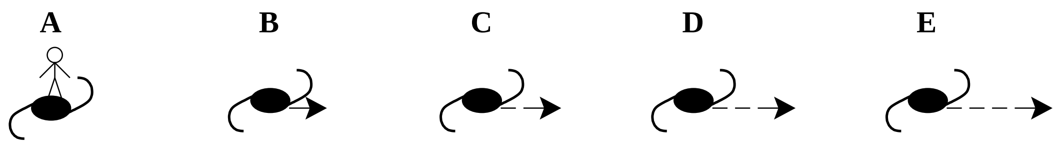
Hubble Diagram



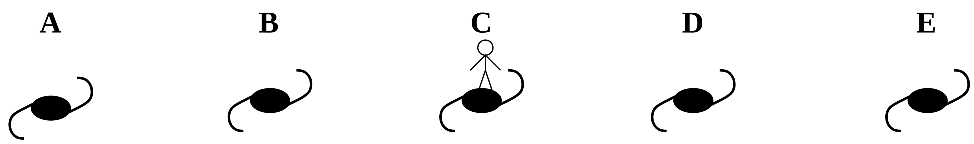
You have just done the same calculations that the astronomer Edwin Hubble did in the late 1920's. The relation you described in d. between the distances and speeds of galaxies is called *Hubble's Law*, and the slope of the line in question d. is known as the *Hubble Constant*.

What does Hubble's Law tell us about the Universe? At first it may seem as if we (in the Milky Way) are in a "privileged position" in the Universe, since all other galaxies are moving away from us. Are we at the center of the Universe?? We will perform a "thought experiment" to find the answer.

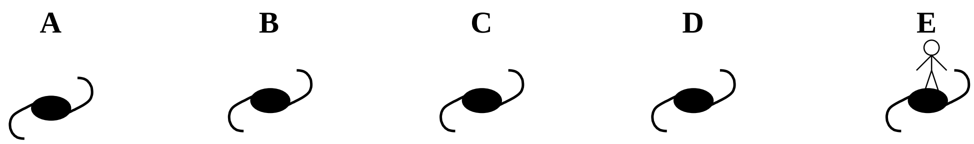
Imagine that A, B, C, D, and E are galaxies. The arrows represent the speeds of the galaxies as seen from A (longer arrow = higher speed). This diagram represents what Hubble's Law states.



6. **What would an observer sitting in galaxy C see when s/he looked at the other galaxies? Draw arrows to represent the speeds that this observer would measure.**



7. **Change your perspective again and do the same for an observer sitting in E.**



8. **Look at the diagrams in questions e. and f. What relation will observers in galaxies C and E find between speeds and distances of galaxies? Is the Hubble law the same for observers in all galaxies?**

What you have seen in this thought experiment is precisely the explanation of why the proportionality between galaxy distances and speeds leads to the deduction that the Universe is expanding. All galaxies are getting farther and farther apart all the time!

It is also possible to make an estimation of how long the expansion has been going on; this is the time which astronomers take as the "age of the Universe," or the time since the Universe began to expand.

Note: There are 3×10^{19} kilometers in a Megaparsec (Mpc), and there are 3×10^{7} seconds in a year.

9. For any galaxy except the one in the Coma Berenices cluster, take the distance and speed you have calculated. By imagining backwards in time, calculate how many years this galaxy has been moving away from the Milky Way. That is how long the Universe has been expanding; your answer is the age of the Universe! Explain how your answer is achieved.

10. Summarize the important concepts presented in this lab, as well as your main conclusions. Your summary should include, but not be limited to, a discussion regarding the general trend in the motion of galaxies and what this tells us about our Universe and our location in it. Also include a discussion regarding how we determine velocities of stars and galaxies. Include any additional questions you may have.

Galaxy Name	Photon Count	App. Mag. (m_V)	λ_K measured	λ_H measured	$\Delta\lambda_K$	$\Delta\lambda_H$

$\lambda_{K,\text{rest}} = 3933.67$ Å $\quad \lambda_{H,\text{rest}} = 3968.847$ Å

Galaxy Name	Distance in pc	Distance in Mpc	Vel.(H) km/s	Vel.(K) km/s	Vel.(Avg.) km/s

VI. Appendix: Apparent Magnitude, Absolute Magnitude, and Distance Modulus

Around the second century B.C., a Greek astronomer by the name of Hipparchus decided to rank the stars in the sky that could be observed with the unaided eye. He classified the brightest stars as "first class" and the dimmest stars as "sixth class". All of the stars of intermediate brightness fell into a category somewhere in between. This property of stars is called the **magnitude** of the star. Even though astronomers today have more sensitive instruments for measuring the brightnesses of stars, Hipparchus' classification scheme is still used. After making minor adjustments to the Hipparchus' scheme, the magnitude system obeys a few rules:

(a) Brighter stars are classified as having smaller magnitudes, numerically. Hipparchus labeled the brightest stars as having a magnitude of 1, and the dimmest stars (as seen by eye) as having a magnitude of 6. This is contrary to our normal way of thinking (usually, bigger is brighter).

(b) A star which is brighter by 5 magnitudes (therefore, has a value 5 magnitudes lower) is actually 100 times brighter in flux. In other words, a difference in magnitudes of 5 corresponds to a ratio in brightness of 100. It turns out that the human eye measures changes in brightness on a logarithmic scale; what appears to us as an incremental step up in brightness is actually a multiplicative increase.

Because the magnitude of a star is a measure of how bright it appears to us, astronomers call this the **apparent magnitude** of a star, which is analogous to flux. This value may change for a star, depending on our position relative to it. The actual amount of energy emitted by a star does not change on our timescales, and the property related to this is called **absolute magnitude**. The absolute magnitude of a star is the apparent magnitude it would have if it were exactly 10 pc away from us. Absolute magnitude is analogous to luminosity, an intrinsic property of a star.

Just as knowledge of the flux and luminosity of a star can tell us its distance, so can a knowledge of a star's apparent and absolute magnitudes. The relationship between apparent magnitude, absolute magnitude, and distance is given by the formula:

$$\mathrm{m_V} - \mathrm{M_V} = 5\log\frac{\mathrm{d}}{10\ \mathrm{pc}}$$

Where m_V is the apparent magnitude of the star, M_V is the absolute magnitude of the star, and d is the distance to the star. The quantity m_V - M_V is known as the distance modulus, since by knowing this value you can determine the distance of the star.