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# The Hubble Ultra Deep Field

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A laboratory exercise for students in AST 114

Arizona State University

## Project Overview

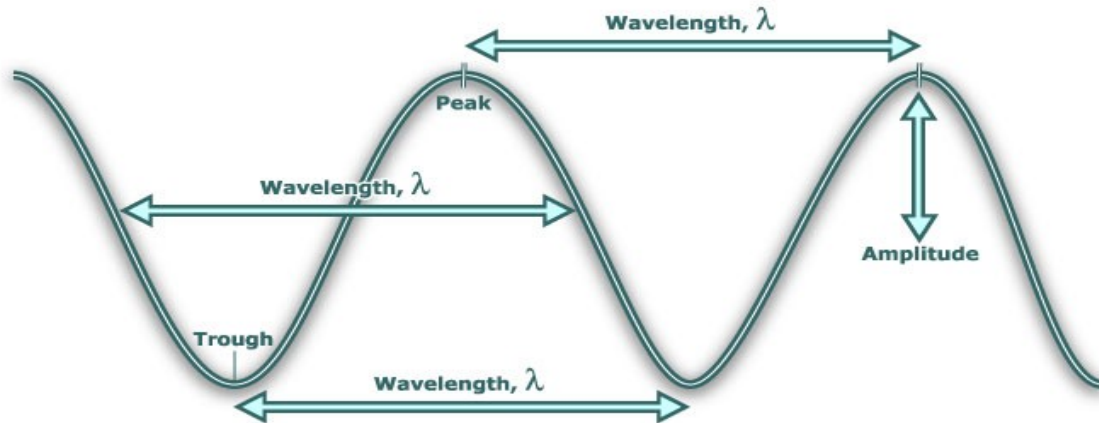
In this project, you will explore the 20<sup>th</sup> century discovery that the Universe is expanding, or similarly, find that the further away an object is, the rate at which it is moving increases. Using the Hubble Ultra Deep Field, in which a variety of galaxies distances and cosmological redshift velocities have been calculated. You will use this dataset, in combination with the principle of the Doppler Shift of light, to determine the rate of this expansion, which is named in honor of the American astronomer Edwin Hubble who first discovered it. Upon completing this exercise, you will have explored the most significant astrophysical “photograph” ever produced and develop your understanding of:

- 1) the Doppler Shift of Sound and Light
- 2) galaxy type, morphology, and the evidence for galaxy formation models
- 3) the Hubble Expansion of the Universe and the estimate to the age of Universe

## A primer on the qualities of waves

The electromagnetic phenomena that we call “light” can be adequately understood by its wave-like properties. If you are unfamiliar with the physical description of waves, consider the following figure.

A wave can be fully defined by its wavelength and amplitude, which are outlined below.



A wave can similarly be described by its frequency. The definition of the frequency is: Frequency =  $1 / \text{Period}$ . The definition of Period is simply the time it takes for the wave to cycle between peaks (or troughs, or any similar amplitude)

What do these terms mean physically? For sound waves, the relationship between wavelength/frequency and “pitch” of a wave:

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HIGH “pitched” sounds have SMALL Wavelengths and HIGH Frequencies

LOW “pitched” sounds have LARGE wavelengths and LOW Frequencies

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Light waves are a different physical phenomenon than sound waves. They are manifestations of oscillations in electro-magnetic fields, whereas sound waves are pressures disturbances in a dense medium. For light waves, the relationship between wavelength/frequency and “color” of a wave is:

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REDDER light has LONGER Wavelengths and LONGER Frequencies

BLUER light has SHORTER wavelengths and SHORTER Frequencies

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Christian Doppler observed, in the 1800s, that the pitch of a sound emitted from a source that is moving with respect to the observer varies as a function of the moving object's velocity. This is a phenomena you are all familiar with, if you have ever noted the change in the sound of a firetruck's or police car's siren that occurs as the sound sources moves away or towards you at a high velocity. This fundamental physics phenomenon is, in honor of its discover, called the Doppler Shift of Sound.

