M31 galaxy: Andromeda

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Abstract

Assignment about M31 galaxy.

1 Introduction

You walk into astronomy class one day and find the following question on the board: “What is the radial velocity of the galaxy M31 with respect to our galaxy?” You had already learned that radial velocity means the velocity in a straight line toward or away from something, so the challenge is to find out how fast M31, also known as the Andromeda galaxy, is moving toward or away from our home galaxy, the Milky Way. Once everyone is in class, your professor says that the first person to solve this question using astronomical experiments and data (instead of looking up the answer on the Internet or in a book) will be excused from exams for the rest of the year.

Your professor tells you that the resources you can use include the University’s intro astronomy equipment (for example, an optical telescope), as well as astronomical data available in print and on-line. Use your understanding of the laws of physics to select an experiment which will help you to find the answer.

2 About M31

M31, also known as the Andromeda galaxy, can be seen with the naked eye in the constellation of Andromeda. M31 our nearest spiral galaxy neighbor. The Milky Way has a number of dwarf companion galaxies that lie closer than M31, like the Large and Small Magellanic Clouds, but M31 is the nearest major galaxy neighbor. Andromeda is also the largest galaxy in the Local Group, the cluster of galaxies of which the Milky Way is also a member.

Andromeda could be seen by the earliest people; however, it was not recognized as a galaxy until relatively recently. Through early telescopes, Andromeda was seen as a fuzzy spot in the sky and was assumed to be a nebula of gas lying within the Milky Way. In 1887, Isaac Roberts took the first photograph of Andromeda, which revealed its spiral structure. But even then, Andromeda was still assumed to be a local nebula.

In 1917, Heber Curtis observed a nova in Andromeda. Combing the photographic records, he found a number of other nova, and discovered that they were much fainter in Andromeda than elsewhere in the Milky Way. This bolstered the ”island universe” hypothesis that spiral nebulae, like Andromeda, were actually separate from the Milky Way. Ultimately, this hypothesis was shown to be true by Edwin

Figure 1: M31 galaxy!

Figure 2: Caption

Hubble in 1925. He identified Cepheid variable stars in Andromeda, which enabled him to measure its distance. The measured distance put Andromeda firmly outside the Milky Way.

Modern measurements have put the Andromeda galaxy at about 2.5 million light years from Earth.

https://imagine.gsfc.nasa.gov/features/yba/M31_velocity/

3 Methods

Recap: Your astronomy professor has tasked the class with determining the velocity of Andromeda with respect to the Milky Way. You thought of three possible ways to do this, one of which will give you the right answer.

3.1 Intensity

You've decided to try using the $1/r^2$ relationship to find the distance to M31 at two different times and then calculate the velocity from the difference in the two distances.

You know that the apparent brightness of an object changes as its distance changes, so you should be able to see how much the M31 moves by observing its change in brightness over a given time period. Finding its velocity is then just a matter of dividing this distance by the time interval. A snap. You can use a light curve of M31 to discern how the galaxy's brightness changes over time.

The equation that describes how apparent brightness changes with distance is given by the relationship:

$$I = \frac{I_0}{r^2}$$

In words, the intensity light varies as the inverse square of the separation from the light source (r).

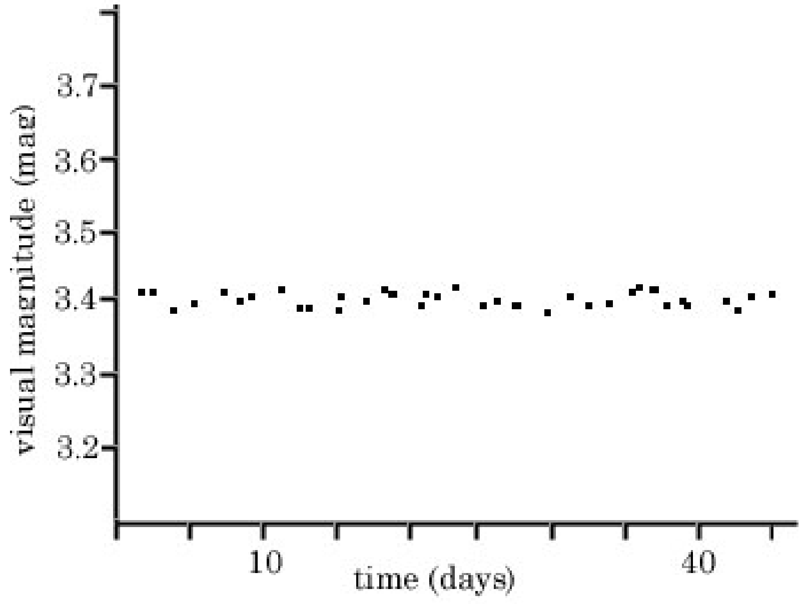

Figure 3: Light curve for M31 from a local telescope.

