

Astronomy 1 – Introductory Astronomy

Spring 2014

Lab 6: The Hubble Law and the Expansion of the Universe¹

Quick overview

Meet at 8 p.m. in Science Center Room 187. This is an indoor lab. We will use real data, taken with a large, robotic telescope that has surveyed most of the sky. It's called the Sloan Digital Sky Survey, and it has spectra of over a million objects, many of them galaxies. Galaxies are huge collections of stars (and gas and dust and whatever planets orbit those stars, but the stars are responsible for nearly all the light we see). If you are doing this lab before we read and talk about galaxies in class, you should spend a few minutes on the Astronomy Picture of the Day website looking at pictures of galaxies (see the next section for links).

It was discovered, in the 1920s, that all but a few of the nearest by galaxies are moving away from us (measured using the Doppler shift – nearly all galaxies have a red shift), and that the farther away they are, the faster they appear to be moving. This linear relationship, called the Hubble Law, shows that the Universe is expanding and furthermore, the ratio of distance to velocity tells us how fast it's expanding. Finally, since the Universe is expanding, we can ask ourselves how long it's been expanding for (i.e. how old is the Universe?). In this lab, you will measure the redshifts of ten galaxies, look up the redshifts of five more, and also estimate the distances of each galaxy and thereby measure the expansion rate of the Universe (called the Hubble constant, H_0) and from that, estimate the age of the Universe.

This document has quite a bit of background information. Please read it all before coming to lab, and reread the actual procedures and the questions you'll have to answer (in sections 2, 3, and 4).

Introduction and Goals

Early in the 20th century, it was discovered that stars are not uniformly

¹ This lab is adapted from the University of Wisconsin *Astronomy 100 Lab Manual* ©1996 by Robert D. Mathieu, Chris Dolan, and Eric Wilcots. Used by permission. Further modified by Chris Burns to use the Sloan Digital Sky Survey.

distributed throughout the Universe; instead they are found in enormous aggregates that we call *galaxies*. A single galaxy can have billions of stars, and can exist in various shapes - elliptical, irregular, and spiral. Our Solar System is located in a spiral galaxy we call the Milky Way.

Go to astronomy picture of the day and search of pictures of spiral galaxies: http://antwrp.gsfc.nasa.gov/cgi-bin/apod/apod_search; you might also read about spiral galaxies here: http://en.wikipedia.org/wiki/Spiral_galaxy and see beautiful images of them here: <http://tinyurl.com/y8depg3>.

Virtually all the galaxies in the Universe (with the exception of a few nearby ones) are moving *away* from our galaxy, the 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 than those observed in the spectra of stationary objects. Assuming that these “redshifts” were caused by the Doppler shift, Slipher concluded that the redshifted **galaxies were all moving away from us**.

For more information on absorption line spectra (vs. emission line spectra like the ones you measured in the *properties of light* lab), see: http://en.wikipedia.org/wiki/Spectral_line.

In the 1920’s Edwin Hubble measured the distances to a sample of galaxies. When he plotted these distances against the velocities of the galaxies he found a remarkable trend: the further a galaxy was from the Milky Way, the faster it was moving away. (So dim galaxies tend to have bigger red shifts.) Hubble’s plot is shown in Figure 1 (on the next page).

Was there something special about our place in the universe that made us a center of cosmic repulsion? No. Astrophysicists readily interpreted Hubble’s relation as evidence of a **universal expansion**. The distances between all galaxies in the Universe were getting larger with time, like the distances between raisins in a rising loaf of bread. An observer on any galaxy, not just our own, would see all the other galaxies traveling away, with the farthest galaxies traveling the fastest.

The entire Universe is expanding, one of the truly remarkable discoveries in intellectual history. Today the expansion is believed to be a result of a “Big Bang” associated with the beginning of the present Universe. The *rate* of expansion tells us *how long ago* the Big Bang occurred. So Hubble’s discovery

of the correlation between velocity and distance is fundamental in reckoning the history of the universe (and specifically, its age). This relationship is called “Hubble’s Law” and Hubble’s constant quantifies the expansion rate of the Universe. Mathematically (see below) the relationship is $v = H_0 d$, where v is the speed at which a galaxy is moving away from us and d is its distance. H_0 is the constant of proportionality and is referred to as the **Hubble constant**.

We will be covering this topic in class during the last week of the semester.

