Lab #18: Hubble's Law

The single most important discovery about the structure of the Universe, made in the early 1920s, was that the Universe is expanding. This fact implies the Big Bang, some 14 billion years ago. Edwin Hubble, an American astronomer working at Mt. Wilson observatory in California in the 1920's, established that the recession velocity of galaxies (that is, the speed of expansion) is proportional to their distance. This relationship is now called Hubble's Law, and the constant of proportionality is called Hubble's constant. The reciprocal of Hubble's constant is nothing else but the age of the Universe (since the Big Bang).

Far-away galaxies move away from us with high speed then. This motion can be detected with spectroscopy: the lines in the spectra of galaxies are shifted towards the red (the Doppler effect). The amount of redshift will tell us how fast each galaxy is receding. Hubble's law relates this to the distance to the galaxy. It is quite difficult to precisely measure the distance to a galaxy, and here is the hard part of setting up Hubble's Law.

In this laboratory exercise we will see the simplest, although not very accurate proof of Hubble's law. Essentially, we will repeat Edwin Hubble's original discovery, but we will use much more spectacular pictures (taken by the Hubble Space Telescope) and much more precise and detailed spectra (taken by the Sloan Digital Sky Survey, SDSS for short, in New Mexico).

The essence of our work (in Part 1) will be to establish Hubble's Law, the relationship between redshift *z* and the distance *d* of a few galaxies,

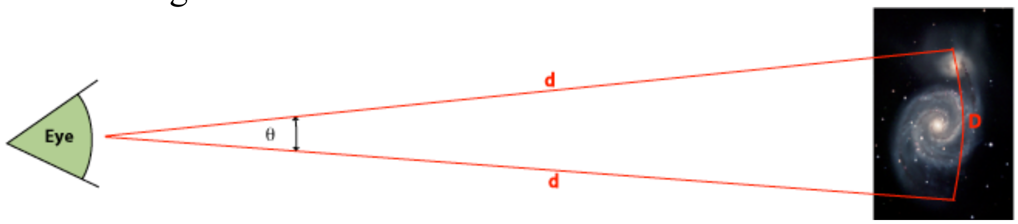
$$v = H \times d$$

where H is the Hubble constant. We'll take the redshift from the spectra. Astronomers use the relative change in the wavelength of a spectral line to describe the amount of redshift, $z = \Delta\lambda / \lambda$, which then equals the speed of recession relative to the speed of light. For not too large speeds this will mean $z = v / c$. It will be easy to read off Δλ and λ from SSDS spectra with decent precision.

The hard part is to tell the distance to our galaxies. We will follow a quite visual, but not very precise method to tell how far a galaxy is: a far-away galaxy looks smaller than a close-by one. Of course, we need to assume that all these galaxies are the same size as our Galaxy (about 100,000 light years across.) This is not quite right; and this will be the main source of error in our results. It is remarkable though, that even with such a crude assumption, we still get a reasonable approximation to Hubble's Law.

We have a few pictures of galaxies taken by the HST. For your convenience, there is a scale indicted on each; the scale is in arc seconds (*as*), the unit of apparent size of an object in the sky. You'll take a 100,000 light year (=30,000 pc) sized galaxy and measure its apparent diameter in arc seconds.

The apparent size will be related to its true size though the simple relation $D = d \times \theta$, where D is the diameter of the galaxy, d is the distance to it, and t is its apparent size. This is nothing more sinister than the length of the arc of a circle that you might remember from 7th grade, indicated in this picture, with the angle θ in radians:



When you convert from radians to arc seconds, you find $D = d \times \theta[as]/200{,}000$ simply because a radian is about 200,000 arc seconds. We are assuming that our galaxies are D=30,000 pc across, so our formula for finding the distance to a galaxy $d = {}^{6{,}000\,Mpc}\!/_{\theta[as]}$ comes out in *megaparsecs* (1Mpc=1 million parsecs). You will estimate how large the galaxy looks on the pictures in arc seconds and calculate how far it is using this relation.

PROCEDURE AND LAB REPORT

Date:_______ Your name: ___________Partner's name: ___________ Section: ___/___

Maximum two students may work together as partners!

For this lab you'll need a packet of laminated images as well as a copy of the graph paper entitled "HUBBLE'S LAW". These are available in the lab. A copy of the laminated sheets is also posted on the web.