The intensity or brightness of light as a function of the distance from the light source follows an inverse square relationship. Suppose you were to use a light meter to measure an initial intensity I_0, or brightness, a distance r from a light source. Suppose that some time later the brightness of the light is either greater or lesser; if the intensity diminished you would know that the source was moving away from you and if it became brighter you would know that the source was moving towards you (assuming the light source itself remained the same).

This relationship can be illustrated by the diagram below, which shows the apparent brightness of a source with luminosity L_0 at distances $r, 2r, 3r$ etc. Notice that as the distance increases, the light must spread out over a larger surface and the surface brightness decreases in accordance with a "one over r squared" relationship. The decrease goes as r squared because the area over which the light is spread is proportional to the distance squared.

If a galaxy is traveling away at a recession velocity V_r, then the increase in its distance from us during a time interval Δt would simply be $V_r \cdot \Delta t$. If its intensity at a distance r is I_0, then the final intensity at the end of the time interval would be given by:

$$I_f = I_0 \frac{r^2}{(r + \Delta r)^2}$$

By convention, if the galaxy is moving away from us, V_r and therefore Δr, is positive, and the intensity decreases, whereas if the galaxy is moving towards us $\Delta 4$ is negative and the intensity increases. Substituting for Δr we get

$$I_f = I_0 \frac{r^2}{(r + V_r \Delta t)^2}$$

or

$$I_f = I_0 \frac{r^2}{r^2 + 2V_r \Delta t + V_r^2 \Delta t^2}$$

Here is a graph of the light curve of M31, as observed with a ground telescope at the local university/high school:

Question 1. The light from M31 has decreased by percent over the timescale observed graph. What is that percentage?

Question 2. Now consider what must happen for this effect to be seen with the intensity of M31. While M31 is traveling very fast, when you take your first measurement of M31's intensity from its light curve, it is starting at an enormous distance from the earth. So, even at a tremendous speed, M31 covers only a small fraction of the distance between us over the course of your measurements. In fact, even over the lifespan of a human, it still only travels a tiny fraction of that distance. M31 is at a distance of approximately 450,000 parsecs (pc) away from the Earth. For scale, parsec is about 200,000 times the distance between the Earth and the Sun. To help make some sense of this, it might help to look at the equations again The final intensity proportional to the initial intensity and inversely proportional to the distance to M31 squared. But what happens to the equation when Δr is very, very small as compared to r? It changes very, very slowly. So, hopefully that helps you understand why the light curve for M31 looks so flat, and why this method isn't the best way to measure the velocity of M31. What is the limit when $\Delta t \to 0$ of the intensity law given above? Take that $V_r \sim 100 km/s$ and plug numbers in Δt comparing with r, the distance to M31.

Question 3. A light bulb looks dimmer the further away it is because
☐ Most people are near sighted.
☐ More light is absorbed by gas in between the bulb and the observer.
☐ The same number of photons from the light bulb are spread out over a larger area.
☐ Of the Doppler shift effect.
☐ Light gets fainter with age.

Question 4. Walking into your basement one night, you notice you can see only 10 feet with your trusty 50 Watt flashlight. How strong must your flashlight be in order to see the full 20 feet of your basement?
☐ 25 Watts.
☐ 50 Watts.
☐ 100 Watts.
☐ 200 Watts.
☐ 20 feet is too far to see with any flashlight!

Question 5. While waiting for your bus you see in the distance the familiar glare of its headlights. With your handy light meter you measure the intensity of its light as 10 lumen. After 10 seconds you measure the intensity at 20 lumen. What can you infer about the bus during that 10 second interval?
☐ The bus moved half the distance to you in those 10 seconds.
☐ The bus was accelerating during those 10 seconds.
☐ The bus was decelerating during those 10 seconds.
☐ The bus moved less than half the distance to you in those 10 seconds.
☐ The bus moved more than half the distance to you in those 10 seconds.

3.2 Doppler shift

Recap: Your astronomy professor has tasked the class with determining the velocity of Andromeda with respect to the Milky Way. You thought of three possible ways to do this, one of which will give you the right answer. You've decided to try using the Doppler shift of emission lines from M31's spectrum to find the velocity of M31.

You learned that the spectrum of a source can be shifted when that source is moving toward or away from you. The amount of the shift in the spectrum depends on the velocity of the source – a higher velocity results in a larger shift. The effect is called Doppler shift and is described mathematically by the following equation:

$$\lambda' = \lambda_0 \left(1 + \frac{v}{c_0}\right)$$

In this equation, λ' is the shifted wavelength, λ_0 is the wavelength of light emitted in lab (or at rest with respect to the observer), v is the velocity of the source, and c_0 is the speed of the wave in a stationary medium.