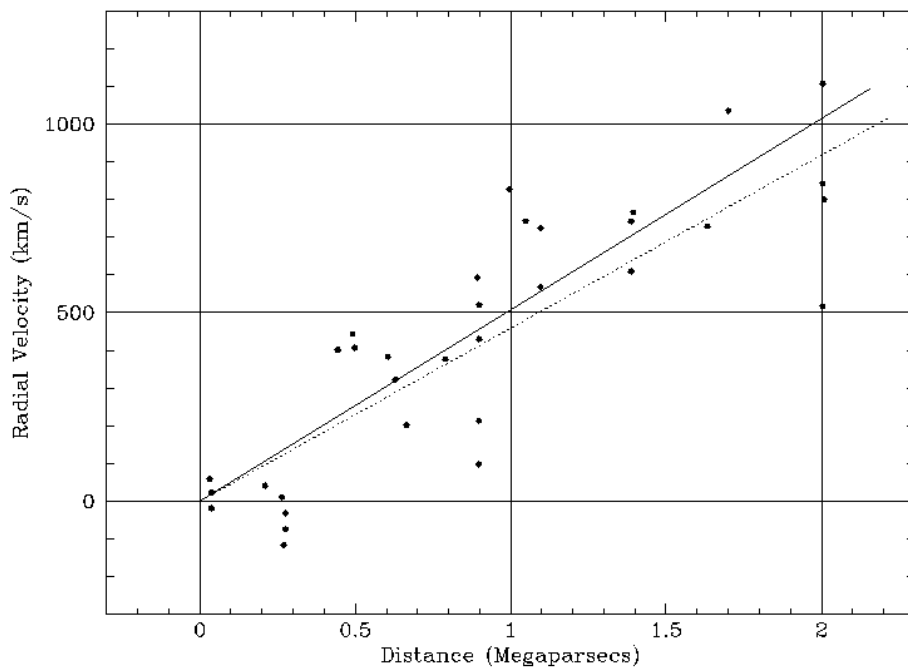


Figure 1. Graph of Hubble’s Galaxies; the dotted line is a fit to all the data, and the solid line is a fit to only the galaxies with positive radial velocities. This type of plot is called a *Hubble diagram*.

Determining the rate of expansion and thus the age of the Universe is one of the primary endeavors of observational cosmologists today, and also the goal of this lab. Using modern instrumentation you will repeat Hubble’s observations. The techniques you will use are employed today for cosmological research at every major observatory. Even though Hubble’s first measurements were made three-quarters of a century ago, we have still

only measured the velocities and distances of a small fraction of the galaxies we can see, and so we have only small amount of data on whether the rate of expansion is the same in all places and in all directions in the universe. The mapping of the Universe that Hubble began continues today at a rapid pace, although in fact future generations may look at our maps today in much the same way as we look at maps of North America from the 16th century.

The Sloan Digital Sky Survey

In this lab, we will be using real astronomical data from the Sloan Digital Sky Survey (SDSS). The SDSS is the most ambitious survey of the night sky to date. The survey covers approximately one quarter of the sky, imaged through 5 different filters, or colors. Not only that, the survey also includes over one million spectra of stars, galaxies and quasars². The first phase of this project was completed in June 2005, and this wealth of astronomical data was released to the astronomical community in June 2006. We will be working with the final Data-Release 5 (or DR5), which contains spectra (and therefore redshifts) of 1,048,960 objects. We will be using these data to measure the spectra and brightnesses of several galaxies in order to plot a Hubble diagram and determine H_0 .

The goal of this lab is to introduce you to the relationship between the redshifts of distant galaxies and the rate of expansion of the universe. You will be introduced to:

- Using an online interface to the Sloan Digital Sky Survey data archive.
- Measuring Doppler shifted spectral lines to determine recessional velocities.
- Determining distances using the brightnesses of galaxies.

Once you have applied these techniques to a sample of galaxies, you will be able to:

- Calculate the Hubble Constant H_0 , a measure of the rate of expansion of the Universe.
- Calculate the expansion age of the Universe.

² Note that you can measure the color of a star or galaxy more easily and quickly than you can measure its spectrum.

Before You Come to Lab

Read the lab completely. Your time in the lab is best used observing the “sky,” not reading these instructions!

We recognize that many of you will be doing this lab before we cover the material in class. It would be an excellent idea to at least skim the material in the textbook (Ch. 20, especially 20.2).

Bring to class these lab instructions, a pencil or erasable pen, a straight edge, and a scientific calculator.