The posting indicates, on each picture, how large an average 30-pc galaxy would look like. This is a bit of cheating, of course, but it makes the graph much more precise. Find the links under < https://www.phy.olemiss.edu/Astro/Lab/LabResources/LabResources.htm>.

To make sure you understand, and you know what you are doing, answer the following questions.

1. ***In the expression for redshift, what do $\Delta\lambda$ and λ mean?***
   $\Delta\lambda$:______________________; λ:______________________________
2. $d = {6{,}000\,Mpc}/{\theta[as]}$ ***means that the farther a galaxy is the _____ it looks.***
3. $z = {v}/{c}$ ***means that the more redshifted a galaxy is the _________________.***
4. ***How many light years is a Mpc? _________________________***

Determine the apparent size, then the distance of each galaxy in the pictures.

(Here, NGC stands for "New General Catalog", "Arp" is a catalog compiled by Halton Arp, and "COSMOS" is a collaboration based on the Hubble Space Telescope.)

Look at each picture except 3C273 and read out how large, compared to the indicated scale, each galaxy is. Enter the answers in the table, then calculate the distance to these galaxies.

Note these peculiarities: #1. COSMOS3127341 and Arp148 look small, so they are far away. The full extent of these galaxies is larger than they look at first sight. #2. NGC 4911 has a large, faint halo, which extends to farther than the size of a normal galaxy: do not include all of this halo into the diameter of the galaxy. #3. NGC 5584 looks as if it did not completely fit in the picture; estimate its diameter a little larger than it looks in the picture.

Galaxy	Apparent size [as]	Distance [Mpc]	Hβ line [nm]			Hα line [nm]			z	v km/s
			λ galaxy	Δλ	z	λ galaxy	Δλ	z		
NGC 3434										
NGC 4911										
NGC 5584										
COSMOS 3127341										
Arp 148										

Determine the redshift, then the recession speed of each galaxy in the pictures.

Examine the SDSS spectra in the posters. The poster shows three spectra; the middle one is the spectrum of the galaxy in true colors. Notice that some spectral lines are dark (absorption lines from starlight), and others are bright (emission lines from interstellar gas). There is also a black-and-white version of the same (galaxy) spectrum on the top, for easier viewing, and also a *spectrogram*, which is nothing else but the spectrum turned into a graph.

The bottom spectrum, on black background, is the spectrum of hydrogen as you have already seen in the Spectroscopy lab.

Look at the spectrum of NGC 3434 now. You'll notice that this galaxy has a bright H_β line (H_β in emission), and it is redshifted. The same is true of the H_α line. But there are additional lines in the spectrum of the galaxy, and we have to make sure that we do not misidentify them. A look at the H_γ and the H_δ lines convinces you that they are similarly redshifted, so they have not been confused with some other lines.

Now, you are ready to read off the wavelength of the spectral lines for each galaxy. Try to estimate the wavelengths to one decimal precision, and insert them into the table.

Your next job is to calculate the redshift of each galaxy using the relations that you learned in the introduction. Keep three decimals and insert your numbers for *z* in the table.

You will have two values of z for each galaxy. If they do not match within reasonable error, you either made a mistake in the calculation or confused the lines and have to correct it.

Make the Hubble plot.