Have you noticed that when an emergency vehicle with its siren blaring passes you that the tone that you hear changes in pitch? This is an example of the Doppler shift, and it is an effect that is associated with any wave phenomena (such as sound waves or light).

Consider a case where the firetruck is at rest in the fire station driveway waiting for the firemen to board, as shown in the image below. If the siren is on, a listener some distance away to the right will perceive the siren at the same frequency at which it is emitted. In fact, another stationary person on the left side of the truck would hear the same tone also.

Now consider how this situation changes when the truck is moving towards the stationary observer with a constant velocity, v, as pictured below.

The frequency of the fire engine's siren as heard by a person on the firetruck has not changed! However, the waves in the direction of the truck's motion bunch up as the fire truck is catching up to its own sound waves. The pressure variations, which are represented by the sine waves, impinge upon the eardrum of the stationary observer at an increased frequency. The stationary observer to the right therefore perceives a higher tone than the one actually emitted from the fire truck.

Notice that the waves behind the fire truck (on the left side of the diagram) are spread out because the siren is moving away from its own sound. This would cause a stationary observer to the left of the truck to perceive a decrease in the frequency of the of the siren.

For a source moving to the right, a stationary observer to the right would perceive a higher tone and one to the left would perceive a lower tone.

The non-relativistic Doppler shifted frequency of an object moving with speed v with respect to a stationary observer, is:

$$f' = f_0 \left(\frac{1}{1 + \dfrac{v}{c_0}} \right)$$

and the Doppler shifted wavelength can be shown to be:

$$\lambda' = \lambda_0 \left(1 + \frac{v}{c_0} \right)$$

In these two equations, c0 is the speed of the wave in a stationary medium (the speed of sound in this case), and the velocity is the radial component of the velocity (the part in a straight line from the observer). Both these formulas are non-relativistic approximations that are true as long as the velocity of the moving object is much less than the speed of light.

As a convention, the velocity is positive if the source is moving away from us and negative if the source is moving towards the observer.

Thus:

- If the source is moving away (positive velocity) the observed frequency is lower and the observed wavelength is greater (redshifted).
- If the source is moving towards (negative velocity) the observed frequency is higher and the wavelength is shorter (blueshifted).

How does this affect the spectra of distant objects in the Universe? Does light experience the Doppler shift?

Think about the spectrum of visible light: red-orange-yellow-green-blue-indigo-violet (or ROY G. BIV for short). If the Doppler shift also works for light then it must be possible to move so quickly towards a red traffic light that it would appear green to you! You might find it clever to use this argument if you get stopped for running a red light. However, the police officer might then give you a ticket for speeding.

It turns out that light from any part of the electromagnetic spectrum can be shifted up or down in frequency depending upon your relative motion to the emitting source. The following diagram illustrates this phenomenon:

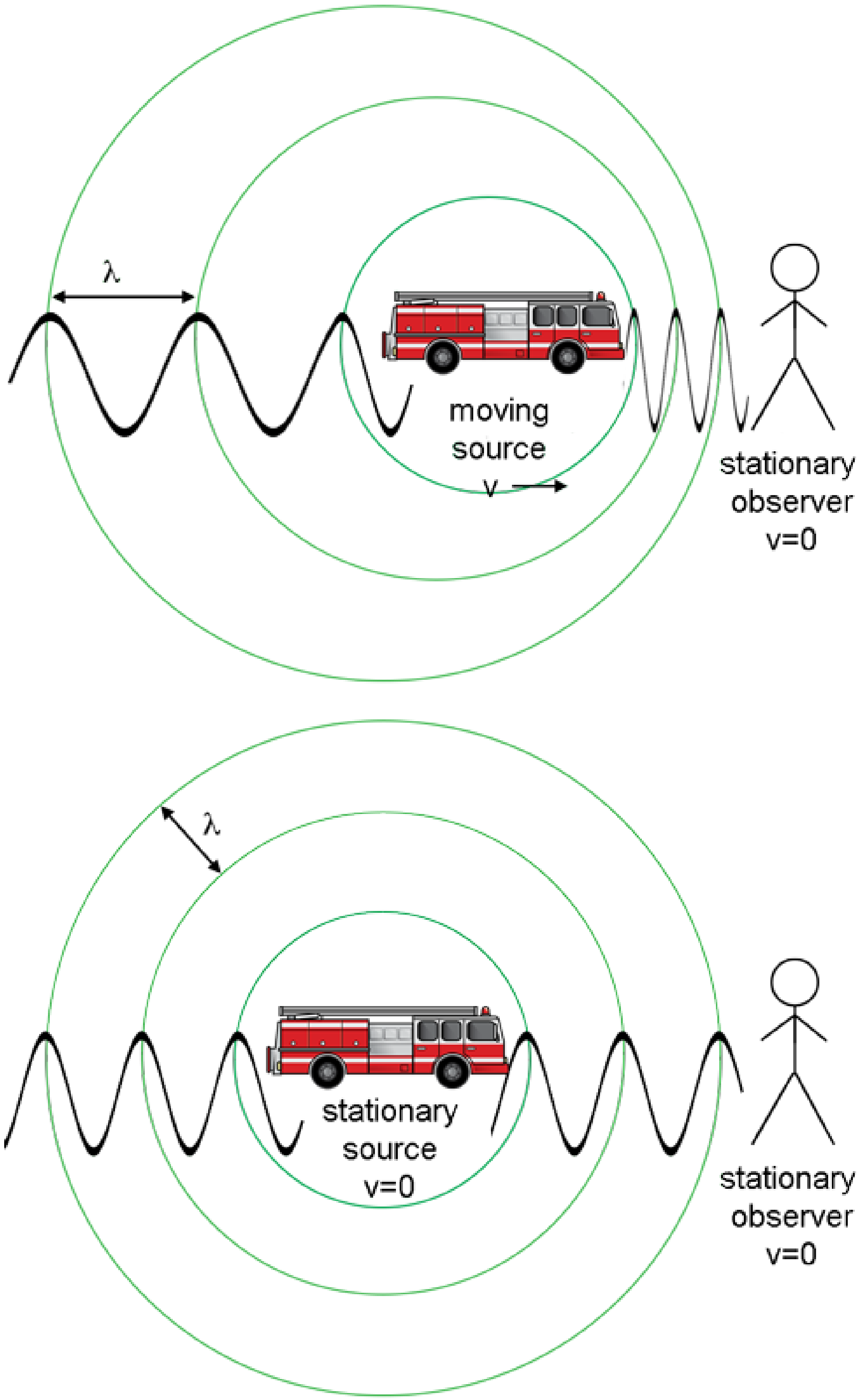

Figure 4: Doppler shift from siren

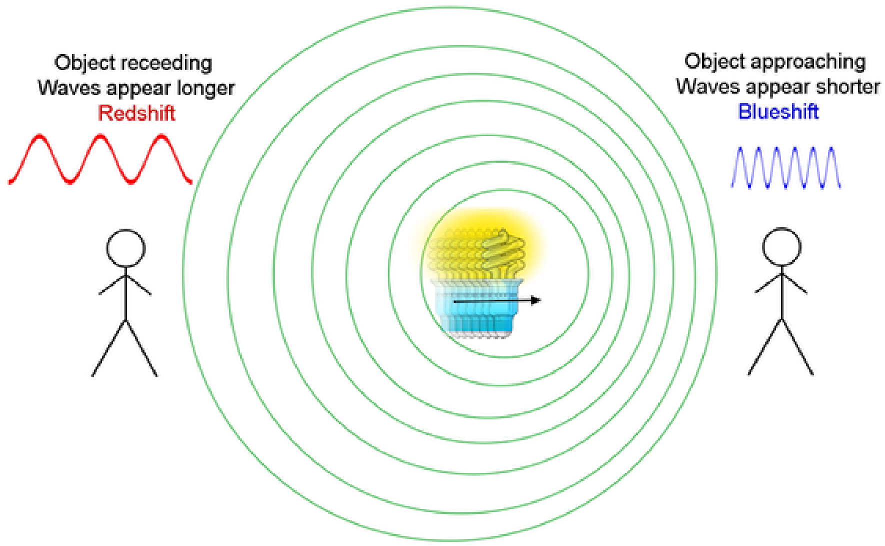

Figure 5: Doppler shift for light

3.3 Examples of redshifted galaxies

Examples of redshifted spectra from galaxies are provided in this subsection.

The images below show historic spectra and images of several galaxies. Each galaxy was observed to be traveling toward or away from ours with a different velocity – by convention, negative velocities indicate motion toward the observer and a positive velocity indicates a motion away from the observer. The velocities are determined by the shift of the spectral lines.

In the image of each spectrum, the middle section shows the observed galactic spectrum. The lines shown on the top and bottom of each spectrum are the characteristic lines of hydrogen as it appears in the laboratory (at rest). The red arrow in the NGC 221 spectrum indicates the segment of the galaxy's spectrum that is of interest – the bright hydrogen line. In each spectrum, that line is shifted in comparison to the laboratory spectrum. The horizontal arrow in the other spectra indicates the extent of that shift. Study the diagrams carefully, and you will notice that the galaxies displaying higher velocity show the greatest Doppler shift.