Section 1: Instrumentation and Strategy

The SDSS observations are made using a wide-field telescope equipped with a large camera, consisting of 30 CCD detectors (the same type of electronic detectors used in digital cameras) arranged in a 5x6 array. Each row is for a different color (u, g, r, i, and z corresponding, roughly, with ultra-violet, green, red, and two infra-red wavelengths) and each column images a strip of the sky. Each of the CCD detectors has over 4 million pixels, so you can imagine that the final survey will contain a very large amount of information (about 40 Terabytes). Unlike most telescopes, the SDSS telescope does not attempt to move with the sky: it remains parked and the sky drifts by the CCD detectors. Data is read from successive rows of pixels at a rate that exactly matches the movement of the sky across the CCD, effectively freezing the image although it keeps moving. The end result is a series of *stripes* of the sky, each being subdivided into separate frames of about 2048 x 1489 pixels. Together, the 5 frames consisting of the different colors form a *field*.

Sophisticated software is used to reduce the raw data (remove defects, calibrate against standard stars, etc) and identify the objects in each field. This software is also capable of flagging “interesting” objects, which are later observed using a spectrograph. Therefore, in each field, there are thousands of identified objects (stars, galaxies, quasars), each of which has a computed brightness, in magnitudes (see Appendix A) for each filter. For a subset of these objects, a spectrum has also been taken. Later in the lab is a list of objects to find in the SDSS that have both measured brightnesses and spectra.

Recall that when an object is moving away from you, the photons emitted by that object appear to have longer wavelengths and we therefore say they have been red shifted. Due to the expansion of the universe, all but the closest galaxies are moving away from us and so we expect their light to be shifted to redder wavelengths. Some galaxies are intrinsically redder than others, so it is hard to measure redshift based solely on their colors. Luckily, the spectra of galaxies have *absorption lines*, just like stars, at very specific (and known) wavelengths. They can also have emission lines if they have enough hot interstellar gas. Because the wavelength of an absorption (or emission) line is fixed for any particular atomic species (element), any observed shift in their positions must be due to a redshift.

Each of the objects we study will have a spectrum as well as a measured magnitude in each of the 5 colors. You will use these magnitudes as a way to determine the distance to the object. **We will assume that all galaxies have the same luminosity L.** Therefore, according to the inverse-square law (which you verified in the properties of light lab),

$$B = \frac{L}{4\pi D^2},$$

the observed brightness is only a function of the distance. Using the red-shift tool (see below), you will be able to measure the redshift of the lines in the galaxy's spectrum and hence its recessional velocity. These are the only two variables we need in order to draw a Hubble diagram and find the value of the Hubble parameter, H_0 .



Figure 2: The SDSS telescope and camera.

Section 2: Data Mining

We have set up a special webpage with the links to all the tools you will need in order to complete the lab:

http://astro.swarthmore.edu/astro5/hubble_lab/. The interface to the SDSS archive is called SkyServer. It is composed of several tools that allow you to navigate the data. The three tools we will be using are called the Redshift tool, the Navigate tool, and the Explore tool. There are links to all three on the lab webpage.

Determining the Redshift

When the SDSS telescope takes a spectrum of a galaxy, light of all wavelengths enters the spectrograph. Using either a prism or a grating, the spectrograph spreads the light out into a spectrum. Effectively, the spectrograph is sorting the photons into bins of different wavelengths, and keeping a running count of the number of photons at each wavelength. Every time a photon of a given wavelength is detected, the computer increases the count of such photons by one. This running count is displayed on the screen as a spectrum.

In each field of the SDSS survey (an area on the sky about the size of 25 full moons), the survey scientists take 640 spectra of interesting objects. This is done by placing 640 fiber-optic cables at the locations of the objects in the focal plane of the telescope and then passing the light from the fiber-optics through a prism. This way, astronomers can take 640 spectra simultaneously! We chose one plate and 10 galaxy spectra, which are listed in Table 1. Your job now is to examine the spectra of these galaxies and determine the redshift. While the SDSS software does this automatically for each galaxy, you will measure the redshift yourself and then double-check your results with those of the SDSS automated routine.

Galaxy Number	Right-Ascension	Declination	Plate/MJD	Fiber
447	178.159602	1.065881	284/51943	447
453	178.181587	0.974815	284/51943	453
455	178.152989	0.915193	284/51943	455
522	178.284613	1.122492	284/51943	522
523	178.298482	1.013871	284/51943	523
525	178.250348	1.01977	284/51943	525

526	178.223119	0.894336	284/51943	526
527	178.270391	1.02839	284/51943	527
530	178.260702	1.040549	284/51943	530
580	178.379049	0.972351	284/51943	580

Table 1: The galaxies and their object ID's.

Every galaxy has absorption lines in its spectrum (most of a galaxy's light comes from stars, after all!). Some of them have emission lines as well. There are different types of galaxies, each of which has a somewhat different spectrum. To help us figure out the redshift, we can compare the galaxy's spectrum to several template spectra of typical galaxies. We shift the spectrum of the most-similar-looking template to longer wavelengths until it matches up with the observed galaxy spectrum. We can then read off the redshift. We will do this using the Redshift Tool. Click on the link to the Redshift Tool. You should see something like what is shown in Figure 3.

