**Morphological types, spectra of galaxies,
and the Hubble expansion law.**

"The history of astronomy is a history of receding horizons." — Edwin Hubble

1 Introduction

In 1920s the University of Chicago alumnus Edwin Hubble[1] (Ph.D., 1917) solved four fundamental questions in astronomy and cosmology[2]:

- 1922-1926. Hubble proposed a classification system for nebulae, both galactic (which we still call "nebulae") and extragalactic (which we know call "galaxies"). The classification system of galaxies has become known as the Hubble morphological sequence of galaxy types.
- In 1924 Hubble decisively showed that spiral "nebulae" (or galaxies) are huge "island universes" of stars similar to our own Milky Way, with his discovery of Cepheids in nearby galaxies NGC 6822, M33 and M31 (The Andromeda galaxy) which allowed to measure distances to them.
- Having established the fact that galaxies are distant stellar systems like the Milky Way, Hubble used their distribution in various areas on the sky to show that the overall distribution of galaxies in space on large scales is quite homogeneous. This was a crucial fact as it justified the cosmological principle of homogeneity and isotropy used to obtain dynamical models of expanding universe from the Einstein's equations of general relativity.
- In 1929 Hubble with a lot of technical help from his assistant Milton Humason has discovered linear relation between redshift of lines in galaxy spectra and their distance from the Milky Way: *the more distant a galaxy, the greater its redshift.* This discovery lead to the notion of the expanding universe and is the most fundamental discovery and observational fact that we know about our observable Universe.

In this lab we will redo (in a simplified way) the Hubble's analysis that resulted in the first, third, and fourth of these fundamental discoveries using modern tools. The lab has four parts.

[1] You can find detailed information about life and work of Edwin Hubble on this website: `http://www.time.com/time/time100/scientist/profile/hubble.html`

[2] See essay by Hubble's student, Alan Sandage at
`http://antwrp.gsfc.nasa.gov/diamond_jubilee/d_1996/sandage_hubble.html`

In the first part you will explore the morphological types of galaxies and the overall shapes and features of their spectra, including the features in the spectra called "spectral lines." In the second part, you will count galaxies in randomly chosen patches of the sky to see how homogeneous their distribution over the sky really is. In the third part, you will measure the wavelengths of spectral lines in real galaxy spectra. To determine galaxy redshifts you will compare the measured redshifted galaxy lines to the laboratory measurements of the line wavelength on Earth. Finally, using the apparent brightnesses of the brightest cluster galaxies as proxy for their distances you will plot your measured redshifts and distance against one another to produce the Hubble law, which you will use to measure the Hubble constant.

Morphological types of galaxies

Hubble classified galaxies into a sequence, now called *the tuning-fork Hubble diagram* (due to the its ressemblance of a tuning fork viewed horizontally) based on their visual appearance: shape, smoothness, and presence of features such as bars and spiral arms. All this collectively is called "galaxy morphology" and classification scheme is called "morphological classification." Hubble has conjectured that the sequence represented the path of galaxy evolution. Although this was not confirmed by further observations, the classification is still widely used by astronomers.

Hubble's classification contains many sub-classes of galaxies[3], but the two main classes of galaxies are the elliptical and spiral galaxies. Ellipticals tend to be smooth in their light distribution and roundish in their appearance. Spiral galaxies tend to have features such as bars and spiral arms.

To familiarize yourself with main morphological types of galaxies, go to the Galaxy Zoo website at `http://www.galaxyzoo.org/Tutorial.aspx` and review Part 1 of that page.

Lab tasks.

- *What are the typical colors of elliptical and spiral galaxies? Discuss why these classes of galaxies tend to have the colors they have from what you know about colors of stars.*
- *Sketch six examples of the ellipticals and six examples of spiral galaxies in your lab report indicating their type (spiral or ellipticals) and providing your best guess for their sub-type according to the Hubble's classification (e.g., E3, Sc, SBb, etc.). It may be useful to review this portion of the Galaxy Zoo's website:*
  `http://beta.galaxyzoo.org/howtotakepart.aspx` *(see also the corresponding chapter of your textbook).*

[3]See the diagram at
`http://cas.sdss.org/dr3/en/proj/advanced/galaxies/tuningfork.asp`

If you are curious and have time, explore the Galaxy Zoo website and help scientists in their exploration of galaxies by performing some simple classifications in their Galaxy Analysis section.