In the raw data, the horizontal axes of the spectra would be labelled "wavelength" or "energy". Measuring the shift in wavelength from the laboratory frame enables you to calculate the galaxy's velocity. Historic spectra of selected galaxies:

Question 6. Search for information about these objects and how far are they from internet data: NGC 221, NGC 4473, NGC379, Galaxy in UMa Cluster (not specified), Galaxy in Gemini Cluster (not specificied). Try to identify the 2 unknown galaxies.

Question 7. While waiting for your bus you hear in the distance the familiar drone of its engine. After a short while the tone begins to sound lower and lower. Knowing about it's Doppler shift, what should you do?

☐ Pick up your back-pack and get ready, because the bus will soon stop for you.
☐ Run because the bus is accelerating uncontrollably toward you.
☐ Walk home because the bus has already passed you and is accelerating toward the school.
☐ Start walking toward the spot where the school bus is stopped.
☐ None of the Above.

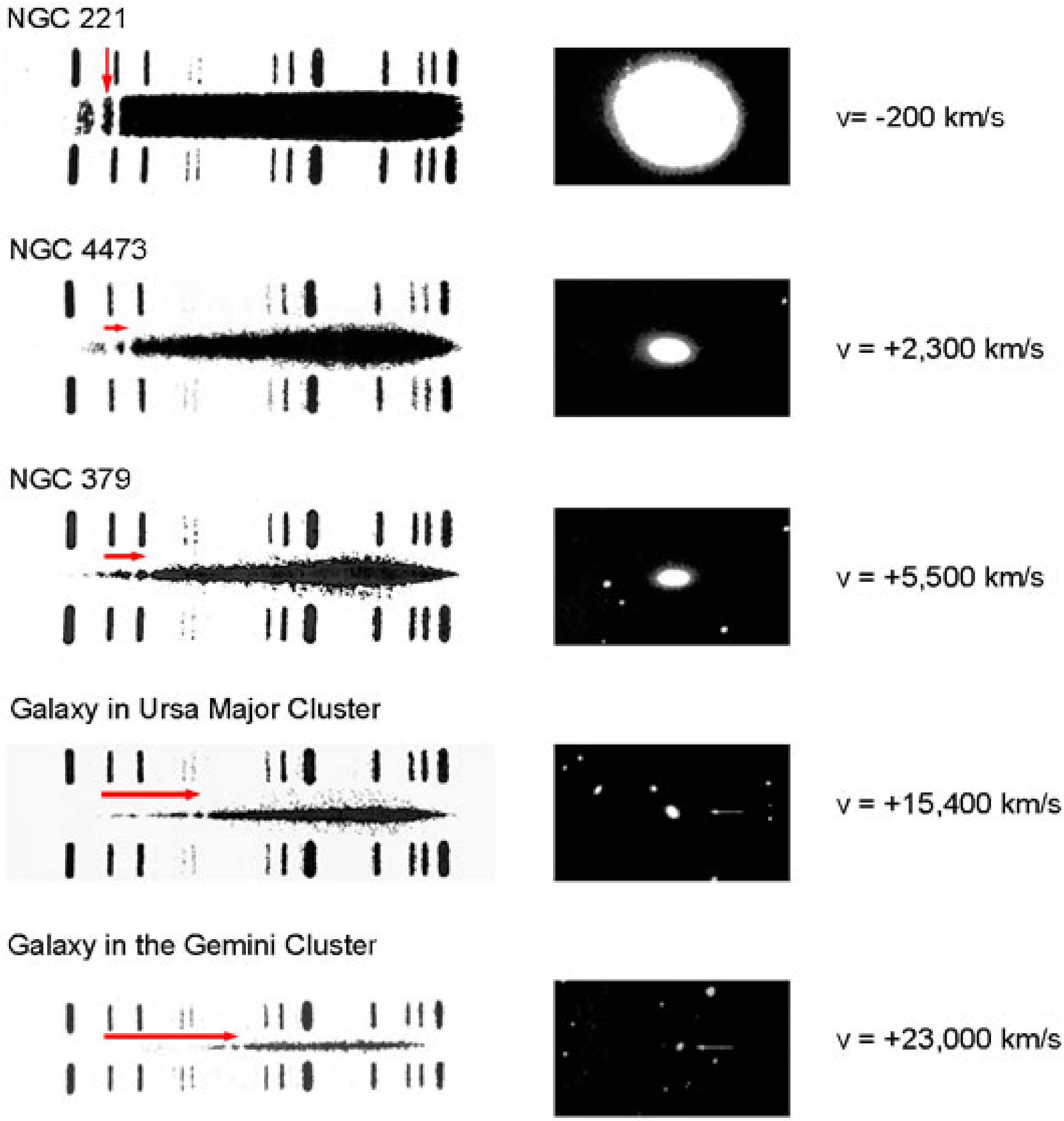

Figure 6: Spectrum of redshifted galaxies: examples.