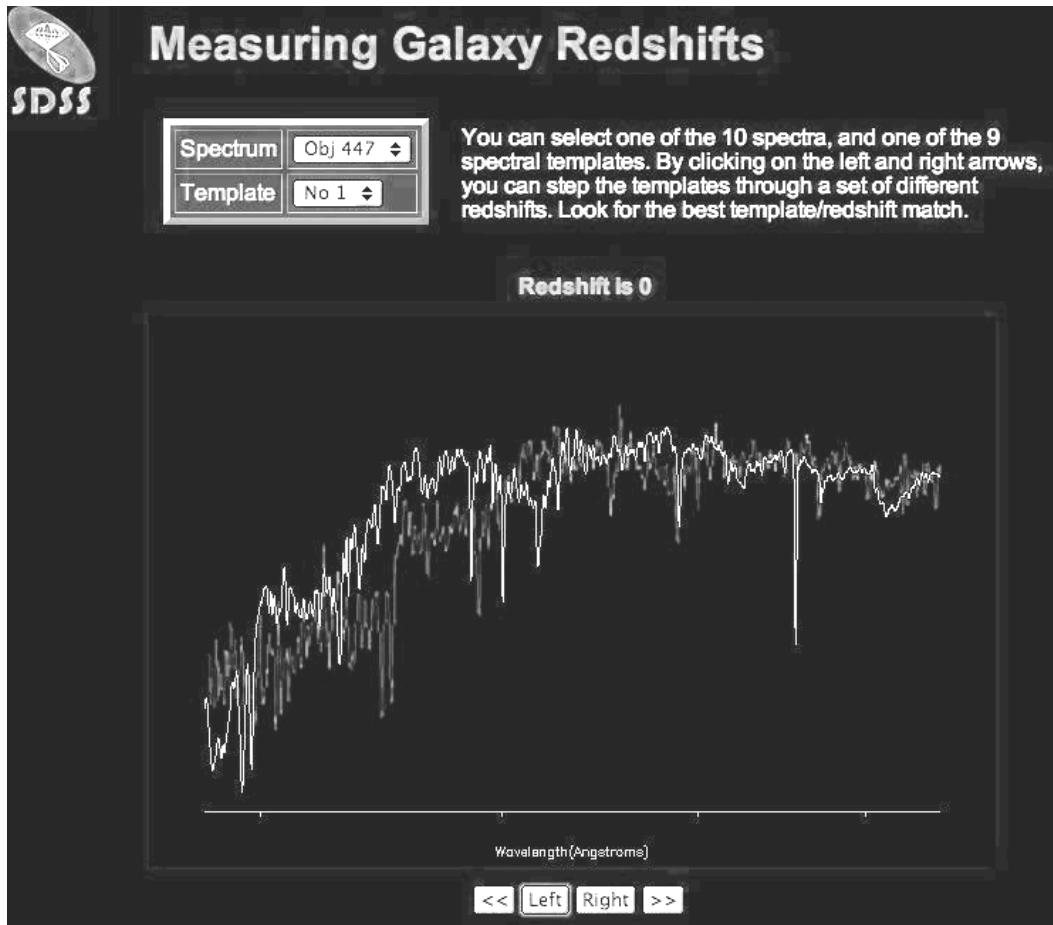


Figure 3: The Redshift Tool

- **Use the spectrum drop-down menu to select each galaxy in Table 1**
- **Use the template drop-down menu to choose the template that best resembles the galaxy in question.**
- **Use the left and right buttons below the spectrum until the galaxy spectrum and the template spectrum match up.**
- **Record the redshift of the galaxy and the template number you used.**

You may come across a spectrum that does not seem to fit any template. In this case, try to find some feature in the spectrum that matches up with some feature in the template. We will be double-checking the redshifts later, so do not worry about getting it wrong the first time. At least one of the spectra has a prominent feature that is not part of the galaxy's intrinsic spectrum, and so doesn't match any feature in the templates. Such features can be caused by cosmic rays (high-energy particles) hitting the detector, or by emission lines from the Earth's night sky.

