Astronomy 1143: Assignment 2

This assignment is due at the beginning of class on *Friday*, September 28.

You may consult with others in the class when you are working on the homework, but you should make a first attempt at everything on your own before talking to others, and you must write up your eventual answers independently.

You are *welcome* to come to my office hours or Dan Stevens's office hours for advice. You should get as far as you can on the assignment *before* you come to office hours, so that you know what points you are stuck on.

The office hour times and office numbers are listed on the syllabus. Wednesday afternoon office hours will start out in the classroom (right after class), and we'll stay there unless/until we need to vacate the room for another class. If you are unable to attend the scheduled office hours because of unavoidable conflicts, you can e-mail Dan or me to schedule an appointment.

Homework assignments turned in to my mailbox after class but before 5:30 pm on Friday will be accepted but marked down 10 points for lateness. Homework assignments turned in after that but before 5:30 pm on Monday will be accepted but marked down 20 points. Assignments will not be accepted after 5:30 pm on Monday.

The last of the attached sheets has marked graph paper that you should use for Part II and turn in with your answer. Other than that, please write your answers on separate sheets (not this handout). Please staple or paper clip all sheets together. Be sure that your name is on your assignment. It's your responsibility to write clearly enough that we can grade your answers. For questions that require calculations, you should first work out your answers on scratch paper, but the solution you turn in should show enough of your work that we can tell how you got to your answer.

Part I: Some Short Questions (35 points)

Parts (a)-(c) are worth 5 points each, parts (d) and (e) are 10 points each. For (d) and (e), an answer of one or two paragraphs is fine, but be sure that you answer the question and explain the reasoning for your answer.

(a) Order the following list in terms of *photon energy*, starting with the highest energy and going to the lowest: ultraviolet photon, radio photon, blue visible light photon, X-ray photon, infrared photon, orange visible light photon.

(b) When an ambulance is speeding towards you, the sound waves from its siren and the light waves from its flashing red light are both shifted by the Doppler effect. When the ambulance passes by, so that it is now moving away from you instead of moving towards you, you may notice a change in the pitch of its siren, but you won't notice a change in the color of the light. Why is one effect noticeable but not the other? (You may want to look back at the discussion of the Doppler effect in the book.)

(c) How does Hubble's law help us to make 3-dimensional maps of the distribution of galaxies in the universe? (A couple of sentences is sufficient, if they convey the key idea.)

(d) Over the course of the semester, we will encounter several lines of strong evidence that the universe has a finite age, of about 14 billion years. Does this result (*both* the finiteness and the actual value of the age) surprise you? Why or why not?

(e) Looking to the future instead of the past, do you expect the universe to last forever? Why or why not? How long do you expect the *human species* to last, and what is the reason for your expectation?

Part II: Measuring Galaxy Redshifts (25 points)

Part (a) is worth 5 points; parts (b) and (c) are worth 10 points each.

In Homework 1 you measured periods of Cepheids, used the period-luminosity relation to infer the luminosities of the Cepheids, then used their apparent fluxes to determine the distance to the galaxy M81. Another key ingredient in determining the Hubble constant is measuring galaxy redshifts.

Remember that our Doppler shift formula is

$$\lambda_o = \lambda_e \times \left(1 + \frac{v}{c}\right).$$

We will want to convert wavelength measurements into velocities, so we should convert this equation to the equivalent:

$$v = c \times \left(\frac{\lambda_o}{\lambda_e} - 1\right).$$

Recall that the speed of light is $c = 300,000\,\mathrm{km\,s^{-1}}$.

Example

On the attached pages, the panel marked A shows the spectrum of a galaxy NGC 1832. (It is the 1832nd object in the "New General Catalog," a list of astronomical objects compiled by John Dreyer in 1888.) In class I referred to the wavelengths of light in nano-meters (1 nm $= 10^{-9}$ m), but here they are marked in a different unit called Angstroms; 1 Angstrom is 0.1 nm.

Panels B and C show expanded views of two regions of the spectrum, which are marked in panel A. In panel B, there are two deep dips, which occur at wavelengths where calcium atoms absorb light. If there were no Doppler shift, these two lines would occur at the wavelengths 3933.7 Angstroms and 3968.5 Angstroms, marked by short vertical lines. Instead, as the long vertical lines drawn from the centers of the absorption dips show, these dips are centered at 3960 Angstroms and 3996 Angstroms (read off the x-axis).

Using the first calcium line, I can conclude that the velocity of the galaxy is:

$$v = c \times \left(\frac{3960}{3933.7} - 1\right) = 2006\,\mathrm{km\,s^{-1}}.$$

I can check this using the second calcium line:

$$v = c \times \left(\frac{3996}{3968.5} - 1\right) = 2079\,\mathrm{km\,s^{-1}}.$$

These values are similar, and the difference between them is an indication of the uncertainty in my velocity measurement.