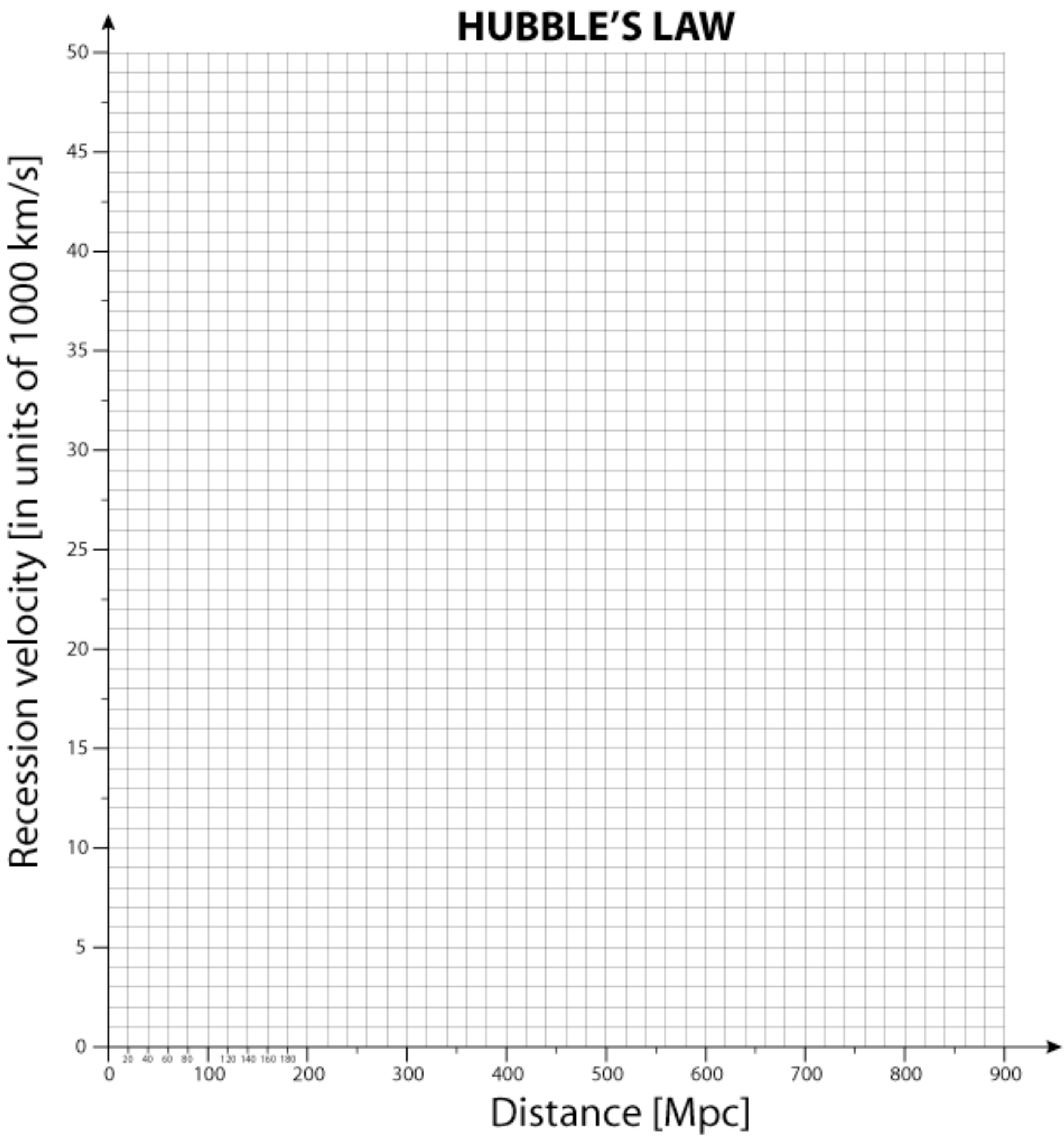
Use the provided graph paper with the scale on it. Include all the five galaxies, mark which one is which, and include our Galaxy (you know its *d* and *v*, right?)

Finally, connect the six points with a straight line. You want the line to cross exactly through the origin. If drawing a *straight line* seems possible within reasonable error, then you know *Hubble's law is correct*.

Determine the Hubble constant and the age of the Universe.

The Hubble constant is the slope of your straight line in the Hubble plot. To calculate it, read off the recession velocity of a galaxy that would be at 500 Mpc distance: _______ km/s. Calculate H = v/d = (_________km/s) / (500Mpc) = _____ km/s/Mpc.

We now calculate the size and the age of the Universe. Take an extreme object receding with the speed of light: it would be as far as the size of the Universe. Hubble's law says c=H×d, which we solve as d=c/H=300,000km/s / (______ km/s/Mpc) = ______ Mpc = ____ billion ly. As light goes one light year a year, we conclude that the Big Bang happened ______ years ago.



Notice that astronomy is a mathematical science: You are doing (very simplified) calculations to determine things like the age and size of the universe; or in the next section, to determine the nature of a galactic nucleus. Without the math, you would get nowhere: the quasar could have been a planet or the Universe could have been as young as a few thousand years old; you would not understand anything about the world you live in.