Finding Magnitudes (brightnesses) and Verifying Redshifts

Begin by following the link to the Navigate tool from the lab webpage. You should see something like the following:

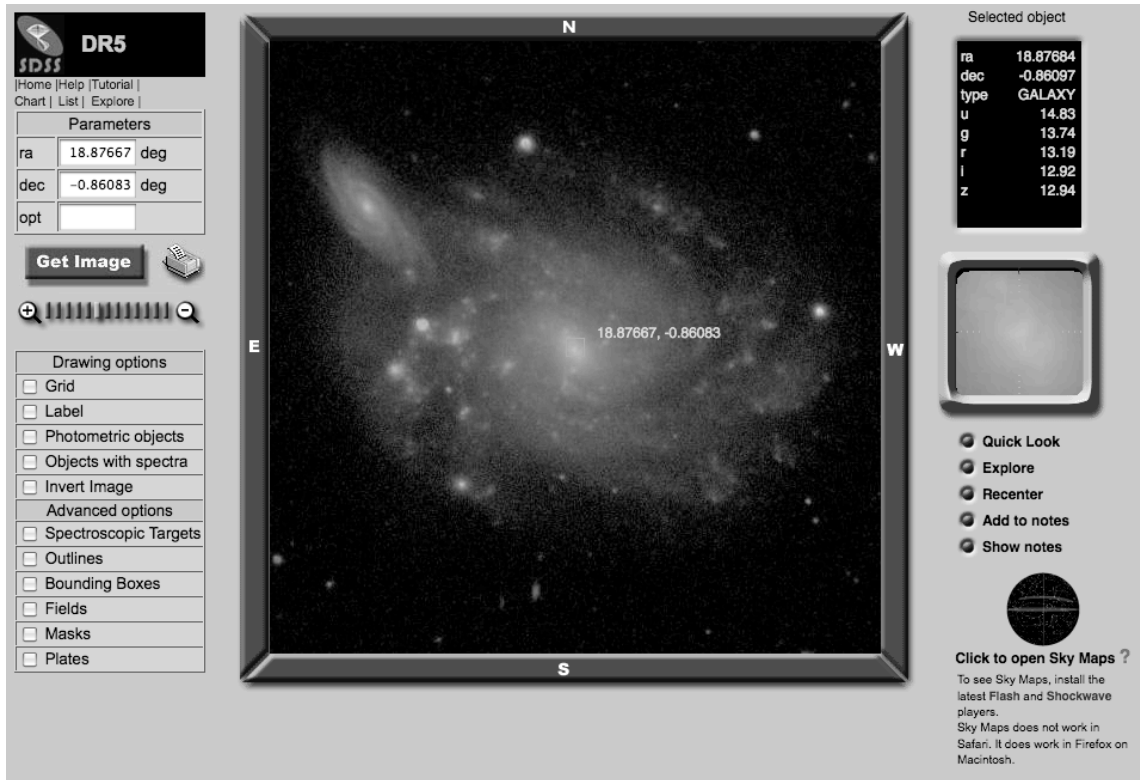


Figure 4: The SDSS Navigate Tool

There are several components to the navigate tool, which we will describe presently. The box to the upper-left shows your current location (ra stands for right ascension, dec for declination). These are analogous to latitude and longitude, but on the sky rather than on the surface of the Earth. Below the “Get Image” button is a map-like control bar that allows you to zoom in and out. Below that, there are a number of visualization options that will be useful later on. The box at the upper-right tells you information about the object you have selected in the main view: the coordinates of the object, what type of object it is (galaxy, star, quasar, etc) and its brightness in the 5 colors. Below that, there is a zoomed-in view of the selected object. Below that, there are a number of links, the most important of which is the Explore link, which we will use in a moment.

Begin by finding the galaxies in Table 1 and measuring their magnitudes. Everyone will do this sample of 10 galaxies. Later, you will go hunting for five or more of your own. The easiest way to find these 10 galaxies is to look up their coordinates in Table 1 and enter them into the upper-left box in the

Navigator, under “ra” and “dec”. Click on the “Get Image” button, and you will have an image of the galaxy.

- **In the ra box, input 178.159602 (the ra of the first galaxy in the table), then input 1.065881 into the dec box.**
- **Click on the “Get Image” button.**
 - **The galaxy should be in the center of the main view, inside a green box. If the green box is not present, simply click on the galaxy. The right-hand panel should now have the following information:**

RA	DEC	Type	U	G	R	I	Z
178.15960	1.06588	GALAXY	19.74	18.04	17.08	16.70	16.37

Record the value of the magnitude in the “r” band only.

Note that the “magnitude” is an arcane method of describing the brightness of an astronomical object. We’ll describe below how to turn these magnitudes into brightnesses with the usual mks units.

Now, click on the “Explore” button below the right-hand information panel. A window will appear that gives all the information (including redshift) related to the object that is currently selected in the main view. (Notice that the magnitudes are also displayed here.) Use this feature and record the SDSS redshift. Make note of any discrepancies. Repeat this procedure for each of the galaxies in Table 1.