(a) In panel C, the high peak is an *emission* line where illuminated hydrogen gas is producing extra light at an emitted wavelength $\lambda_e = 6562.8$ Angstroms.

Measure the observed wavelength λ_o of this emission line and compute the velocity v of the galaxy. Does your result agree with the results from the calcium lines? Show your work.

(b) On the last of the attached pages, panel D shows just the calcium region of the spectrum for the galaxy NGC 2775. Measure the observed wavelengths for each of the two calcium lines, and compute the velocity of the galaxy from each of them.

Do the same thing for the galaxy NGC 3368, whose spectrum appears in the panel marked E.

(c) By applying Hubble's law with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, with your velocities measured from part (b), determine the distances to the galaxies NGC 1832, NGC 2775, and NGC 3368, in Mpc.

Part III: Measuring H_0 (25 points)

Each part is worth 5 points.

If you already know Hubble's constant H_0, then you can find the distance to a galaxy from its redshift (with some uncertainty because of peculiar velocity). However, to *measure* H_0 in the first place, you need to determine the distance to a galaxy *without* using Hubble's law. If you also measure the galaxy's redshift, you can then find H_0 from $H_0 = v/d$.

A Type Ia supernova results from the explosion of a white dwarf star. We still don't know completely why they occur — there are a few possible explanations, and we don't know whether one of these explanations is right, several of them are right, or all of them are still missing some key idea. But one way or another, these explosions do happen: the exploded star brightens dramatically over the course of a couple of weeks, often becoming luminous enough to outshine the entire galaxy of stars that it resides in. The supernova then fades, though it may remain visible against the light of its host galaxy for months or years.

When we refer to the peak luminosity of a supernova, we mean the luminosity it has when it is at its maximum brightness, a couple of weeks after the explosion. It turns out that all Type Ia supernovae have about the same peak luminosity, so we can use them as *standard candles* to infer distances. (I'm sweeping some details under the rug here, but this description will be sufficient for our purposes.) Because supernovae are *much* more luminous than any normal star, they can be seen even when they are very far away, making them useful cosmological tools.

(a) First, one has to calibrate these standard candles. Using our general equation $f = L/4\pi d^2$, show that if a supernova has apparent flux f and distance d then its luminosity is

$$\frac{L}{L_\odot} = \frac{f}{f_\odot} \times \left(\frac{d}{d_\odot}\right)^2 .$$

Hint: This is very much like part IId of Assignment 1, so look at the solution set for Assignment 1 if you're not sure what to do.

(b) In a paper on the Hubble constant published in 2011, Adam Riess and his collaborators used Hubble Space Telescope measurements of Cepheid distances to eight nearby galaxies that had hosted Type Ia supernovae. We'll consider three of those galaxies here, and just call them Galaxy 1, Galaxy 2, and Galaxy 3, hosting Supernova 1, Supernova 2, and Supernova 3.

For Galaxy 1, the distance inferred from Cepheids is 15.2 Mpc $= 3.1 \times 10^{12}$ AU, where for your convenience I have multiplied by $206,265 \times 10^6$ to convert from Mpc to AU. At its peak, the apparent flux of the supernova in Galaxy 1 was $f/f_\odot = 4.4 \times 10^{-16}$. What was the luminosity $L/L_\odot$ of Supernova 1 at its peak?

(Use the formula from part a. Your answer should be more than 1 billion and less than 10 billion.)

For Galaxy 2, the distance inferred from Cepheids is 21.6 Mpc $= 4.5 \times 10^{12}$ AU. The peak apparent flux of Supernova 2 was $f/f_\odot = 1.9 \times 10^{-16}$. What was the peak luminosity $L/L_\odot$ of Supernova 2?

For Galaxy 3, the distance inferred from Cepheids is 26.6 Mpc $= 5.5 \times 10^{12}$ AU. The peak apparent flux of Supernova 3 was $f/f_\odot = 1.2 \times 10^{-16}$. What was the peak luminosity $L/L_\odot$ of Supernova 3?

For the next part of this problem, take the median of your three results (i.e., the middle of the three values you got here) to be the typical peak luminosity of a Type Ia supernova.

(c) To compute H_0, Riess et al. used average results from a set of 240 more distant Type Ia supernovae, which other astronomers had discovered and measured over the course of many years. We'll take just three of those supernovae and see what answer they give.

Supernova 4 had peak flux $f/f_\odot = 8.7 \times 10^{-18}$. Its host galaxy has velocity $v = 7940\,\mathrm{km\,s^{-1}}$.

Supernova 5 had peak flux $f/f_\odot = 2.0 \times 10^{-17}$. Its host galaxy has velocity $v = 5010\,\mathrm{km\,s^{-1}}$.

