

## ASTR 121 – Spring 2015

### Lab 6 – Hubble's Law<sup>1</sup>

#### Important dates:

- Prelab due: Monday, 4/24
- Rough draft due: Monday, 5/1
- Final draft due: Friday, 5/5

#### Science Goals:

At the end of this lab, you should be able to...

- Retrieve data from [NED](#) (NASA/IPAC Extragalactic Database)
- Determine the recessional speeds of galaxies from optical spectra
- Determine Hubble's constant

#### MATLAB Goals:

In this lab, you will apply MATLAB knowledge to...

- Open compressed (.gz) files
- Read in data from files in FITS ([Flexible Image Transport System](#)) format
- Fit experimental data with a custom equation

## Background

The late biologist J.B.S. Haldane once wrote: “The universe is not only queerer than we suppose, but queerer than we can suppose.” One of the queerest things about the universe is that virtually all the galaxies in it (with the exception of a few nearby ones) are moving away from 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 (were “redder”) than those observed from stationary objects. Assuming that the redshift was caused by the Doppler shift, Slipher concluded that the redshifted galaxies were all moving away from us.

In the 1920s, Edwin Hubble measured the distances of the galaxies for the first time, and when he plotted these distances against the speeds for each galaxy, he noted something even queerer: The further a galaxy was from the Milky Way, the faster it was moving away. Was there something special about our place in the universe that made us a center of cosmic repulsion?

Astrophysicists readily interpreted Hubble’s relation as evidence of a universal expansion. The distance between all galaxies in the universe was getting bigger with time, like the distance 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 furthest galaxies traveling the fastest.

This was a remarkable discovery. The expansion is believed today to be a result of a “Big Bang” that occurred between 10 and 20 billion years ago, a date that we can calculate by making measurements like those of Hubble. The rate of expansion of the universe tells us how long it has been expanding. We determine the rate by plotting the recessional speeds of galaxies against their distances, and measuring the slope of the graph, a quantity called the Hubble constant,  $H_0$ , which tells us how fast a galaxy at a given distance is receding from us. So Hubble’s discovery of the correlation between speed and distance is fundamental in reckoning the history of the universe.

## Theory

The redshift of a galaxy can be determined by comparing the measured wavelength of a specific emission/absorption line (or set of lines) to the known wavelength of the line(s) when the emitter/absorber is at rest. For this lab, we use absorption of the K and H lines of Ca II (i.e., singly ionized calcium), with rest wavelengths of 3933.7 Å and 3968.5 Å, respectively, as well as emission of the H $\alpha$  line of hydrogen, with rest wavelength 6562.8 Å. The lettering scheme for calcium is left over from the way astronomers initially identified prominent absorption lines in the Sun’s spectrum. See [Fraunhofer lines](#) for more information. The H $\alpha$  line of hydrogen is the  $n = 3$  to  $n = 2$  electron transition in neutral hydrogen. It is the lowest-energy (thus longest-wavelength) line of the [Balmer series](#) of hydrogen.

The recessional speed  $v$  of the galaxy is then given by,

$$v = \frac{c \times (\lambda_o - \lambda_s)}{\lambda_s}$$

where  $\lambda_s$  is the appropriate “stationary” wavelength for the line being considered, listed above,  $\lambda_o$  is the measured wavelength for the line from the galaxy’s spectrum, and  $c$  is the speed of light. For this lab, we will be using spectra from a selection of galaxies given in a widely used paper ([Kennicutt 1992](#)) We will obtain these spectra from [NED](#) (NASA/IPAC Extragalactic Database).

To find the Hubble constant, we also need to determine the distance to the galaxies, independently from the redshift. Typically we use one (or more) of several “standard candle” methods, such as Cepheid variables, Type Ia (white-dwarf) supernovae, the Tully-Fisher relation, etc. A “standard candle” is an object whose intrinsic luminosity (and thus absolute magnitude) is either always the same or directly related to another measurable quantity other than its brightness. By measuring both this proxy for luminosity (absolute magnitude  $M$ ) and the apparent brightness (apparent magnitude  $m$ ) of the target object, we can calculate the distance to it. [NED](#) provides the mean redshift-independent distance modulus as well as the corresponding metric distance in Mpc for each galaxy. This mean is an average of all known (to the database) measurements, made using standard candle methods, of the distance modulus and metric distance for a given galaxy.

Once you have the recessional speed of the galaxies and their distances, you can find the Hubble constant ( $H_0$ ) using Hubble’s Law,

$$v = H_0 \times d$$

which looks like the equation of a line with slope  $H_0$  and intercept zero. You will determine the Hubble constant by fitting a line to your measured speed and distances for a sample of galaxies with known distances determined via other methods. Once the Hubble constant is determined, astronomers can use the relation to find the distance to other galaxies that can’t be measured using a standard candle. Assuming the Hubble constant has been constant throughout the lifetime of the universe (which is not strictly true, but gets you close enough for the purposes of this lab), you can also determine the age of the universe. Hubble’s constant is a speed ( $v$ ) divided by a distance ( $d$ ), which are related by the equation,

$$d = v \times t$$

where  $t$  is time. Thus the age of the universe is approximately  $1/H_0$  (watch the units).