Because light can be described by its wave properties, you might expect that the Doppler Shift phenomenon would exist. In fact, it does and the magnitude of the Effect can be quantified for each of these phenomena by a simple equation, provided below.

For Sound:

$$\lambda = \lambda_0 \left( 1 + \frac{v_o}{v_c} \right)$$

For Light

$$\lambda = \lambda_0 \left( \frac{1 + \frac{v_o}{c}}{1 - \frac{v_o}{c}} \right)^{1/2}$$

Here, the subscript indicates “the source reference frame” and,  $v$ , is the velocity of the object with respect to the observer. You'll note that, though these equations are similar in form, they do differ. In short, this discrepancy arises from the physicist Albert Einstein's theory of Special Relativity, and as a result we typically refer to the Doppler Shift for light as a *relativistic Doppler Shift*. The crux of Special Relativity is that, unlike the speed of sound, the speed of light constant in all inertial frames of reference and is usually abbreviated as  $c$ .

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$$c = 2.99 \times 10^8 \text{ meters per second}$$


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Now for some astrophysics.

Rather than referring the observed shifts in wavelength, astronomers simply refer to the observed shift by the color variation. You can use the table below as a reference:

<i>If the light is....</i>	<i>...then the emitter is....</i>	<i>...and we call this a</i>
“Bluer than expected”	moving towards us	“blueshift”
“Redder than expected”	moving away from us	“redshift”

In a mildly confusing abbreviation, astronomers have developed a short hand notation,  $z$ , called the “redshift” parameter. Making this substitution for the red-shift parameter, the former equation can be rewritten in a form that is most familiar to astronomers.

Equation 1:

$$1 + z = \left( \frac{c + v_0}{c - v_0} \right)^{1/2}$$

Here, the red-shift,  $z$ , is defined simply as the magnitude of the observed shift:

Equation 2:

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

For source velocities *much much less* than  $c$ , we can appropriately define  $z=c/v$ . But, If you are considering light from extremely distant objects, though, you can not use this approximate to quickly determine the recessional velocity,  $v_{\text{source}}$ . Instead, you have to use the following equation to determine the recessional velocity, which is a simply a different representation of Equation 1.

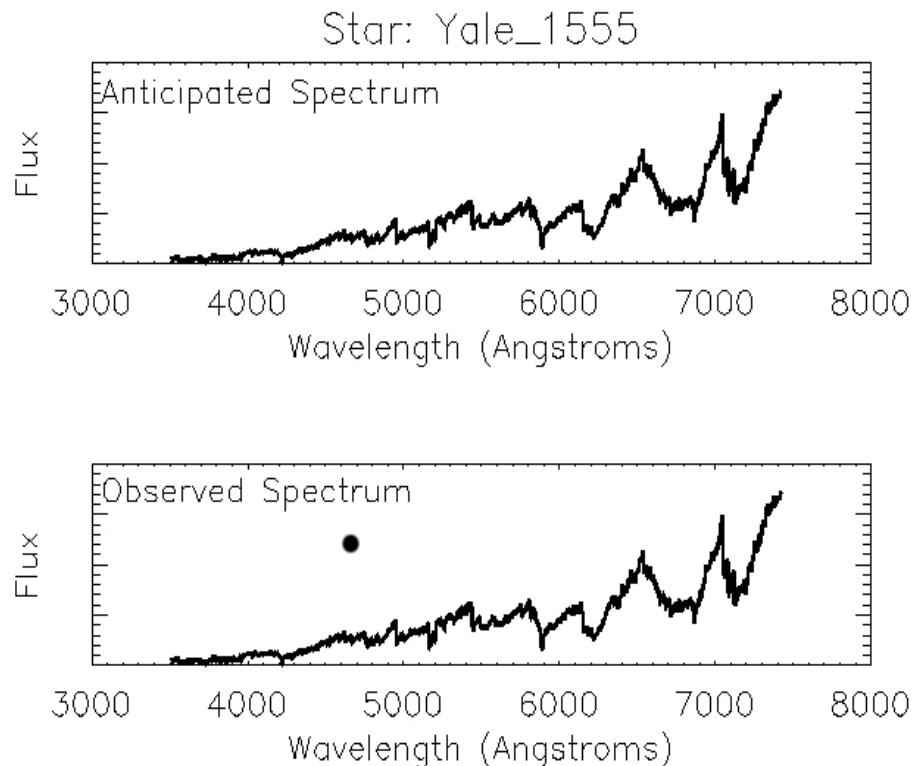
Equation 3:

$$\frac{v_o}{c} = \frac{(1+z)^2 - 1}{(1+z)^2 + 1}$$

Now, that we have an understanding of the mathematics behind the Doppler Shift of light, how do astronomers figure out what the specific emission from a distant object is telling them about the Universe? A *spectrometer* will “break apart” light into its components. White light is actually composed of all the colors of the rainbow (Red, Orange, Green, Blue, etc.) in with varying intensities. So too is light from distant galaxies and stars composed (the superposition) of a wide array of wavelengths. Thus, a spectrometer attached to the business end of a telescope can be used to understand the nature of light, as well as the sources that emitted this light, for distant objects.

## Redshifts in Practice

Consider the spectrum below, taken of a star near our Sun.



The vertical axis is the flux (measured in units of energy per time per area) of the light as it is received by the telescope, the x axis is the *wavelength* of the light and moving right

to left you are considering light that is more and more “red”. The depressions or “troughs” in this *spectrum* are absorption lines, and because they are produced when an atom of a certain type absorbs a very specific energy photon (a particle of light); we can predict the wavelengths at which they should appear for a given system of atoms.

Believe it or not, the light from this star is redshifted, though you probably could not immediately identify this shift. The shift for this star is quite small in fact. If the absorption line at  $6366 \text{ \AA}$  was predicted by atomic physics to be at  $6364 \text{ \AA}$ , you can calculate how fast the star is moving away from the observer (assume the observer is at rest with respect to the star). To find this velocity, you can use the *relativistic Doppler equation*. How fast is that star moving towards or away from the observer, if the observer is assumed to be at rest?

As always, write down what you know (note that  $1 \times 10^{-8} \text{ cm} = 1 \text{ \AA}$ ):

What is  $\lambda_0$ ? \_\_\_\_\_ in cm? \_\_\_\_\_

What is  $\lambda$ ? \_\_\_\_\_ in cm? \_\_\_\_\_

Is this object moving towards or away from the Earth? That is, is the observed wavelength longer (redder) or shorter (bluer) than expected?

\_\_\_\_\_  
\_\_\_\_\_

Using the definition of the red-shift, that is:

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

how much has this light been red-shifted/blue-shifted?

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Lastly, what is  $v_{\text{source}}/c$  ?

Given the value for  $c$ , how fast is this object moving towards or away from the Earth in centimeters per second?

Last, but not least, if 55 centimeters per second is roughly equivalent to 1 mile per hour, how fast is this star moving away, in miles per hour?

The velocity you calculated for this star is much less than the speed of light, so we could have found a decent approximation to the answer using  $z = v/c$ . But, if you use the approximation equation to calculate the recession velocity based on the spectral shift from the spectrum of a distant galaxy you would find that those velocities are greater than the speed of light! That can't be—the speed of light is the “ultimate” speed limit. If you use Equation 3, though, you would find that these galaxies are moving away at a more reasonable 99.99999% of the speed of light.

*But the mechanism behind these shifts are different.*

In the case of the nearby star, the red/blueshifts observed are due to true motion of the emission source with respect to the observer. In the case of the distant galaxies, though, this observed recession occurs because these galaxies reside in a Universe that is itself expanding (and in fact accelerating in this expansion) and this expansion itself red-shifts the light. Spacetime itself is “stretching” out over time and this causes the light from distant objects to be red-shifted. That is, the length of your ruler, measured across cosmic times is itself increasing and so correspondingly, the wavelength of light emitted over cosmic distances itself increases. As progressively longer wavelengths correspond to progressively redder “colors” the light that we observe from distant galaxies is redder than “expected” if it were emitted in the viewer’s rest frame. These red-shifts are often referred to as *cosmological red-shifts*. If the Universe were “standing still,” there would be no cosmological red-shift.