Homogeneity of galaxy distribution on the sky

Start Google Earth and click on the "Saturn" icon on the top bar which switches to the Sky portion of Google Earth[4] on the lab computer (or on your laptop after you install Google Sky and download the SDSS Galaxy Query kml plugin from the directory showed to you by TA and activate the `SDSS Galaxy Photometric Layer` by clicking on it, make sure the `SDSS Galaxy Spectroscopic Layer` is turned off (by unchecking it). Load the kml file `Hubble_lab_random_SDSS_fields.kml`.

Find the corresponding folder in the `Places` window on the left hand side of the Sky window and click on + to see the folder contends (`field 1, field 2, ..., field 10`). These are ten random locations in the area of sky covered by the Sloan Digital Sky Survey away from the plane of the Milky Way and in the areas devoid of very big bright galaxies and stars (which can block a significant part of the field of view).

Click on the `field 1` field and the Sky will take you to the first field down to the zoom level at which the field has some approximately 5 minutes of arc size (verify that the label in the lower right hand corner of the Sky window shows number close to $0°05'$). Please do not zoom in or zoom out after that. If you do or if you decided to choose your own random field (feel free to do so), please zoom again to the point when the label is as close to $0°05'$ as possible. This is because we want to compare counts of galaxies within the same area of the sky in different places, which requires that the size of the patch we use is the same (5 arcminutes in our case). Also do not resize the Google Earth window as you count galaxies in different fields, your counts may be affected if you resize the window.

Once the Sky finishes its zoom, wait until the SDSS Galaxy Query layer identifies galaxies brighter than apparent magnitude in r band of $m_r = 21$ in the SDSS catalog. Once the layer queries the SDSS database over the internet, the galaxies in the field will be marked by circles. Count the number of marked galaxies in the field and then click on `field 2` and repeat the exercise.

For this part of the lab we need to discuss a little bit of statistics. As you know, statistics is a big part of analysis of data in various fields: physics, biology, economics, etc. The statistics of counts of relatively small random samples of objects is typically governed by what is called the Poisson distribution. For example, if galaxies were distributed completely uniformly on

[4]Google Sky is an extension of Google Earth software into the sky (the simple version of which, Google Maps, you probably have used to get directions, view a map, etc.). See the description of Google Sky that will be distributed to you, as well as video introduction to Google Sky at `earth.google.com/sky/skyedu.html`

the sky, we would expect that the probability to find a given number of galaxies in a field of a given size is given by the Poisson distribution. The key feature of this distribution is that if the average number of galaxies per field of a given area is $\bar{N}$, the typical variation from field to field should be $\sqrt{\bar{N}}$.

Lab tasks.

- *Count the number of galaxies brighter than* $m_r = 21$ *(the galaxies marked by circles) and record the number for each field.*
- *Calculate the average number of galaxies per field using counts from all ten fields. You can choose more fields of your own within the areas covered by the SDSS survey, just make sure that they are all 5 arcminutes on a side.*
- *Compare counts in each field to the average and expected variation from field to field. Does it look like the distribution of galaxy counts in these fields is close to the Poisson distribution (i.e. distribution of galaxies on the sky is uniform)?*

Galaxy Spectra

In Google Sky activate `SDSS Galaxy Spectroscopic Layer`, make sure the `SDSS Galaxy Photometric Layer` is turned off. On the lowest zoom, find the strips of sky that were observed by the SDSS. Now zoom in and look for some cool nearby (i.e., bright) galaxies that have spectra available (circled in brown). Remember, circles are only placed around the brightest galaxies in your field of view, so if you'd like to check whether SDSS has a dim galaxy's spectrum, just zoom in on that galaxy until it is alone or is one of the brightest galaxies. Find a few disk/spiral galaxies, and a few elliptical galaxies. You can mark galaxies and go back to them later with the `placemark tool` (thumbtack in the top toolbar). To view their spectra click on the desired circled galaxies, and follow the link at the bottom of the popup bubble.