## About the Data

You will be retrieving the spectra for 15 galaxies (specified in the table provided) from [NED](#). You will be downloading them in a FITS ([Flexible Image Transport System](#)) format, which is also compressed using [gzip](#). The gzip compression format is similar to zip, which you may be more familiar with, but gzip is the more commonly used compression application on Linux-based systems. Fortunately MATLAB has a built-in command ('gunzip') to decompress the files, which unpacks the FITS file into your directory. FITS is the standard format for observational data in astronomy and requires a specific reader. The appeal of the FITS format is that information about the observation, such as time, date, location, exposure time, and many more items, can be stored in a header associated with the data itself. Unfortunately, there is no one MATLAB function that can process all of this information: the FITS reader in MATLAB ('fitsread') can read in the data, but does not provide the header information, while the MATLAB command 'fitsinfo' can read the header information, but is not sophisticated enough to handle the wealth of information astronomers often include. Professor Bolatto at U Maryland has written a FITS reader (rfits.m), which we provide, that handles the header information more gracefully. You will see this reader again if you take ASTR310.

The headers for FITS files only contain the information that the creator of the file wishes to put in them. Many observatories follow a common format for the header information that they include in the raw data from their telescopes. They use standard keywords to mark the information. Certain astronomical data analysis software packages have particular keywords that they add to headers as well. The spectra for this lab have been processed and calibrated, and so the keywords contain some information about the calibration, such as the wavelength scale. If you take ASTR310, you will learn more about the processing required to take raw data and prepare them for measurements.

## Part 1: Retrieving the Data

In this part of the lab, you will gather the data from [NED](#) that is needed for part 2. This includes the galaxies' spectra that you will be measuring, the wavelength information for these spectra, and the distances (with uncertainties) to these galaxies.

1. The [NED](#) homepage has many options for searching the vast amount of data stored in the database. You are looking for data, particularly spectra, so select that link.
2. Search for the spectrum of the first galaxy on the provided list of targets. Look for the spectrum from the specific reference, "1992ApJ...79...255."
3. From your search results, download the gzipped FITS file (i.e., .fits.gz extension) of the spectrum for each of the 15 listed galaxies. Record the wavelength information given on the search results page. We are interested

in the starting wavelength, ending wavelength, and the step size, so we can reconstruct the wavelength data for plotting. Note that the step size is NOT the same as the resolution. The resolution is related to the accuracy of the instrument (a spectrograph, in this case), while the step size indicates the size of the camera's pixels for recording the data.

4. Go back to the main NED page. Instead of the spectra search, follow the link to search objects by name. Search for each of the listed galaxies. Scroll down the results page until you find the redshift-independent distances. Record the mean metric distance (in Mpc) and the standard deviation (if given) for each listed galaxy. A few of the objects only have one measurement, and so they lack a value for the standard deviation. The standard deviation provided by NED is the uncertainty in the distance. Estimate an uncertainty for the galaxies that do not have one (*you should explain your reasoning in your report*).

## Part 2: Determining Hubble's Constant from Observations

Now we will look at the spectra, measure the recessional speeds, create a plot of recessional speeds as a function of distance, and use this plot to estimate  $H_0$  and the age of the universe.

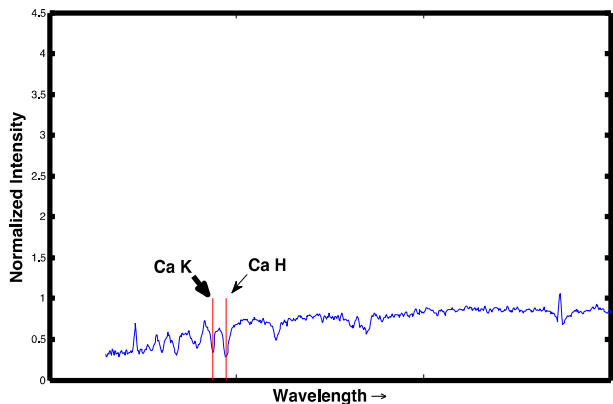
1. Using MATLAB, unzip the .fits.gz files. (Try the 'gunzip' command.)
2. Download 'rfits.m' from ELMS. Use it to read in the unzipped FITS file for the first galaxy in the provided list. *What happens if you do not suppress the output of the command? Where do you suppose the intensities are stored? There are two keywords in the header information that also give you information about the wavelength scale. Using your knowledge of the wavelengths for the observations from Part 1, which keywords are they?*
3. Plot the spectrum, using the intensity data from the FITS file, and a wavelength array that you create from the wavelength information.