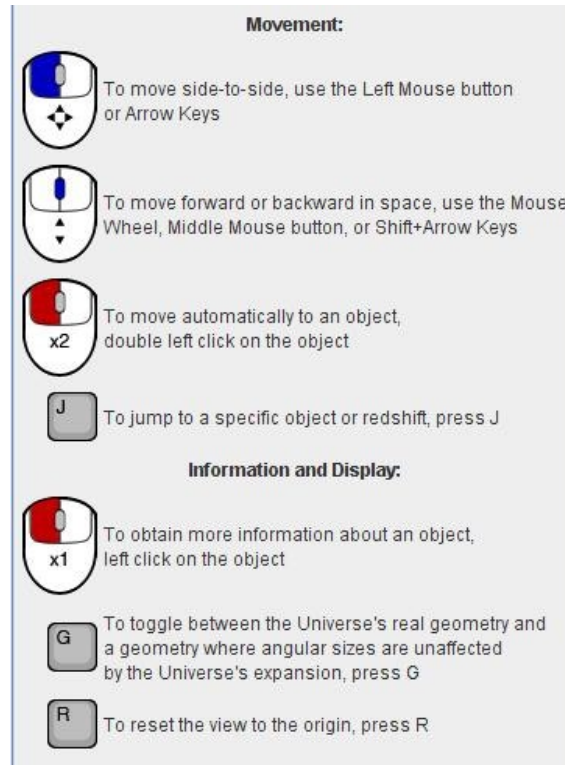
## **The HUDF as an astrophysical tool**

In the following sections, you will explore the idea of an expansion Universe. To do this, you will use one of most tantalizing images ever taken with a telescope. This image is called the Hubble Ultra Deep Field and it was produced using the Hubble Space Telescope, as part of the GRAPES program whose PI was ASU faculty member Dr. Malhotra. After the data were collected ASU students and professors led by Dr. Rogier Windhorst, Matt Mechtley, and Lisa Will developed a software program that allows a person to “zoom” through space and time to gain a better understanding of the distant Universe. This package is called “Appreciating the Hubble Ultra Deep Field at

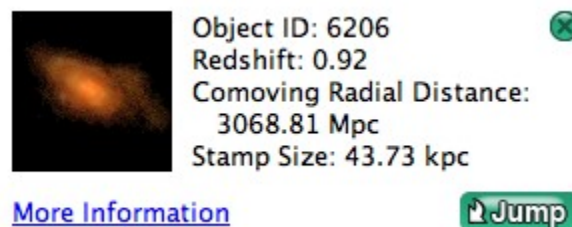
Hyperspeed,” and you will use this software package to understand this expansion of the Universe.

### *Introduction to AHah:*

For this exercise you should choose one partner. In the next few minutes, you and your partner should familiarize yourself with the aHah software. Click on the objects that you see in the image, zoom around, and move around in the image until you feel comfortable with the layout of the program. A mouse and keyboard is all that is necessary to use this software package. The mouse functions are provided below:



If you find an interesting galaxy, and would like to see more information about it, you can left click on that object to bring up a screen that resembles the one below.



This information lists a few important points regarding each galaxy. We will directly use the first three in the following exercises. The first quantity is the Object ID, which is an arbitrary number assigned to each of the galaxies in the HUDF/AHah field, and should be copied for each galaxy you observe. The second point is the redshift; this is equal to  $z$  in the aforementioned equations, and is a unitless measurement of the redshift. The third important quantity in this infobox is the Co-moving Radial Distance, CRD. This value corresponds to the distance along the line of sight to the objects. Here, distances are

provided in units of Mega-parsecs, which are roughly equivalent 3 Million lightyears, or  $6 \times 10^{11}$  Astronomical Units.

For those interested, the CRD equation is provided in the appendix to this exercise. Suffice it to say that the geometry of the Universe is dependent a number of constants that have been well-constrained by observation. In the AHah software package, the Concordance Model is assumed, but you can change these parameters and explore how varying the relative densities of “stuff” in the Universe can change this distance measure.