Lab tasks.

- *Review the spectra of six elliptical and six spiral galaxies, observe general pattern and similarities in spectra of galaxies of either class.*
- *What is the relationship between the morphological class of a galaxy and its spectrum? Sketch a typical spectrum characteristic for elliptical and spiral galaxies.*
- *Discuss the main differences in the spectra of elliptical and spiral galaxies and give your explanation for the origin of these differences.*

Measuring Redshifts

The gas and stars in all galaxies are made of basically the same stuff – the same elements and molecules – they are just often at different density and temperature, with different abundances from galaxy to galaxy. For example, oxygen we breathe here on Earth is still oxygen in a distant galaxy, so we can use its properties measured in a lab on Earth to figure out in what state it is in an observed galaxy. Since each chemical element has a specific atomic structure, it has a fingerprint of light emission or absorption that it plants in the spectra of galaxies in the form of emission or absorption spectral lines. The lines of some chemical species or ions are particularly prominent.

Now that you know what galaxy spectra look like, we will use them to measure shifts of spectral lines with respect to their laboratory wavelengths. Because these shifts in most galaxies tend to be towards longer wavelengths corresponding to redder color, they are called redshifts. You can find laboratory values for spectral features of elements in the table below (the wavelengths are given in units of Ångströms: 1Å=10^{-8} cm, named after the Swedish physicist Anders Ångström, one of the founders of the field of atomic spectroscopy)

Element-Transition	Laboratory wavelength (Å)
Hydrogen:	
Hα	6563
Hβ	4861
Hγ	4341
Hδ	4102
Heavy elements (metals):	
Mg	5150
Na	5892

Different lines in the spectrum of a given element are indicated in greek, and roman numerals mark different ionization states, which have their own distinct spectral fingerprint.

You will measure the redshifts of a set of some of the brightest galaxies in the universe, which are found in clusters. Load file `Hubble_lab_BCGs.kml` into Google Sky and click on + in front of the folder with the same name in the left window to see the list of the brightest cluster galaxies from the list in the Table given at the end of this document. Click on the first object in the list and Sky will take you to the field showing this object. Activate the SDSS Galaxy Spectroscopy Layer (and switch off the SDSS Galaxy Photometric Layer), the brightest galaxy should be marked by a circle after the Sky queries the SDSS spectroscopic database. Click on the brightest galaxy in the cluster marked by circle and follow the link to its spectrum in a bubble that pops up. Determine the redshift of each galaxy by comparing the measured wavelength of spectral features (absorption or emission lines) with the wavelength given in the table above as follows

$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm lab}} - 1$$

Where $\lambda_{\rm obs}$ is the measured wavelength of the spectral feature and $\lambda_{\rm lab}$ is the wavelength from the "lab" measurement from the table.

Lab tasks.

- *For each galaxy use two strong absorption lines of magnesium and sodium, labeled Mg and Na. Estimate the wavelength of the lines following the corresponding vertical dotted line to the horizonthal x-axis and reading off the wavelength number as accurately as you can. Please, indicate the lines you used and provide the actual calculations of redshifts using these lines in your lab report.*
- *Each line gives an independent estimate of redshift. Make sure that they are consistent (close to each other; for example 0.171 and 0.175 are close but 0.05 and 0.20 are not) and then calculate the average number using the two measurements and record this number to the table below. The difference between redshifts from individual lines and the average gives you a rough measure of the error of your redshift estimate, which results from the visual estimate of the observed wavelength $\lambda_{\rm obs}$ from the spectrum. Indicate this error along with the average number.*
- *Click on the galaxy, and a popup bubble should appear containing measurements of light from the galaxy. Record the galaxies apparent brightness in the r band (e.g., $r = 13.6062$) to the table below. The r band is a range of wavelengths in the red part of the spectrum. r band brightness is measured by using a special filter that filters out light from other wavelengths.*
- *Describe the visual appearance of the brightest cluster galaxies and their spectra and interpret their color and spectra in terms of their stellar populations. Do the brightest galaxies vary much in color or shape?*