4. Measure the wavelength of the K and H Ca II absorption lines in this spectrum, as well as the H $\alpha$  emission line. (Remember 'ginput' from lab 5?) When measuring, you want the center of the line. (*Is this the maximum or the minimum for absorption lines? For emission lines?*) Estimate the uncertainty on your measured wavelength. You may want to plot a vertical line at the rest wavelength of the three lines of interest, to help you locate the redshifted line. The Ca II K and H lines always appear as a pair, and they usually occur next to a drop in the overall intensity (the continuum) near a rest wavelength of 4000 Å. See Figure 1 for an example of the K and H lines. The H $\alpha$  emission line is frequently surrounded by two emission lines from ionized nitrogen, at rest wavelengths 6548 Å and 6583 Å. Sometimes one or both of the nitrogen lines are absent. See Figure 2 for an example including all three lines. There are also two ionized sulfur emission lines that almost always appear at longer rest wavelengths, 6717 Å and 6731 Å. *How might you double check that you are choosing the right three lines?*

Figure 1: Zoomed view of the blue end of a sample spectrum. The intensity scale is the same as in Figure 2

5. Measure the three spectral lines for each of the galaxies in the list

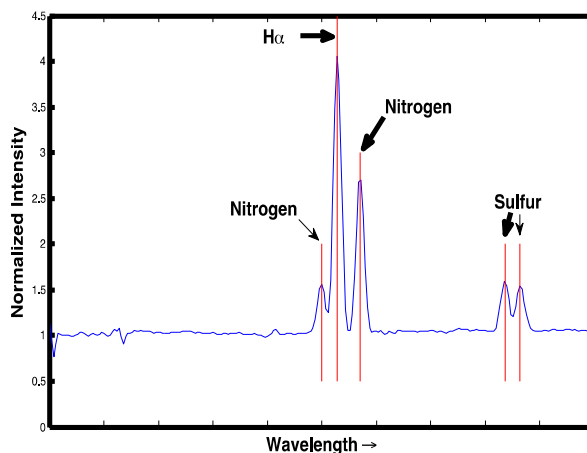
Figure 2: Zoomed view around H $\alpha$ .



provided. Using the appropriate equation given in the Theory section, calculate the recessional speed for each galaxy from each of the three spectral lines. Then find the average recessional speed for each galaxy, and the corresponding uncertainty.

6.

7.



Make a plot of recessional speed vs. distance. Include x and y error bars.

Fit a line to your data, and plot it on the same plot as your data. *Does a non-zero y-intercept make sense, given our model? Why or*

*why not? What value of  $H_0$  does your fit give you? What is the uncertainty in your value of  $H_0$ ?*

8. We'd like to have the linear fit pass through the origin. MATLAB does not have a built-in equation in the Curve Fitting toolbox quite like this - you will have to create it yourself. (Hint: Look at the "Tools" menu in 'cftool'.) Plot this line on your plot with your data and your fit from step 8. *What value of  $H_0$  does this fit give you, and what is the uncertainty?*
9. For the value of  $H_0$  that you calculated with your custom fit, determine the age of the universe, assuming that  $H_0$  has been constant over time, and include the associated uncertainty. *Given the assumption here, is your calculated age an overestimate or underestimate of the age? How does your calculated age compare to the value given in class? Is this consistent with what you expect?*

## Report

Your report should contain the following:

1. *Cover page:* Follow the model and guidelines in the rubric.
2. *Abstract:* In a paragraph or two, summarize the scientific purpose of the lab, what was done, the results, and your conclusions.
3. *Introduction:* In several paragraphs, discuss the background information regarding the purpose of the lab and its goals.
4. *Methodology:* Describe the data you used in this lab, including both the spectra and the distances. Explain where you retrieved the data, and how you arrived at the uncertainties for the distances. Include a table with the galaxy name, distance, and uncertainty in the distance. Describe the measurements you made, including what lines you measured, how you measured them, and how you made sure you were measuring the correct lines.
5. *Analysis:* Explain the calculations of recessional speed, as well as your uncertainties. Include a table with values of the measured wavelengths and recessional speeds for each galaxy for each of the 3 spectral lines, as well as your average speed, and all uncertainties. Additionally, include a figure showing your data and best-fit lines, including error bars on your data. Explain how you got the two values of  $H_0$  from your data. Explain your calculation of the age of the universe and give the result (in reasonable units) with associated uncertainty.
6. *Discussion:* Compare your value of  $H_0$  from the linear fitting with a  $y$ -intercept to the value from the custom fit through the origin. Discuss why the solution

through the origin may be preferable. Compare your values of  $H_0$  to the accepted values from other methods discussed in class and from the astrobite from the pre-lab. The galaxies used in this lab are all relatively nearby. Comment on any unusual data points. Is there some physical reason (i.e., not errors) you may have gotten a value different from the accepted value(s) of  $H_0$  (whether you actually did or not)? Discuss how the age of the universe you calculated compares to the accepted value(s). Make sure to also answer any questions in this handout (in italics).

7. *Appendix:* Include all scripts, functions, and data that aren't already represented in your report.

Remember to upload any MATLAB code as .m files on ELMS, along with a PDF of your lab report. When uploading a .m file that will run on its own, replace any interactive commands (e.g., 'ginput') with variables containing the values that you got from the command. If you have a lot of variables from interactive commands, put their values directly in the script. If you have only a few variables, you might investigate the 'save' and 'load' commands.



1 Introduction taken from Project CLEA's "[The Hubble Redshift Distance Relation](#)."  
Data selection based on the University of Washington's "[Hubble's Law: An Introductory Astronomy Lab](#)."