Question 8. Your youngest sibling is amazingly able to produce a long steady whine for hours on end. While trying to hide from her, you hear the pitch of the irritable noise increase and then decrease. What has just happened?
☐ Your sibling ran away from you. (A)
☐ Your sibling ran past you. (B)
☐ You are amazed at how fast your sibling can run since you are able to notice the Doppler shift in her voice. (C)
☐ A and C.
☐ B and C.

Question 9. While driving your car, you are stopped for running a red light. You tell the police officer that because of the Doppler shift, the red light (650 nm) was blueshifted to a green light (470 nm) as you drove towards the stop light. How fast would you have to be going in order for this to be true? (use the non-relativistic Doppler shift equation)
☐ 0.5 times the speed of light
☐ 0.3 times the speed of light
☐ 0.1 times the speed of light
☐ 0.01 times the speed of light
☐ 70 mph

Now, we are ready to use Doppler shift to find out M31 speed. Below is the spectrum of M31. The locations of laboratory-measured lines of calcium K and H lines are indicated in red, and the laboratory wavelengths for them are given below. The corresponding calcium H and K lines from M31 can be seen in absorption. Look carefully in making your comparison. You may find it easier to print the image and estimate the Doppler shifted wavelengths using a ruler.

Possibly helpful quantities:

- Calcium K laboratory wavelength, λ_0, Ca K = 3934 angstrom.
- Calcium H laboratory wavelength, λ_0, Ca H = 3969 angstrom.
- Speed of light, $c_0 = 3 \cdot 10^5 km/s$.

Question 10. The radial velocity of M31 away from the Earth is, including sign and with 2 significant figures: $v =$.
The number is not only the thing I will evaluate. I will also check the procedure and your numbers from the following plot (figure 7,7).

3.4 Hubble law

Recap: Your astronomy professor has tasked the class with determining the velocity of Andromeda with respect to the Milky Way. You thought of three possible ways to do this, one of which will give you the right answer. You've decided to try using Hubble's Law to find the velocity from M31's distance.

You learned in astronomy class that Hubble's Law is a relationship between the radial velocities of distant galaxies and their distance from us. The relationship can be stated:

$$v = H_0 d$$

where v is the recessional velocity of the galaxy, d is its distance away, and H_0 is Hubble's constant. So, for distant galaxies, if you know the distance and the value of H_0, you should be able to solve for the velocity.

Looking at the skies from Mt. Palomar in the 1920s, Edwin Hubble found that nearly all far away spiral nebulae (now known as galaxies) in the Universe are moving away from us. This motion, called their recession velocity, is greater the further they are from us. In fact, he found the relationship