Supernova 6 had peak flux $f/f_\odot = 1.2 \times 10^{-18}$. Its host galaxy has velocity $v = 17,800\,\mathrm{km\,s^{-1}}$.

For each of these supernovae, compute the distance in Mpc using the formula

$$\frac{d}{1\,\mathrm{Mpc}} = 4.85 \times 10^{-12} \times \sqrt{\frac{L}{L_\odot}} \times \sqrt{\frac{f_\odot}{f}}.$$

This is the same as the formula from Assignment 1, Part IId, except that I have saved you a small amount of work by putting in the factor 4.85×10^{-12} that converts from AU to Mpc.

You may want to look back at the solution to Assignment 1, Part IIe. Pay particular attention to the fact that $f_\odot/f$ is the reciprocal of $f/f_\odot$.

(d) Using these distances and the velocities of the host galaxies, compute $H_0 = v/d$ from each of the three supernovae. Your answer should have units of $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (which means the same thing as km/s/Mpc).

How do your three answers compare to each other and to the value I gave for H_0 in class?

(e) As you saw from part (b), Riess et al. already had Cepheid distances for several galaxies (the three I told you, plus five more at similar distances). Why did they bother with supernovae instead of just computing $H_0 = v/d$ using the redshifts and distances of those galaxies?

Hint: What goes wrong when you measure H_0 using galaxies that are too nearby?

Part IV: Hubble's Law and the Age of the Universe (15 points)

Each part is worth 5 points.

(a) Based on Hubble's law, $v = H_0 d$ with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, what is the velocity of a galaxy at a distance of 10 Mpc, in km/s? What is the velocity of a galaxy at a distance of 50 Mpc, in km/s?

(b) With a bit of multiplication, you can show that 1 Mpc is 3.09×10^{19} km. (You may want to check this for yourself, remembering that 1 Mpc is 1 million parsecs, but you don't have to include this in your answer.) You can also show that one year is 3.16×10^7 seconds. Referring back to part (a), how long would it take for the first galaxy to go 10 Mpc at the velocity that you computed for it? How long would it take for the second galaxy to go 50 Mpc at the velocity that you computed for it? Give your answers in years, and show your work.

(c) If all went well, you got the same time for both of the galaxies you considered above, and indeed you would get the same answer for a galaxy at any distance. Thus, this calculation suggests that the expansion of the universe that we observe today has been going on for about 14 billion years, and that this is in fact the age of the universe.

Suppose, however, that galaxies have been slowing down over time, so that they were moving faster in the past than they are today. Is the implied age of the expanding universe *smaller* than the one you calculated above, or *larger*? Explain your answer.

(For purposes of this question, don't worry about the fact that light takes time to travel from the galaxy to us; assume that the velocity you measure for a galaxy is the velocity it has today.)

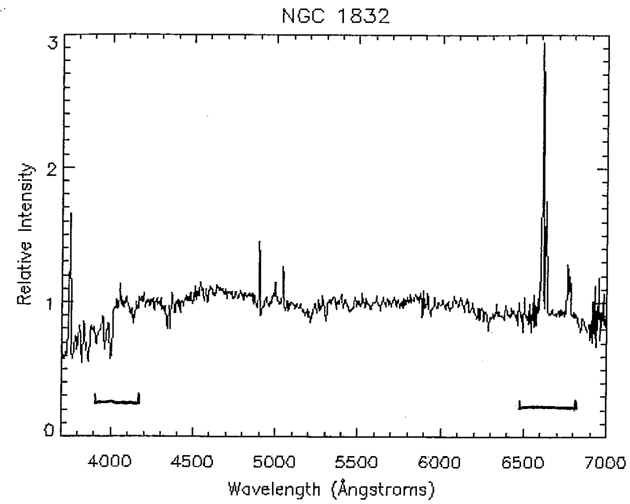
Extra Credit (up to 5 bonus points)

Look back at Assignment 1, Part III.

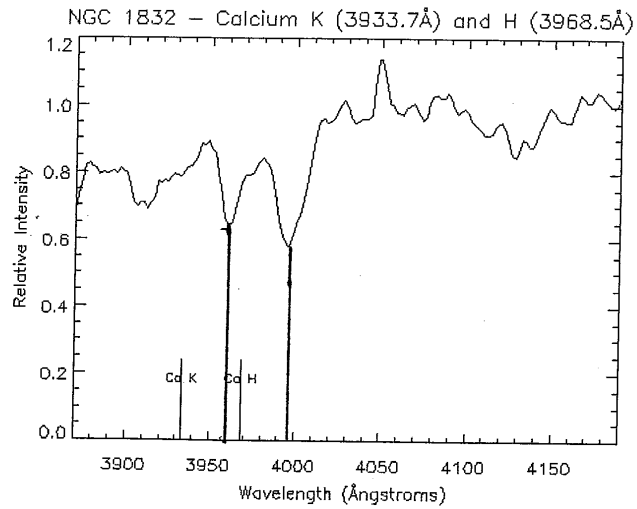
Suppose that you lived in an alternative universe, in which the astronomer Alvin Q. Jubble discovered that galaxies are receding from the Milky Way with a velocity-distance relation described by the equation $v = J_0 d^2$. The value of "Jubble's constant" J_0 is measured to be 70 km/s/Mpc^2.