When you are done, make sure you have all the pertinent information about each galaxy:

Object: The galaxy’s coordinates (or just galaxy number from Tab. 1)

Apparent magnitude in r filter: the apparent magnitude of the in the r (red) filter. There are magnitudes listed for five different filters/colors, but we’ll just be using one.

Redshift (measured): the redshift you measured using the Redshift Tool.

Redshift (SDSS): the redshift according to the SDSS software. *Don't confuse the z for redshift with the magnitude in the ' z ' filter; the redshift will be between 0 and 7 (and generally much closer to zero); the z magnitude will probably be in the 15–30 range.*

Data Collection

Q1: Make a data table that contains the following for each galaxy:

- The galaxy's "name" (e.g. the object number or coordinates—something to identify it³).
- The galaxy's apparent magnitude in the r (red) filter.
- The measured redshift. Note whether you choose to use the SDSS redshift or your own.

You may want to enter your data in a spreadsheet as you take it, for ease of calculation later. You can print out the spreadsheet to use as your data table as long as you clearly label each column.

You will also be adding a new column (instructions below), with the distance calculated from the r magnitude.

Now add some more (5 or more) galaxies to your sample. Choose any galaxies you like from SDSS. The SDSS navigate tool has a handy option to identify objects in the field which have measured spectra. Click the "Objects with Spectra" box and zoom out until you see several red squares. The objects inside these squares have spectra. Simply click on them to select the object and then click on the "Quick Look" link to see the spectrum and read off the redshift. Try to get a few low redshift (0-0.1) and a few high redshift (0.1 – 0.3) galaxies. To go to a completely different part of the sky, you can input different coordinates in the upper-left box. However, only parts of the sky are available (Figure 5). You can easily go to parts of the sky that do have coverage by using the "SkyMaps" feature in the lower right of the Navigate Tool window. Areas of the sky with coverage have a light blue background. Also, remember the assumption we made: all the galaxies have the same luminosity. Clearly, this is not the case and will contribute errors

³ When you add 5 more galaxies of your own choosing (see below) they will not have galaxy numbers, like the ten galaxies listed in Table 1 do. In your table, we recommend identifying them by listing their RA coordinates.

to our final result. Can you think of a way to lessen the impact of this assumption, perhaps by being more selective in which galaxies you choose?

Q2: Repeat the measurements in the previous question for at least five or more galaxies of your choosing, recording the same data requested in question 1. The more galaxies you add to your sample, the better. *Explain why.*