Apply Hubble's law to a quasar.

Now that you have set up Hubble's law, you are ready to use it the way astronomers usually do. They take the spectra of all sorts of galaxies, determine the redshift, and read off the distance to the object from the Hubble plot. You will be doing this with the brightest quasar in the sky, known as 3C273 (the 273rd object in the 3rd Cambridge catalogue of radio sources), and find some rather astonishing conclusions.

This object, a known radio source, looks like a nondescript 13-magnitude star in the sky. (Look at its Sloan picture on the left of its poster.) It is variable star that changes its brightness by a half a magnitude within hours, proving that it cannot be much larger than a few astronomical units, which is not surprising for a star at all.

The spectrum of this "star" reveals the true surprise: its spectral lines are hugely redshifted. Check it yourself: measure the redshift of the H_α and H_β lines the same way as you did with the galaxies; fill out the values for λ, Δλ, z, and v in the table below. The huge speed indicates that this object cannot be part of the Galaxy: it moves away much faster than the escape velocity from the Galaxy (which is ~ 500 km/s). But then it must be an extragalactic object, and the redshift must follow Hubble's law.

Object	Apparent size [as]	Distance *d* [Mpc]	H_β line [nm]			H_α line [nm]			*z*	v
			λ galaxy	Δλ	z	λ galaxy	Δλ	z		
3C273										

Once you reach this conclusion, you can use your Hubble diagram to tell the distance to 3C273. Do that: indicate its position on your graph, read off its distance and insert it into the table. Obviously, you find that is farther than any of the five galaxies that you studied previously.

Because you have established that this quasar ("quasi-stellar radio source") is very distant, you may suspect that it might have to be something like another galaxy. Yes and no: a more detailed Hubble Space telescope image (the middle one in the poster) detects no galaxy, and no spiral structure, but only the bright star and a jet flying out of it. However, on the right panel in the poster they used a "coronograph" on the space telescope: they placed a small black disk in the way to block out the 13^{mg} bright star. And indeed, the star gone, the faint haze of a galaxy is revealed around the blocked-out star. To check that this is correct, estimate the diameter of this galaxy in arc seconds, and insert it into the table. As before, use the relationship $D = d \times \theta[as]/200{,}000$ and substitute in θ and d to find the true diameter of this galaxy. Your result is: ___________ pc = ____________ ly. Does this support our hunch that the glow is indeed a galaxy? ____.

Now see what you found out. There is a galaxy, about the same size as our Milky Way, and in the center of it there is a *very* bright star-like object, whose light completely overwhelms the light of all the hundred billion stars of a regular galaxy! We now calculate the absolute brightness of this 'active galactic nucleus' (AGN). The distance modulus is found from the distance, $\Delta = 5 \times lg(d)-5 =$ ________^{mg}, and you'll recall $\Delta = m - M$. The apparent magnitude of this object is $m = 13^{mg}$, you find that the absolute magnitude of this AGN is $M =$ _______^{mg} . *(A hint: a very far-away object has to be much brighter than 13^{mg} to shine at 13^{mg} for us. That makes its absolute magnitude a much smaller number than 13^{mg}, so subtract!).* This object, viewed from as far as some of the stars, 10 parsecs, would shine as bright as the Sun!

Such a hugely energetic object, not larger than a few AU's as we saw, can be nothing else but a many-million-solar-mass black hole, gobbling up a few stars' worth of mass every year.

In order to support this conclusion, do this calculation for **extra credit.**

Calculate the energy output of the quasar:

The absolute magnitude of the Sun is $M = 4.8^{mg}$. With your value of the quasar's absolute magnitude, you know that the quasar is _______^{mg} brighter than the Sun (take the difference). This translates to as many times as bright as $10^{mg/2.5}$ =______ *times*. The Sun uses up its total mass as fuel in about *10 billion* years. Compared to this, the quasar will gobble up _______solar masses worth of material every year. (The mechanism is that this amount of mass falls into the black hole that the AGN indeed is, and the light we see is coming from the material being scrunched just before it falls in. We have tacitly assumed that the efficiency of energy production in the Sun and in the accretion disk of the AGN are the same, each about 1%.)

Conclusions: Is a quasar a large thing? ____

How close would you dare to approach a quasar? ______________________