### Exercise 1: Galaxy morphology over cosmic time

In this exercise you will consider a variety of galaxies over a range of redshifts in order to derive any morphological trends which may arise in the HUDF, over cosmic timescales. Though it is a far from perfect classification system, the morphology (or in other words, “the way galaxies look”) of a galaxy can often provide a unique insight into the processes ongoing in galaxies. In general, we find that the broadband morphologies of galaxies fall into one of three categories-spiral, elliptical, and irregulars:

-Spirals: Spiral galaxies are probably the most familiar class of galaxy. They are easily identified by their discs, in which knotty, clumpy star clusters and spiral “arms” may be found. In some galaxies, the arms are quite diffuse and not “tightly wound,” but these galaxies may still be typed as Spirals. In the center of these galaxies, one can typically find a bright “bulge” of concentrated gas, dust and stars. There are two major subclasses of Spiral galaxies, those with and those without a pronounced bar-structure. Spiral galaxies exhibiting a bar structure are given the designation SBx, where “x” is some letter a, b, or c, or some combination thereof. Spirals without bars are denoted Sx, with the same definition of “x” as before. Because these galaxies are often actively forming stars, they appear “bluer” in color.

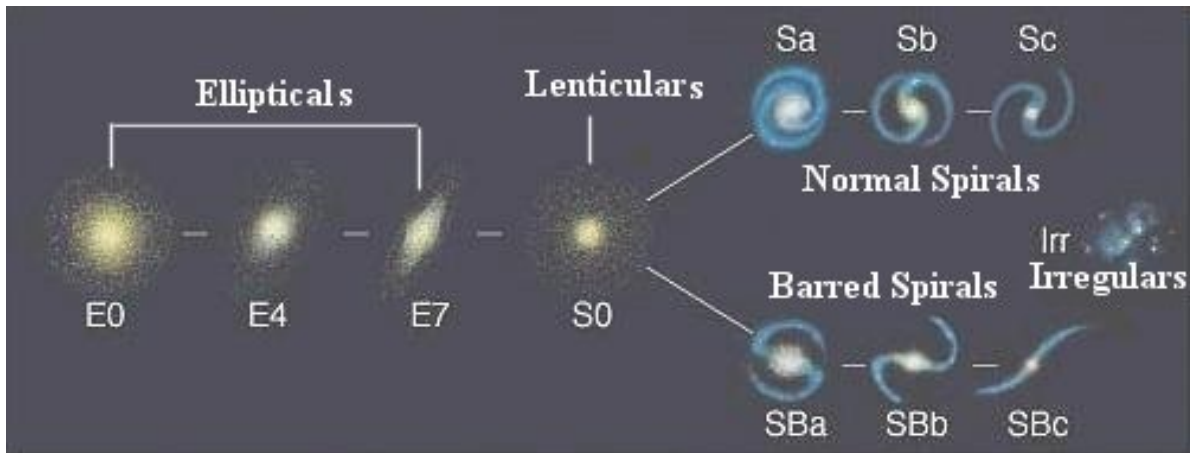
-Ellipticals: As the name would suggest, these galaxies are spherical or elliptical in shape. They lack the “arms” found in Spirals, and often look like reddish footballs, spheres, or cigars. The redness of these galaxies in the local Universe (I.e. at  $z \ll 1$ ) can be attributed to starlight from old-aged stars, comparable in age (or older) to the age of our Sun. A word of caution, though: Don't label every “red” object in this field an elliptical. The galaxies in the HUDF are at high redshift, and as a result their light is redder in the observer's frame. This means that for high redshift galaxies, though you are observing in at optical wavelengths, the emission you observe may have been emitted at much shorter (blue Visible or even UV) wavelengths.

