Cosmic Expansion

(aka The Hubble-Lemaître Law)

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One of the NGSS standards for Earth/Space sciences heavily emphasizes the evidence for the expanding universe, AKA "The Big Bang Theory." A major piece of evidence is the Hubble-Lemaitre Law, which indicates a linear relationship between a galaxy's apparent distance from Earth and its recessional speed.

Both of these are essentially impossible for high school students to measure directly in a classroom setting. Some activities therefore take a high-tech approach involving online databases of galaxies, Cepheid variables and spectra. Other styles simply provide distances and speeds in a table. This style is a middle-ground approach: it remains fairly low-tech but has a more direct connection to the experimental evidence. The main connection is to galaxy spectra, which are used to determine speed. As an optional extension activity, students can also examine graphs of Cepheid variable stars to understand how we calculate distance.

Basic Progression:

1. Hydrogen gas emits specific colors.
2. Those colors shift red/blue due to relative motion.

3. Some galaxies still have lots of free hydrogen.
4. You can see the "color" of a galaxy using spectroscopy.
5. We can measure relative speeds of galaxies by looking at spectra and measuring the redshift for the hydrogen emission lines.

Therefore: If distances to these galaxies are known, we can plot speed vs. distance and produce evidence for an expanding universe.

Curricular Alignment to NGSS

Science and Engineering Practices

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Crosscutting Concepts

1. Patterns
2. Cause and effect
3. Scale, proportion, and quantity
4. Systems and system models
5. Energy and matter
6. Structure and function
7. Stability and change

NGSS content-specific standards

HS-ESS1-2 Earth's Place in the Universe - Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.

PS4.A: Wave Properties

The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. (HS-PS4-1)

PS4.B: Electromagnetic Radiation

Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. (HS-PS4-3)

When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. (HS-PS4-4)

PS4.C: Information Technologies and Instrumentation

Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them. (HS-PS4-5)

A. Prerequisite Learning

Note to Teachers: The section called Review has two purposes. On one hand, it will help teachers understand where the activity fits into the scope and sequence. On the other hand, students might find it helpful to have the review included, so that it refreshes their memory. The student pages present this information as a series of "pre-lab" questions, as opposed to this document which simply provides the information.

Summary of prerequisite knowledge:

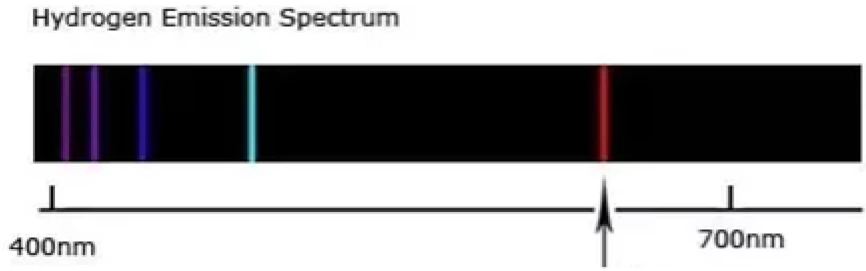
1. Spectrometers are used to measure the intensity and color of objects that emit light.
2. What would appear to the naked eye as a bright emission line in a handheld spectrometer becomes a narrow spike in intensity on a graph of the spectrum.
3. Due to the Doppler Effect and other similar effects, the observed color of a bright object will shift to a higher or lower frequency (blueshift / redshift) when the bright object and observer move towards or away from each other.

4. Galaxy spectra can have many different appearances. The general shape of the curve gives a sense of the overall color and age of the galaxy, and if the galaxy still contains “free” gas, emission lines will be present for several molecular gases.