How would your answer to Part IIId of Assignment 1 have come out differently if you lived in such a universe?

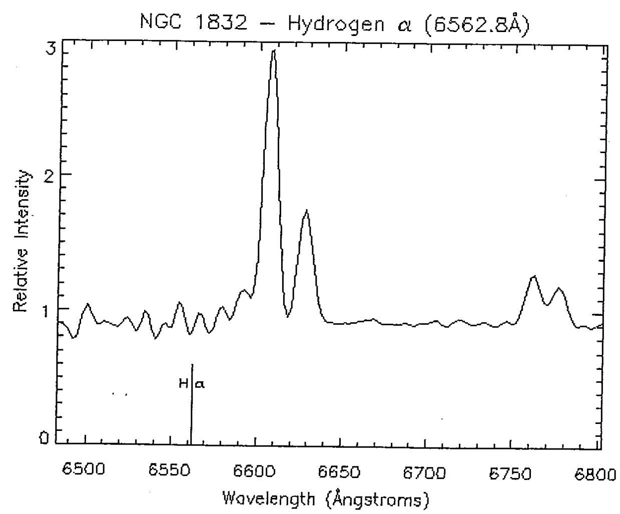
You don't need to repeat parts IIIb or IIIc in your answer, but you may need to try out some of these cases to understand why IIId would be fundamentally different.


NGC 1832
Relative Intensity
0
1
2
3
4000
4500
5000
5500
6000
6500
7000
Wavelength (Ångstroms)

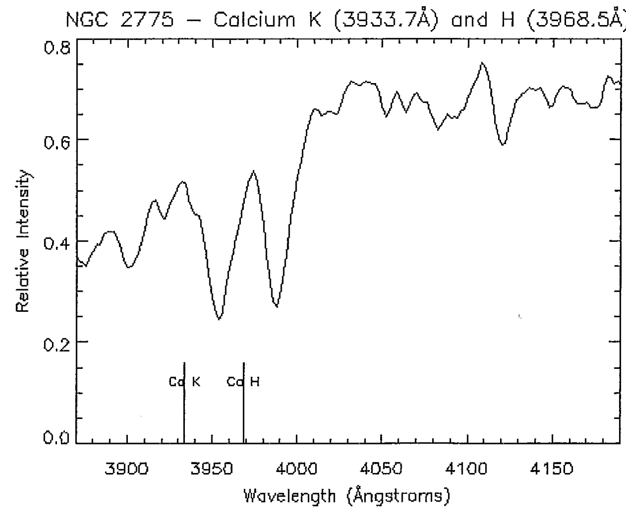
A


NGC 1832 – Calcium K (3933.7Å) and H (3968.5Å)
Relative Intensity
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ca K
Ca H
3900
3950
4000
4050
4100
4150
Wavelength (Ångstroms)

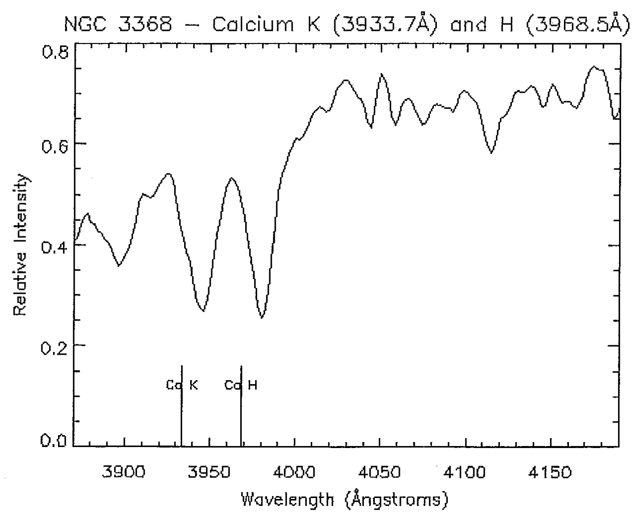
B


NGC 1832 – Hydrogen α (6562.8Å)
Relative Intensity
0
1
2
3
H α
6500
6550
6600
6650
6700
6750
6800
Wavelength (Ångstroms)

C


NGC 2775 – Calcium K (3933.7Å) and H (3968.5Å)
Relative Intensity
Wavelength (Ångstroms)
Ca K
Ca H

D


NGC 3368 – Calcium K (3933.7Å) and H (3968.5Å)
Relative Intensity
Wavelength (Ångstroms)
Ca K
Ca H

E