-Irregulars: Some galaxies can not be classified neatly as Spiral or Elliptical (or some variation thereof). These galaxies are then lumped into a catch-all morphological class designated “Irregular.” There are few similarities in morphology between each of these galaxies in this class: they have a wide range of masses, stellar populations, structures and shapes. Many irregulars, though, can be described as “disturbed.” Within dense galaxy cluster environments, the passage of galaxies near to other massive galaxies, or the collisions between two galaxies, can dramatically disrupt galaxies which could have previously been well-classified as Spirals or Ellipticals.

Pictured below is a classification scheme, the Hubble Tuning Fork Diagram, which is not motivated by physics, but is used traditionally to outline the various morphology classes. One can find ellipticals not pictured here in the HUDF, these can be designated  $E_n$ , where  $n$  is some integer value 1,2,3,5 or 6. Similarly, Spirals may not be nicely categorized



either. For example, a tightly wound spiral galaxy, without a bar and devoid of a dusty, gassy inter-arm region may be adequately classed as an “Sab” or “Sa/b”.



Now, using the AHah software classify at least 5 galaxies per each of the following redshift intervals. Click on each of the galaxies that you classify, and also make a note of each galaxy's ObjID, Redshift, and CRD and record these in the table on the next page.

$$0.0 < z < 0.5$$

ObjID	Galaxy Type	CRD (Mpc)	Redshift

$$0.5 < z < 1.5$$

ObjID	Galaxy Type	CRD (Mpc)	Redshift

$$1.5 < z < 4.0$$

ObjID	Galaxy Type	CRD (Mpc)	Redshift

$$z > 4.0$$

ObjID	Galaxy Type	CRD (Mpc)	Redshift

*Interpreting your results:*

**For the entire sample set:**

What percent of the galaxies in your sample were Spirals? \_\_\_\_\_

What percent of the galaxies in your sample were Ellipticals? \_\_\_\_\_

What percent of the galaxies in your sample were Irregulars? \_\_\_\_\_

**For galaxies at a redshift less than 1.5:**

What percent of the galaxies in your sample were Spirals? \_\_\_\_\_

What percent of the galaxies in your sample were Ellipticals? \_\_\_\_\_

What percent of the galaxies in your sample were Irregulars? \_\_\_\_\_

**For galaxies at a redshift greater than 1.5:**

What percent of the galaxies in your sample were Spirals? \_\_\_\_\_

What percent of the galaxies in your sample were Ellipticals? \_\_\_\_\_

What percent of the galaxies in your sample were Irregulars? \_\_\_\_\_

Do you notice any change in the number density of galaxies as a function of redshift? If so what sort of change?

What you have likely discovered is that the number density of irregular galaxies or spiral galaxies increased as a function of redshift, or similarly that the density of elliptical galaxy decreased. This is not a trivial result.

In the simplest analogy of hierarchical assembly model, smaller galaxies (like spirals) in high density environments merge or assemble to form more massive bulges and potentially elliptical galaxies. Thus one would expect that as you look to greater redshifts, you would find a higher number density of spirals or merger remnants. There is one caveat to the analysis you have just conducted, which has been alluded to already. As you explore galaxy morphology at higher redshifts, you move out of the visible rest-frame and into the UV restframe. In this rest-frame, galaxies can display dramatically different morphologies, and spiral galaxies in particular can begin to display irregular-type morphologies. So, some of the galaxies which you identified as irregular morphology may, in fact, be classed otherwise if they were at low redshifts.

In spite of this, the morphologies of galaxies in the HUDF and similar deep field surveys do seem to support the hierarchical assembly theory.

### Exercise 2: Calculation of the Hubble Law for the Expansion of the Universe

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In this exercise you will derive the Hubble Law, so named for Edwin Hubble the scientist who discovered it. This single insightful calculation single-handedly re-defined modern astrophysics and cosmology by giving tangible evidence for the Hot Big Bang model that was proposed by the Belgian priest George Lemaitre. This model, in its modern iteration, proposes that the Universe began approximately 14 billion years ago in an extremely energetic expansion event. It has been consistently re-confirmed by a wide variety of independent studies, and we now understand the evolution of the Universe from the

present day back to roughly  $10^{-43}$  seconds after the birth of the Universe.