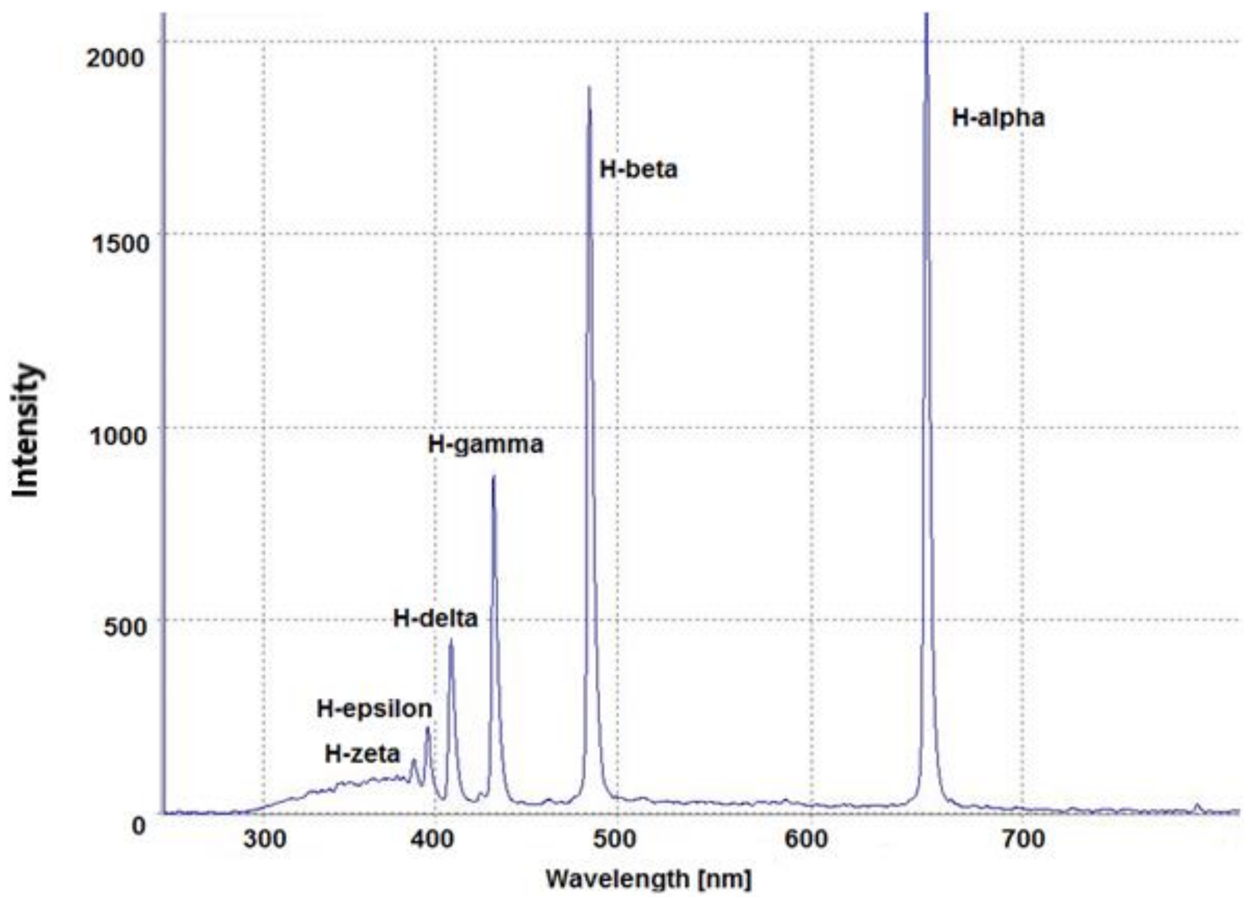
Learning Goal: Identify the relationship between a galaxy's distance to Earth and the observed wavelengths of light, in order to cite evidence for the expanding universe.

Review

In a previous class, you looked at a tube filled with hydrogen gas, and when the tube was turned on it glowed a pinkish-red color. When you looked at the tube with a handheld spectroscope, it looked like this:



If you turn this picture into a graph of intensity (Y) vs. wavelength (X) it looks like this:

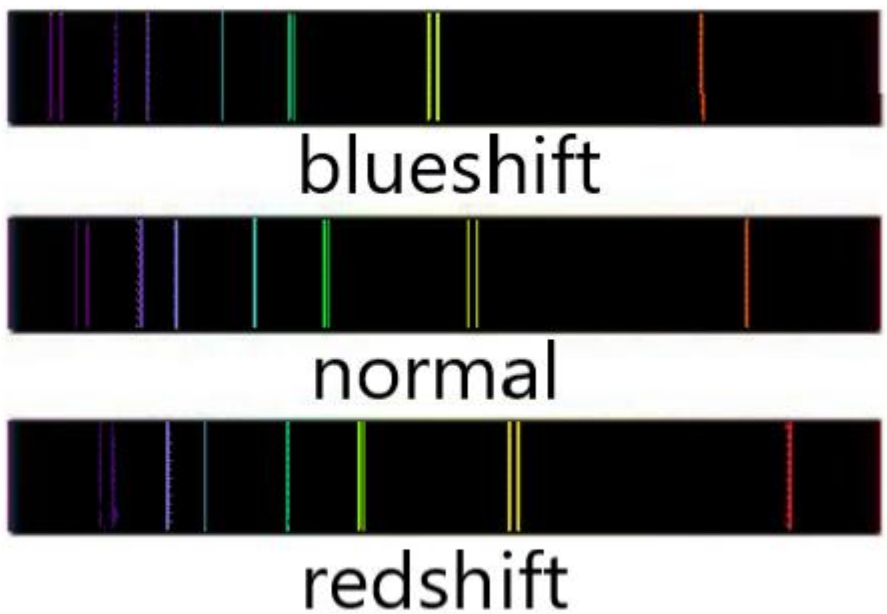


You can see that the same colors that glowed brightly in the tube show up as "spikes" or peaks on the graph. The strongest one is usually at a wavelength of **<u>656 nm</u>** and is called the "hydrogen-alpha" or **<u>Hα</u>** peak.

