

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 Hubble¹ (Ph.D., 1917) solved four fundamental questions in astronomy and cosmology²:

- 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 the labs 1 and 2 we will redo (in a simplified way) the Hubble’s analysis that resulted in the first and fourth of these fundamental discoveries using modern tools. We will do the

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

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

third part next week after we talk about homogeneity of the universe on large scales and the cosmological principle (lab 5). This manual covers labs 1 and 2. In the first lab 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.” You will compare the spectra of galaxies of different types and spectra of special class of extragalactic astronomical objects called *quasars*. In the second lab, 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.

Lab 1. Morphological types of galaxies

Hubble classified galaxies into a sequence, now called *the tuning-fork Hubble diagram* (due to the its resemblance 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 galaxies³, 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://zoo1.galaxyzoo.org/Tutorial.aspx> and review Part 1 of that page. You can also use “User’s guide to the galaxies” under “Education Center” folder in the Layers portion of the left side Google Sky menu.

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*

³See the diagram at <http://cas.sdss.org/dr3/en/proj/advanced/galaxies/tuningfork.asp>

useful to review this portion of the Galaxy Zoo's website:

http://galaxyzoo.org/how_to_take_part (*see also the corresponding chapter of your textbook*).

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.

Start Google Earth and click on the “Saturn” icon on the top bar which switches to the Sky portion of Google Earth⁴ on the lab computer (or on your laptop after you install Google Sky and download the SDSS Galaxy Query kml plugin from the following site: <http://astro.uchicago.edu/~sleitner/outreach/>

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 (You will see Image (c) 2007 SDSS at the bottom of the main view window). Now zoom in and look for some cool nearby (i.e., bright) galaxies that have spectra available (circled). 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.*

⁴Google 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

Spectra of quasars

Download SDSS QSO/Star Query script from the same site and load it into the Google Sky. Uncheck SDSS Stellar Spectroscopic Layer and the Galaxy Spectroscopic Layer you used in the previous section, so that only SDSS QSO Spectroscopic Layer is left checked. This layer will put a circle around each quasar in the SDSS field that you choose to view.

Lab tasks.

- *Zoom-in onto a few of these circles. What do you see? Do these quasars look anything like the galaxies you've examined in the previous section? What do they look like?*
- *Click on some of the objects you have zoomed into and examine their spectra. Sketch approximately what these spectra look like. What are the main differences from the spectra of elliptical and spiral galaxies you saw in the previous section?*
- *Briefly explain the differences between spectra of quasars and galaxies based on what you know about emission mechanism of quasars.*

Lab 2. 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: $1\text{Å}=10^{-8}$ cm, named after the Swedish physicist Anders Ångström, one of the founders of the field of atomic spectroscopy)

Element-Transition	Laboratory wavelength (Å)
Hydrogen:	
Ly α	1216
H α	6563
H β	4861
H γ	4341
H δ	4102
Heavy elements (metals):	
Mg	5150
MgII	2800
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

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

Where λ_{obs} is the measured wavelength of the spectral feature and λ_{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 horizontal 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 λ_{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 Quasar redshifts

Load the SDSS QSO Spectroscopic Layer used in the previous lab and uncheck other layers you have used. When you view an SDSS field the layer should mark quasars in the SDSS field by circles.

Lab tasks.

- Take a look at the spectra of some of these quasars. Try to find spectra in which can see prominent lines from those listed in the table above ($\text{Ly}\alpha$, MgII , $\text{H}\beta$) and use the lines to calculate the redshifts (show your work indicating which line you used and how you calculate the redshift).
- How the redshifts you get for quasars compare to those of galaxies you measured in the previous section? Explain briefly why there is a difference.

3 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,

$$V = cz = c\Delta\lambda/\lambda, \quad (1)$$

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

$$V = H_0 d, \quad (2)$$

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:

$$f = \frac{L}{4\pi d^2}, \quad (3)$$

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/cm².

Different galaxies naturally have different intrinsic brightnesses (called luminosities in the following). However, Hubble and others showed that galaxy of a certain type, namely the brightest elliptical galaxies (typically residing in the centers of groups and clusters of galaxies), have luminosities within a rather small range. Such bright galaxies can then serve as good "standard candles" (objects with known intrinsic brightness). Their usefulness stems from the fact that if we know the distance one "standard candle" and we know the relative apparent brightness of another standard candle galaxy we have observed, then we can work out the distant to this galaxy easily.