To begin this exercise, identify an additional 10 galaxies with redshifts  $z < 1.0$ . Add these to the following table. To determine the velocities of these objects use Equation 3.

Object ID	Redshift	CRD (Mpc)	Velocity ( $\text{km s}^{-1}$ )

The Hubble Law defines the expansion rate of the Universe. Thus, we can use the straightforward rate equation to determine the magnitude of this expansion.

$$\text{Rate} = \frac{\text{Velocity}}{\text{Distance}}$$

You should not convert your redshifts in the table above to velocity. These numbers should all be less than one, and you can use an equation defined previously in this exercise. We will leave them in terms of the speed of light for now, and make the conversion at the conclusion of this exercise.

To determine the Hubble Relation:

- 1) On the attached graph paper, for each of the  $z < 1.0$  redshift galaxies, plot on the vertical axis the velocity of the galaxy with its corresponding CRD on the horizontal axis.
- 2) Calculate the slope of the best fit line to these datapoints. You should use a straightedge, and you can minimize the error of the fit by eye.

3) Determine the magnitude of this slope. Convert this slope into the units of km/s/Mpc by multiplying by the speed of light in the appropriate units. This constant is called the Hubble Constant,  $H_0$ , and it relates the velocity of a distant galaxy to its line of distance by the following equation

$$v = H_0 d$$

What is the sign and value for  $H_0$ : \_\_\_\_\_

Which galaxies are moving at greater velocity with respect to the Earth, the more or less distant galaxies? \_\_\_\_\_

If the accepted magnitude of the Hubble's Constant is 70.1 km/s/Mpc what is the percent error in your estimation. You can determine the percent error with the following formula:

$$P.D. = \frac{|Calculated - Actual|}{Actual} \times 100\%$$

Report your error here:

Lastly, because the slope of this line effectively has units of time (here, seconds), one can make a first approximation to the age of the Universe, assuming a Hubble rate of Expansion.

To make this estimate, you simply need to convert the units of  $H_0$  to units of time, explicitly. Note that 1 kilometer equals to  $1 \times 10^5$  cm and 1 Mpc equals to  $3.08 \times 10^{24}$  cm. Once you have reduced the units of this constant to  $s^{-1}$  you need only to invert the Constant.

Report your estimate to the age of the Universe here:

Note that 1 yr equals to  $3.15 \times 10^7$  seconds. What is your estimate to the age of the Universe in years?

If the accepted age of the Universe is approximately 13.7 billion years, what is the percent error between your calculated age and the accepted age?

Why the great disparity between ages? What does this imply about the expansion of the Universe over the entire lifetime of the Universe?

## Appendix: A brief note on the Co-moving Radial Distance

The CRD is a cosmological distance measure which can be derived from the General Relativity field equations, a derivation first made by Alexander Friedman and George Lamaitre. Cosmological distance measurements are fundamentally linked to the composition of the Universe (e.g. energy, matter, radiation etc.). Different compositions yield different “curvatures”, which dictate the metric by which universal geometries can be derived.

In layman’s terms, the density of “stuff” in the Universe (e.g. atoms, dark energy, or WIMPs) defines the physical Universe. Each component of the Universe affects this geometry differently, and typically the density of each of these components is represented by the greek Omega as the ratio of the component density with respect to the “critical density.” The critical density is a special case gleaned from the reduced F-L expansion equation which, without going into the details of the equation itself, corresponds to a Universe which continues on without accelerating in its expansion (if it has an initial expansion velocity at all).

The CRD equation can be calculated using the following formula:

$$D_c = D_H \int_0^z \frac{dz'}{E(z')}$$

where  $D_H$  is the Hubble Distance,  $c/H_0$ , and  $E(z')$  equals to

$$E(z') = \sqrt{\Omega (1+z')^3 + \Omega_K (1+z')^2 + \Omega_\Lambda}$$

and

with  $G$  equal to the constant of Universal Gravitation,  $H_0$  the Hubble Constant,  $\Lambda$  the Cosmological Constant,  $k$  the curvature scalar