2 Making a Hubble Diagram

The Hubble's law of expansion relates redshift $z = \Delta\lambda/\lambda$ to the distance between a galaxy and us via a linear relation. The relation is commonly expressed in terms of the indicative velocity of recession by analogy with the Doppler wavelength shift we encounter every day in a sound of an ambulance or a passing train,

$$V = cz = c\Delta\lambda/\lambda, \tag{1}$$

where $c = 3 \times 10^5$ km/s is the speed of light. The redshifts measured for distant galaxies, however, do not actually reflect their physical motion in space but rather expansion of the space itself, in which galaxies are markers of the expanding 'net'. Nevertheless, the language of velocities is usually adopted for historical reasons and convenience. In these terms, the recession law is

$$V = H_0 d, \tag{2}$$

where d is the distance to the galaxy and H_0 is the constant of proportionality called the Hubble constant. Since V is commonly measured in kilometers per second, (km/s) and d is commonly measured in megaparsecs, (Mpc), the units of H_0 must be km/s/Mpc (note that this is equivalent to units of inverse time). If we know the value of H_0 and we have measured the value of V from the shift of spectral lines, we can use the above formula to compute the distance. Thus, our perceived scale of the universe depends on the value of H_0.

Conversely, if we assume that expansion of space have been the same in the past (i.e., the same V), we can calculate the time it took since the moment when distances between Milky Way and a galaxy was zero (the moment of the Big Bang) to the present time when the distance is some value d: $t = d/V$. Given the Hubble law $V = H_0 d$, we can rewrite this as $t = d/V = 1/H_0$, which means that the inverse of the Hubble constant gives us an estimate of the time elapsed since the Big Bang or the age of the Universe. This is a rough estimate because modern observations show that V and the Hubble constant are not constant in time. This estimate however is within a factor of two of the exact age.

In this part of the lab we will work with data that will allow us to verify the linear relation between redshift and distance, and to determine the value of H_0. We need some way to measure distances independently of the redshift. We will use the inverse-square law, where the measured brightness of the whole galaxy can be related to its distance:

$$f = \frac{L}{4\pi d^2}, \tag{3}$$

where L is the luminosity and is measured in erg/s, d is the distance measured in cm, and f is apparent brightness, or flux, f, measured in erg/s/cm^2.

Different galaxies naturally have different intrinsic brightnesses (called luminosities in the following). However, Hubble and others showed that a recognizable class of galaxy, namely the brightest elliptical galaxies (typically residing in the centers of groups and clusters of galaxies), has a small range of luminosity. Such 'first-ranked' galaxies then serve as good "standard candles" (objects with known intrinsic brightness).

It is often useful to express a physical relation directly in terms of "observables" — quantities we can actually measure in observations. Equation 2, called the Hubble law of recession, contains the apparent recessional velocity V, which is not directly observable, and the distance d, which is also not directly observable. However, Equations 1 and 3 show how to relate these quantities to the redshift z and to the flux f which are directly observable. Write down the equation that is equivalent to Equation 2 that is expressed as far as possible in terms of "observables." Your formula should contain both L and H_0. This tells you that an uncertainty in the value of H_0 (the scale of the universe) is equivalent to an uncertainty in the characteristic luminosities of galaxies and vice versa.

There is one more formula that is needed. Astronomers like to express measurements of the flux in terms of magnitudes (see Chapter 1 in the “Universe” textbook). The relation between the magnitude m and the flux expressed in cgs units is

$$m = -48.60 - 2.5 \log_{10}(f) \tag{4}$$

The numerical factor 48.60 is an arbitrary zero point to the magnitude scale set by historical precedent. It makes the star Vega (α Lyr) have a magnitude of 0.0 at a wavelength of 5500 Å. Vega is also used as the zero point for the B, V, R, I filter system magnitudes. For our purposes, the constant factor is not important.