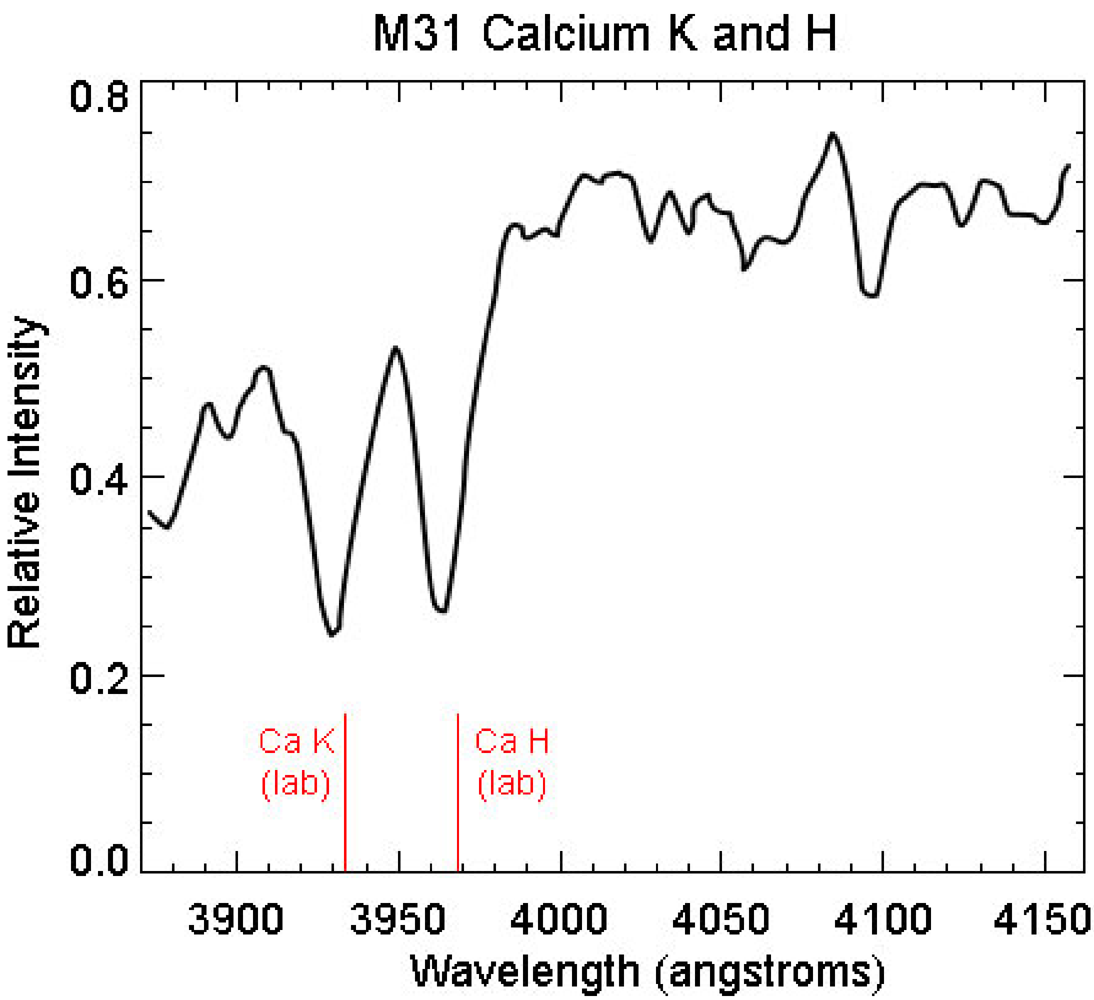

Figure 7: M31 spectral data.

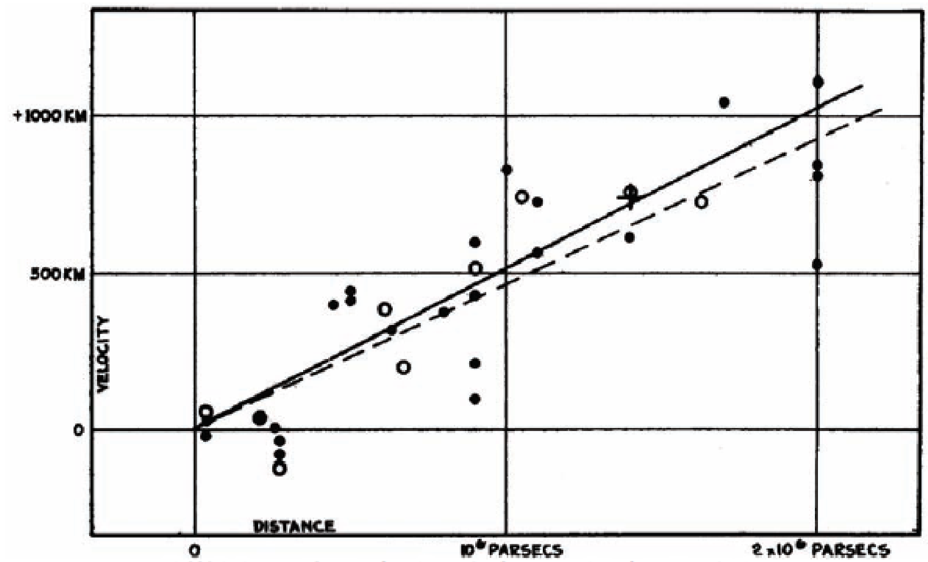

Figure 8: Hubble law plot. Hubble's graph of redshift versus distance. (Hubble, Proceedings of the National Academy of Sciences, 1929, 15, 168).

between a galaxy's velocity away from us (v) and its distance from us (d) approaches a fairly linear one, which is known as Hubble's Law:

$$v = H_0 d$$

where H_0 is an observationally determined constant called Hubble's constant(really, a parameter). Finding the value of Hubble's constant is still a current topic in astronomy, and it has implications for our understanding of how the Universe evolved since the Big Bang.

Hubble's finding built on the work of Vesto M. Slipher who, in 1912, discovered that light from nearly all of the "spiral nebulae" he observed, regardless of the direction he looked, appeared to be redshifted. This meant they were moving away.

In 1924 Hubble discovered that the "spiral nebulae" were actually galaxies outside our Milky Way galaxy. Hubble was able, along with his research assistant Milton Humason, to measure distances to a number of the spiral nebulae.

Edwin Hubble sought to find a relationship between their distance from us and their speed. He plotted recessional velocity determined by the Doppler shift of stellar spectra as a function distance and established what is now know as Hubble's Law. Hubble's law applies to the objects in the Universe on the largest scales, where the force driving their motions is the expansion of the Universe.