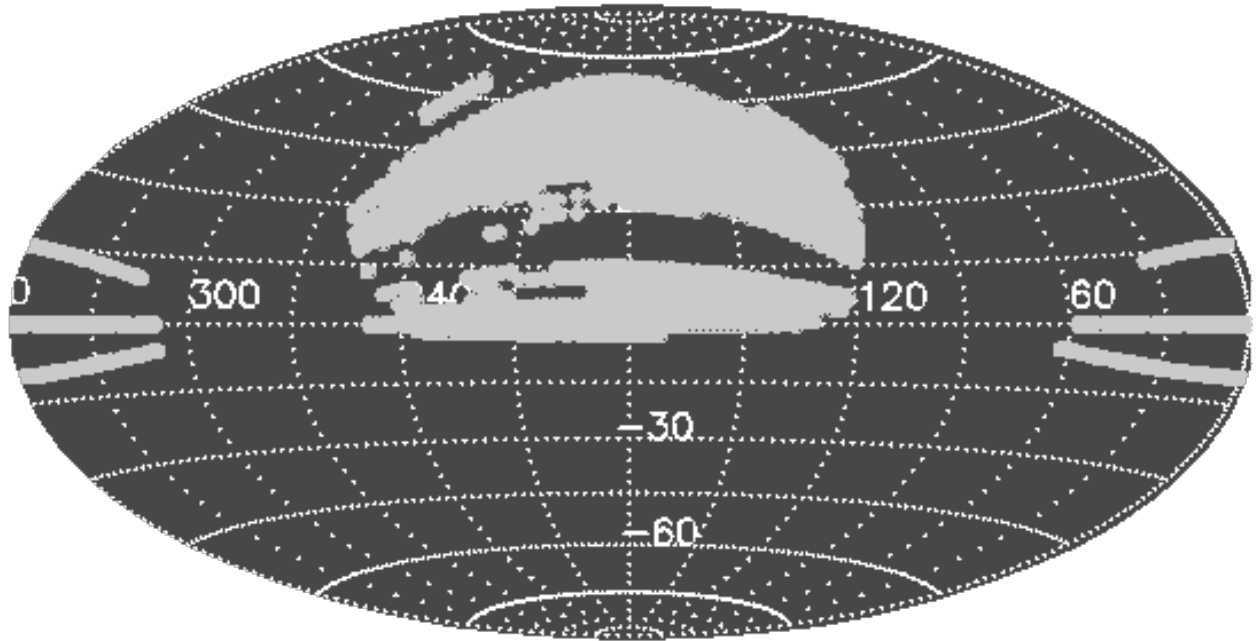


Figure 5: SDSS DR5 spectral sky coverage. The x-axis is RA, and the y-axis is Dec; both are in degrees.

Section 3: Data Analysis

Recession Velocities and Distances

As always, collection of the data is only the first step in astronomical research. After collection, the data must be reduced to useful numbers. These numbers are then analyzed, hopefully (but not always) bearing fruit in the form of a meaningful result.

Your goal is to determine the recession velocities and distances of the galaxies that you have observed. With this information, you can create a Hubble Diagram and calculate the expansion rate and the expansion age of the universe.

The first step is to convert your measured redshifts to recession velocities for each galaxy, using the Doppler formula:

$$z = \frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}$$

where z is the redshift you measured. Your recession velocities should be in km/s. Here, $\Delta\lambda = \lambda_R - \lambda_E$. And the wavelength in the denominator is the emitted wavelength, λ_E . But note that you should already have z recorded.

You might want to review your class notes on the Doppler shift.

Q3: Compute the recession velocity (in km/s) of each galaxy. Record your result in your data table. You can have Kaleidagraph do the calculation for you.

The second step is to obtain a measure of the distance to each galaxy. This is typically done by measuring the brightness of a *standard candle* in a galaxy. If we know the luminosity of the standard candle, then its observed brightness gives us its distance through the inverse square law. In reality, there are few standard candles whose luminosities are securely known. Consequently the distances measured for galaxies are far less accurately known than their recession velocities. This accounts for the very large scatter in Hubble's original figure (Figure 1) and is still the primary uncertainty in Hubble diagrams today.

In this lab you will **assume that all galaxies have the same luminosity**, i.e. that the entire galaxy is a standard candle. Thus the distance to a galaxy can be simply obtained from its observed brightness (or apparent magnitude). The quality of your results will depend on the validity of the assumption that all galaxies are precisely the same. The choice of which color to use is somewhat arbitrary, but since the CCDs are more sensitive in the red part of the spectrum, we will use the r magnitudes.

Q4: Compute the distance to each galaxy, and add these distances to your data table in a new column. The distance calculation is a two step process:

First, convert the r magnitude you've obtained from the SDSS data for each galaxy to a brightness, B , in mks units (Watts per square meter) according to the formula:

$$B = B_0 10^{-r/2.5}$$

Where $B_0 = 1.31 \times 10^{-8} \text{ W/m}^2$. Note that the above equation's order of operations requires you to raise 10 to the power $-r/2.5$ and then multiply that entire quantity by the constant, B_0 .

Second, compute the distance given the brightness, B , you've just measured from the inverse square law for light:

$$B = \frac{L}{4\pi d^2}$$

Where d is the distance (what we're ultimately looking for here), B is the brightness, and L is the intrinsic luminosity of the galaxy. In this lab, we're going to assume that all galaxies have the same luminosity, $L = 10^{37} \text{ W}$ (this is about 2.5×10^{10} times the luminosity of the Sun, and is about equal to the luminosity of the Andromeda Galaxy:

http://en.wikipedia.org/wiki/Andromeda_Galaxy).

Finally, you should record your distance in your table not in meters, but rather in megaparsecs (Mpc). These are the largest unit of distance used by astronomers. One megaparsec is a million parsecs, where a parsec, pc, is equal to 3.26 light years (and is approximately the distance to the nearest star). The overall conversion factor is:

$$1 \text{ megaparsec (Mpc)} = 3.09 \times 10^{22} \text{ meters} = 3.09 \times 10^{19} \text{ km}$$

At this point, your data table should be complete. It should have data for 15 galaxies in it, and for each galaxy there should be:

An identifier (fiber number for the standard 10 galaxies; RA coordinate for the individually selected additional 5 galaxies);

An r magnitude for each galaxy;

A redshift (expressed as a unitless z);

The velocity (in km/s) calculated from the z ;

The distance (in Mpc) calculated from the r magnitude, according the recipe we have just described.

The Hubble Diagram and the Hubble Constant H_0

Q5: Plot a graph of distance (x-axis) and recession velocity (y-axis) for the galaxies you observed. This is known as a Hubble Diagram.