In the last section you compiled a table of redshifts z and apparent magnitudes for brightest cluster galaxies. We will use the symbol m_r for r-band magnitudes to avoid confusion. It is useful to extend the Hubble diagram to very low redshift to increase the lever arm over which we measure H_0. However, measuring very small redshifts using visual estimates of wavelength used for the BCGs is tough due to the errors of redshift estimates. Therefore, we will rely, as is often done in science, on previous accurate measurement done by other people for the brighest cluster galaxy NGC 4472 in the nearby Virgo cluster: $m_r = 9.97$ and $z = 0.004$.

To determine the value of the Hubble constant, H_0, we require that one of the galaxies has a distance that is measured in some fashion that is independent of the measurement of its redshift (otherwise the argument would be circular). Such distance measurement is done using distance estimators from the previous rung of the “distance ladder” (e.g., Cepheid stars). This is an arduous task, and its description will not be attempted here. The most recent measurements of the distance to NGC 4472 (the point that should be in the lower left-hand comer of your plot) is 18.2 Mpc. Given the distance to NGC 4472 and its $r-$band magnitude ($m_r = 9.97$), you can calculate distances to any other BCG galaxy as (make sure you understand where this relation comes from; you can derive it from equations given above):

$$d_{\rm BCG} = 18.2 \times 10^{0.2(m_r - 9.97)}\ \text{Mpc}. \tag{5}$$

Using distance measured in such way and the redshift you measured for a galaxy, you can can estimate value of H_0 for each of the BCGs.

Lab tasks.

1. *Make a plot of the data in the accompanying table, plus NGC 4472, that has $\log_{10} z$ on the x-axis and m_r on the y-axis (note that numerically larger values of m_r correspond to fainter fluxes, i.e. greater distances). This plot is called the Hubble diagram. From the definition of magnitude in Equation 4, a difference in flux f of a factor of 100 is*

equivalent to the difference of 5 magnitudes, which is what is expected for a difference in distance of a factor of 10 by the inverse-square law. Since we are claiming that distance is proportional to redshift, 5 magnitudes should also correspond to a factor of 10 in redshift. Draw two straight lines through the data points which you think best fit the data by eye, one including *and one* excluding *NGC 4472. What is the slope =* $\Delta y/\Delta x$ *that you expect if the universe is expanding uniformly? Is that what you have measured?*

2. *Estimate* H_0 *for a dozen BCG galaxies using redshifts you measured and distances calculated using equation (5). Average the values to get an average estimate of* H_0*. What is the derived value for the Hubble constant* H_0*? What is the limit for the age of the universe that this value implies?*

3. *Hand in your plot with the value of the Hubble constant clearly indicated. Include a written discussion of the following questions: Why don't the points fall on precisely a straight line (give at least two possible reasons)? Estimate the rough estimate of time elapsed since the Big Bang using the value of the Hubble constant you measured* ($t = 1/H_0$)*.*

Name	R.A.	dec	z	m_r
RXCJ0747.0+4131	116.7537	41.5314		
RXCJ0810.3+4216	122.5942	42.2669		
RXCJ0809.6+3455	122.4177	34.9262		
RXCJ0800.9+3602	120.2445	36.0469		
RXCJ0736.4+3925	114.1540	39.4229		
RXCJ0822.1+4705	125.5417	47.0995		
RXCJ0825.4+4707	126.3652	47.1196		
RXCJ0828.1+4445	127.0278	44.7634		
RXCJ0842.9+3621	130.7401	36.3625		
RXCJ0913.7+4056	138.4411	40.9339		
RXCJ0913.7+4742	138.4446	47.7021		
RXCJ0917.8+5143	139.4637	51.7223		
RXCJ0943.0+4700	145.7600	47.0038		
RXCJ0952.8+5153	148.2009	51.8888		
RXCJ0953.6+0142	148.4231	1.7118		
RXCJ1000.5+4409	150.1260	44.1550		
RXCJ1053.7+5452	163.4349	54.8726		
RXCJ1058.4+5647	164.6097	56.7922		