You've probably heard it said that Hubble's Law tells us that the Universe is expanding, but how do we get from the plot of Hubble's Law to an expanding Universe?

One way to think about the expanding Universe is to imagine that the Universe is a loaf of raisin bread. The galaxies are the raisins, and the dough is the space between galaxies or large structures. When the loaf is left to rise, the raisins get further and further apart because there is more space between them.

In real life as a loaf of raisin bread bakes, the yeast in the bread makes the dough rise and expand. This expansion fills some of the "void" in space around the bread pan. Our model of the bread as an expanding Universe takes on a different meaning, since the Universe as we know it is not expanding into anything, such as another dimension. There is just more space itself. The expansion of the dough in our model represents the expansion of space itself and in the process the raisins, which represent the matter we find in space, move away from each other in all directions.

Note that the raisins in our loaf remain the same size even as the bread itself gets larger. This is similar to the matter in our Universe – the matter is not expanding. Instead it's the space around the matter that's expanding.

Think of two raisins, one of which is twice as close to you initially. If the space between everything in the raisin bread is expanding uniformly, in the time it takes the loaf to expand so that the closer raisin is now twice as far away, the further raisin is now four times as far away (the loaf is twice as big). In this time, therefore, the first raisin has traveled a distance d (2d - d) while the second raisin has traveled a distance 2d (4d - 2d). The velocity you would observe for the first raisin is d/t while that of the second raisin is 2d/t. Thus you see that if the loaf is uniformly expanding, the velocity of distant objects is directly proportional to their distance away from you, which is what Hubble found.

Question 11. Traveling in your starship, you observe a distant galaxy that is 870 million light years away and is moving away from you at a speed of 20,000 km/sec. How fast would you have to travel in order to be able one day to catch up to a galaxy twice as far away?
☐ at least 5,000 km/sec.
☐ at least 10,000 km/sec.
☐ at least 20,000 km/sec.
☐ at least 40,000 km/sec.
☐ at least 100,000 km/sec.

Question 12. You observe three distant galaxies and note their apparent radial velocities:
☐ BFG-01 39,300 km/s
☐ BFG-02 79,000 km/s
☐ BFG-03 19,000 km/s
Which of the following is true about these galaxies?
☐ BFG-02 is twice as big as BFG-01.
☐ BFG-03 is the most massive galaxy.
☐ BFG-02 is the least massive galaxy.
☐ All of the Above.
☐ None of the Above.
Reason your chosen answer!

You now know that you need two pieces of information in order to use Hubble's Law to solve for M31's velocity: the distance to M31 and Hubble's constant!

Looking up "distance to M31" on the web, it is easy to find that the Andromeda galaxy (the other name for M31) is 2.5 million light years (or $2.5Mly = 2.5 \cdot 10^6$ light years). Even though that sounds like it's very far away, Andromeda is actually one of our nearest galaxy neighbors.

The value of Hubble's constant, H_0, has been a topic of ongoing research and observation ever since Hubble discovered that there was a relationship between recession velocity and distance. The measured value of H0 changes as our observations improve. The number you find for H_0 in your textbook is 68 km/sec/Mpc, which was reported in 2013 as a result of studies done with data from the Planck mission. You expect that your professor would want you to use this number, even if there has been an update in the research.

Note that "Mpc" stands for mega-parsecs, or 10^6 parsecs. And one parsec is about 3.3 light years. Be very careful keeping all of your units straight!

Question 13. The velocity of M31 relative to the Milky Way is, with to significant figures and sign included, equal to(using the Hubble law): $v =$(km/s). Compare with the previous value in the previous method.

Question 14. Using the Hubble constant, calculate the age of the Universe, the radius of the Universe and the Universe density. Compare the radius of the Universe got from this calculation with the real one (search for it in the web). Are they equal or different? Why? Data: $c = 3 \cdot 10^5 km/s$, $G = 6.674 \cdot 10^{-11} Nm^2/kg^2$.. Use the Hubble constant to get an expression for the total energy of the "bubble Universe" that we live in (local Universe), and then plug the numbers. Guess a formula for the total mass of the Universe, and calculate its value. Compare the radius of the Universe (the real one) with the radius of the Milky Way. Compare the density of the Universe in such a way you can tell how many protons per cubic centimeter you have in the universe. Compare the Universe density with the density of the hydrogen atom in gas phase. Guess how many stars could the Universe have, and how many Milky Way Galaxies, if our galaxy has about 10^{11} stars. If you had a Universe with 10^{12} galaxies, make guesses of how many exoplanets could our Universe have. Write and explain the detailed calculations.

References

[1] https://imagine.gsfc.nasa.gov/features/yba/M31_velocity/