<u>Answers to prelab questions:</u>

- Explain how the spectrum is similar to the colors you observe with a handheld spectrometer. ***The intensity is large for the wavelengths of light that hydrogen gas emits.***
- Search for spectra for elements other than hydrogen (such as oxygen, mercury, helium, etc.). Why does it make sense that some people call these spectra "chemical fingerprints?" ***Each gas has a specific set of emission lines, and no two sets of lines are identical. So each gas can be identified uniquely by its spectrum.***
- The spike labeled "H-alpha" is the brightest color emitted by hydrogen gas. Use the graph to estimate its wavelength in nanometers (nm). ***The H-alpha peak is nearly halfway between 600nm and 700 nm but is clearly closer to 700nm, so 660nm is a good estimate (exact value closer to 656nm).***

In another previous lesson, you also learned that light waves can become blueshifted or redshifted if the light source is moving towards or away from the person seeing the light. The spectrum for a hydrogen-rich nebula might look like one of the pictures below:

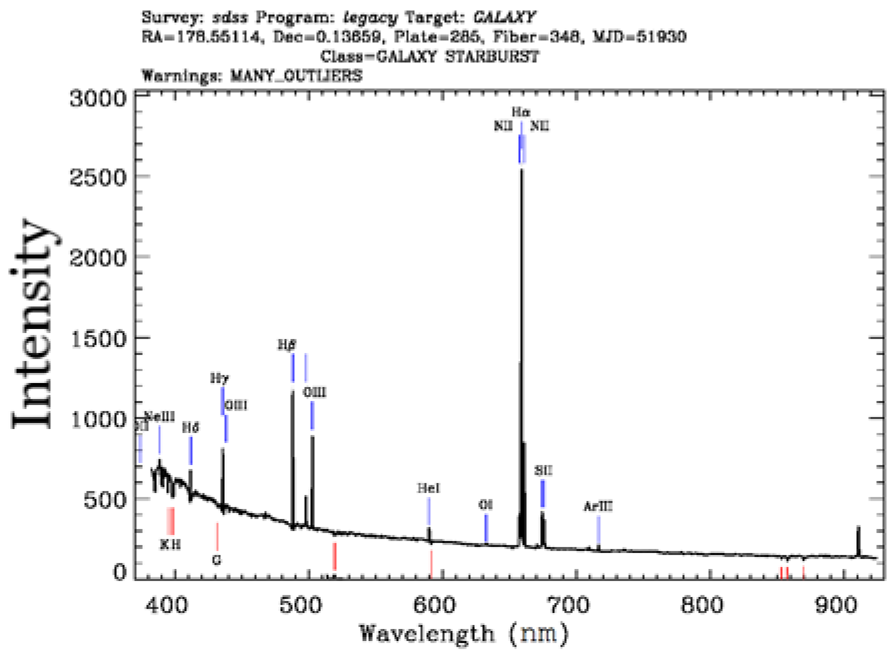


Answers to prelab questions:

• For sounds waves, the frequency of the wave is called the "pitch" (bass notes are low pitch, for example). What do we usually call the frequency of a light wave? ***The frequency of a light wave is its color. Low frequency visible light is red, and high frequency light is blue/violet.***

• The image above shows the spectra for 3 identical clouds of gas. If the middle spectrum in the image above represents a gas that is not moving towards us, then what do you conclude about the top and bottom spectra in the image? ***Blueshift means moving towards us, and redshift means moving away.***

<u>"BASELINE" galaxy</u>: When we look at nearby galaxies that are not moving towards or away from us, we see a spectrum graph that looks like this:



You can see that this galaxy has a very sharp Hα peak at roughly 660 nm. Because many galaxies still contain lots of free hydrogen gas, we can look for this peak on spectrum graphs for galaxies and use it as a marker: if the peak has shifted to the left of 660 nm, we know the galaxy is blueshifted and moving towards us, and if the peak has shifted to the right of 660 nm, it is redshifted and is moving away from us.