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

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

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 brightest 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 we will not attempt it but will use a previously measured value, as is often done in astronomy. The most recent measurements of the distance to NGC 4472 (the point that should be in the lower left-hand corner of your plot) is 18.2 Mpc. Given the distance to NGC 4472 and its r -band magnitude ($m_r = 9.97$), and assuming that intrinsic luminosity of the BCGs is constant, 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):

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

Using distance measured in such way and the redshift you measured for a galaxy, you 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 (i.e. H_0 is a constant)? Is that what you have measured?

2. Estimate H_0 for a dozen BCG galaxies using redshifts you measured and distances calculated using equation (6). 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		

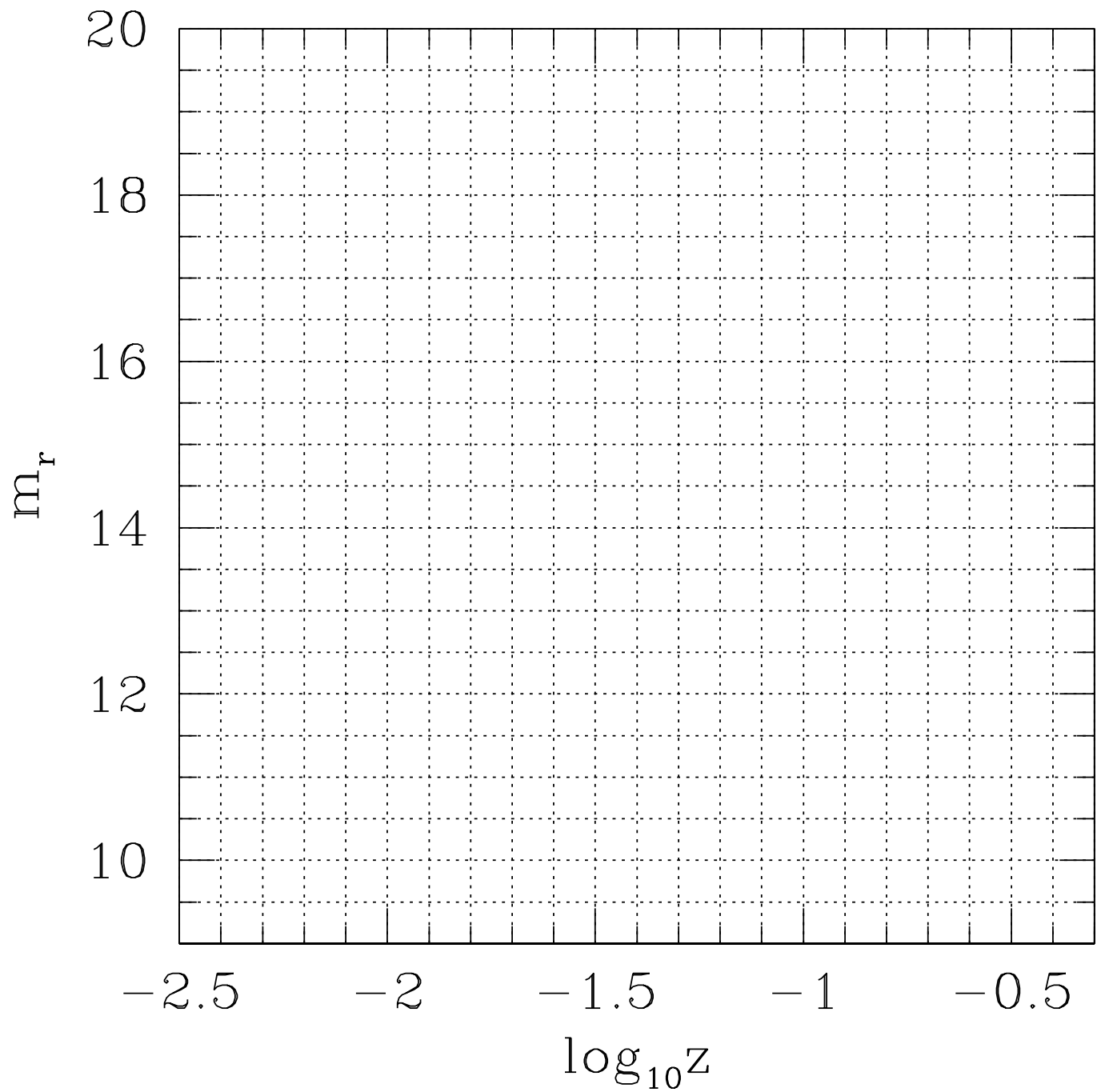


Figure 1: The graph axis for the Hubble diagram.