Draw the **straight** line that best fits all of your data points. (You should use Kaleidagraph to find the best-fit line.) Note: the origin (0,0) is a data point through which the line *must* pass. (We can't be receding from ourselves!). You can force Kaleidagraph to make sure there is no y-intercept in the fitting function. Ask your instructor how to do this if you can't figure it out.

Print out this graph – your Hubble diagram – with the best-fit line on it. Note **that the slope of the line is the Hubble constant**.

Draw 2 more straight lines through the data by hand – one **shallower** and one **steeper** – that you consider to be the shallowest and the steepest lines that could reasonably be said to fit the data. (Both of these lines should also go through the origin.) Note: these lines should *not* simply go through the lowest or highest points; they should be lines that plausibly fit a decent fraction of your datapoints.

Q6: All of the data points will not fall on your best-fit line. Why not?

Think carefully about this. For example, you might compare the differences between your red-shift and the SDSS red-shift in your data table (to get a sense of your measurement uncertainty) and compare this with the amount that your data points deviate from your line. Does simple measurement uncertainty account for the deviations you see?

From such a diagram, Edwin Hubble derived the law that now bears his name, the Hubble Law:

$$v_r \text{ (km/sec)} = H_0 * d \text{ (Mpc)} .$$

He also defined one of the most important numbers in modern cosmology, the Hubble Constant H_0 . This number is used to derive the distances to

galaxies and quasars from their recession velocities, and defines the age of the Universe. It has been claimed, only partly facetiously, that the Hubble Space Telescope was built to measure H_0 !

Q7: Record the value for the Hubble Constant from your graph and the fitted line. Note: the units of H_0 are usually given as (km/sec)/Mpc.

Make an estimate of the uncertainty in your value for the Hubble Constant by calculating H_0 for each of the other two lines (by measuring their slopes), and record your value and its uncertainty.

Q8: Compare your measured value of the Hubble constant to the value $H_0 = 72 \pm 5$ km/s/Mpc derived from recently obtained data. Does your result agree with this value? (Remember, “agreement” for our purposes has to take uncertainty into account.)

Section 4: The Expansion Age of the Universe

Consider a trip in a car. If you tell a friend that you are 120 miles away from your starting point and that you have been traveling at 60 miles per hour, then your friend would know that you had been driving for two hours. That is, your trip started two hours ago.

The same logic can be used to find the expansion age of the Universe. We see all of the galaxies moving away from us at a speed proportional to their distance. If they are all moving apart, there must have been a time when they were all close together. Since we know the distances of galaxies and the rate at which they are receding, we can determine how long they have been traveling since that time, i.e. the expansion age of the Universe.

Though we have described the age in terms of distances and speeds of individual galaxies, the expansion age can be obtained directly from H_0 . To show this, we know that distance equals velocity times time:

$$d = vt.$$

Rearranging we have

$$t = \frac{d}{v}$$

Now for the Universe the Hubble Law tells us that

$$1/H_0 = d/v_r$$

So the time when the galaxies “began” traveling, or the expansion age, is simply $1/H_0$.

Q9: Derive an expansion age from your value of H_0 . (This is primarily an exercise in converting units!) Remember that $1 \text{ Mpc} = 3.09 \times 10^{19} \text{ km}$. What is the uncertainty in your derived expansion age? (Use the two extreme lines on your plot.)

Q10: Compare your expansion age (and its uncertainty) from question 9 to both:

- (a) the age of the Sun (about 4.5 billion years); and
- (b) the ages of the oldest known stars in our galaxy (12.5 ± 3 billion years as estimated from radioactive decay of uranium⁴, or 13.5 ± 1.5 billion years as estimated from stellar evolution theory⁵).

Are your results for the age of the universe consistent with those estimated from the ages of the oldest stars? Are they consistent with the age of the Sun? Explain your answer. (For example, how would you *expect* the expansion age to compare to the ages of the oldest stars?)

Q11: What errors and possibly incorrect assumptions might be affecting your result? Human error (i.e. just recording a number incorrectly) is unlikely to be a major contributor—or if it is, you should go back and fix that point! Instead, think in particular about the assumption of a single luminosity for all galaxies, and explain how that assumption could result in *both* systematic and random errors in your final result.

⁴ Cayrel et al. 2001, *Nature*, 409, 691.

⁵ VandenBerg et al. 2002, *Astrophysical Journal*, 571, 487.

To hand in:

- A short introduction/abstract (just one paragraph);
- Answers to all the numbered questions (and any associated sketches and tables);
- A concluding paragraph or two