Other information that can be determined from the spectrum: the location of the galaxy in the night sky (RA/Dec); the viewing plate and fiber that were assigned by the SDSS experiment to view this galaxy (Plate/fiber); the date the spectrum was recorded (MJD = "mean Julian date"); the class identifier; even the redshift z (which was redacted here to prevent students from obtaining values too easily)

Answers to prelab questions:

- Refresh your memory: what are the wavelengths of blue and red light, using units of nm? ***Red light is ~700nm and blue light is ~450nm.***

- An astronomer would look at the image above and immediately identify it as the spectrum of a bluish galaxy. How could she determine the galaxy's color by looking at this graph? ***If you ignore the spikes representing gas emissions, the galaxy intensity is greatest at low wavelengths (violet and blue).***

- The same astronomer would also say that this galaxy contains a lot of free hydrogen gas that is not "locked up" inside stars. What is her evidence? ***There are spikes representing emission lines for hydrogen and other gases, with the exact same locations and spacing we see for gas tubes in a lab room.***

- Look for the hydrogen-alpha peak, labeled Hα, on the spectrum. How does the position of the Hα peak show us that the galaxy is not moving towards or away from us? ***The H-alpha peak appears to be at 660 nm, so it is not redshifted or blueshifted. This means it's at rest relative to us.***

B. Activity

Instructions

1. Below are 10 pictures of galaxies from the Hubble Space Telescope. To the right of each picture is the emission spectrum for the galaxy, which also lists distances and an image size scale.
2. You and your partners should work to identify some relationship based on the information given, and justify this relationship using a graph.
3. Clearly label your X and Y axes and scale on the graph.
4. Share your results with another group and compare graphs. Did the other group choose a different relationship than yours? If so, what did they discover?

The intended relationship to be discovered is that the more distant a galaxy, the greater the redshift of the galaxy (and therefore the greater the speed). However, students may discover other interesting relationships worth discussing, including such measurements as galaxy size or intensity.

Analysis

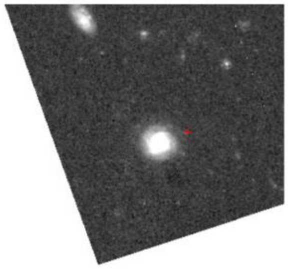
1. What conclusion(s) would you make about these galaxies; based on the pattern discovered or graph you've produced? Justify your answer with evidence from the investigation. ***Answers will vary.***
2. In previous activities, you discovered that light waves can become redshifted or blueshifted if they are moving towards or away from us. Was this fact useful in your investigation or perhaps another group's investigation? ***Answers may vary; ideally some groups will explain that the redshifted H-alpha line allowed them to make statements about a galaxy's recession speed.***
3. This NASA article summarizes important findings made in the 1920s by Edwin Hubble and Henrietta Leavitt. Read the article and discuss with your partner. Do your results provide evidence to support the information in the article?
4. The Big Bang model of the universe includes the idea that the universe is expanding. Explain how the results of your investigation could be used as **evidence** for an expanding universe. ***Answers should clearly state the positive correlation between galaxy speed and galaxy distance, and explain that this implies everything in the universe is moving away from us, just as the blueberries in a muffin spread apart as the muffin is baking. Sample response:***

   "We can tell galaxies are moving away from us because their spectrum is redshifted. If every galaxy is redshifted, then every galaxy is moving away from us. This shows that the universe is expanding. The farther away the galaxy, the faster it's moving, which is what we call Hubble's Law."

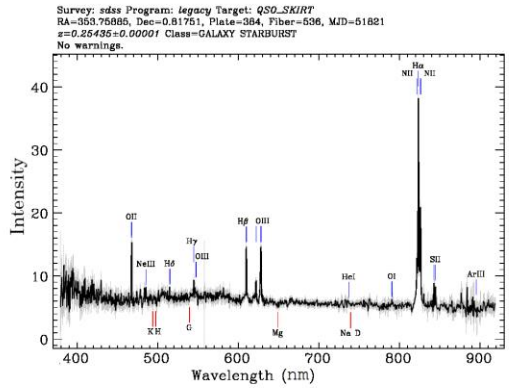
Note: the main goal of the activity has been completed by this point. The extension questions below are useful for differentiation, or to give you flexibility to elaborate on certain implications of the expanding universe hypothesis.

Extensions

1. The image below is of a very distant galaxy. Based on the information given in the image, how far away would you expect this galaxy to be? Justify your answer. ***Estimating the H-alpha line to be 825 nm, this galaxy is approx. 3300 million light years away by extrapolating the graph we produced earlier.***

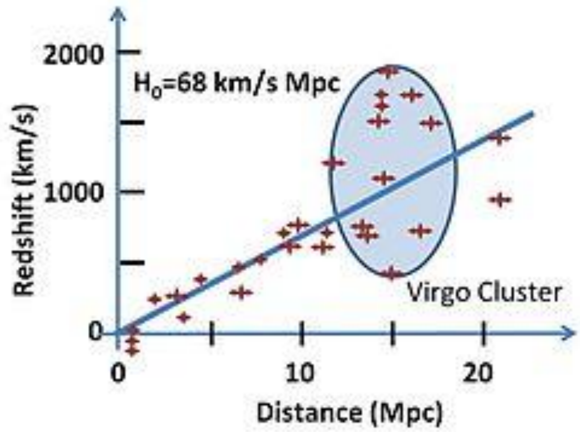


Distant Galaxy



2. Cut a rubber band in half. Use this rubber "string" along with some paper clips and a ruler to make a model for an expanding universe. Justify with measurements. ***If students choose a paper clip nearest their left hand as the "Milky Way," they can show via ruler measurement that when they stretch the rubber band using their right hand, the more distant paper clips move a greater distance than the clips nearer the Milky Way.***
3. Electronic activity: There are two images on the final page- one is a larger version of the other. They have been configured to be mostly transparent, so that you can overlay them and move the small one around in front of the large one. Use these two images to explain the following statement: "***Everyone in an expanding universe believes they live at the center of it***." ***By moving the smaller image around against the larger background image, students can align identical sections, and easily explain that there is an illusion of all nearby points moving outward from the aligned spots.***
4. You were provided a list of distances to the galaxies, without any explanation of how these distances were measured. Try to find out how this was done! (hint: for nearby galaxies we use "Cepheid variable stars" and for distant galaxies we use "supernovae.") ***Cepheid variable stars "pulse" over time, getting brighter and dimmer at regular intervals. There is a well-understood relationship between the pulse frequency and the luminosity of these stars. By measuring both the brightness and pulse frequency of Cepheids in our own galaxy (whose distances can be measured using other means such as parallax), we can develop a distance calibration and apply it to Cepheids that we observe in other galaxies. Similarly, when stars explode in a supernova, they have a consistent and well-understood brightness curve over time. Their extreme (but short-lived) brightness allows them to be seen even at great distances, and therefore are the primary way that we calculate the distance to very far-away galaxies.***

5. Suppose you graph the speed of galaxies on the Y-axis of a graph and their distance on the X-axis, as shown in the article you read and shown below. The slope of this line is called the "Hubble Constant" and written H_0 like on the graph, with units of $\frac{\frac{km}{s}}{Mpc}$. The unit "Mpc" stands for *megaparsec* and is equivalent to 3.26 million light years. A light year is a unit of distance equivalent to 9.46×10^{12} km.



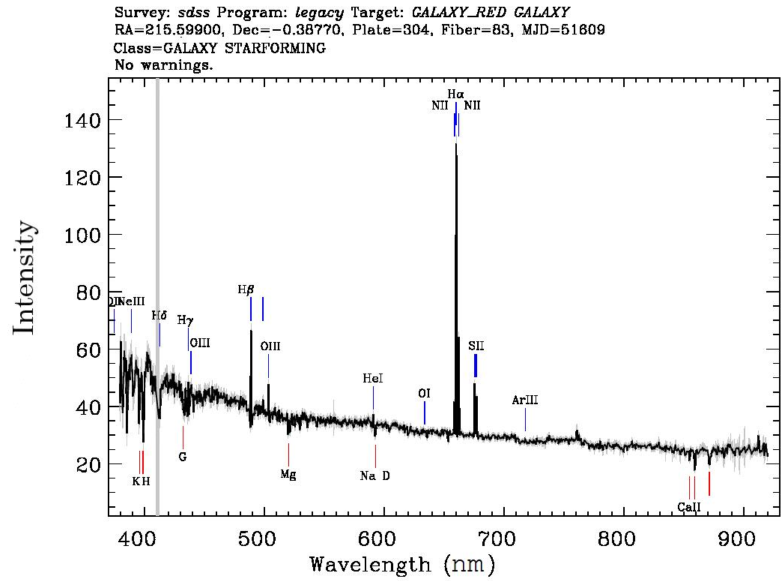
   a. You can convert the Hubble constant to units of $\frac{\frac{km}{s}}{km}$ by first dividing H_0 by the Mpc/light year conversion factor, then dividing by the light year/km conversion factor. What value do you obtain? ***2.2×10^{-18} s^{-1}***

   b. What are the units of this new value for H_0? What would be the units of its reciprocal? ***The units are 1/s or s^{-1} and so the units of the reciprocal are just seconds or s.***

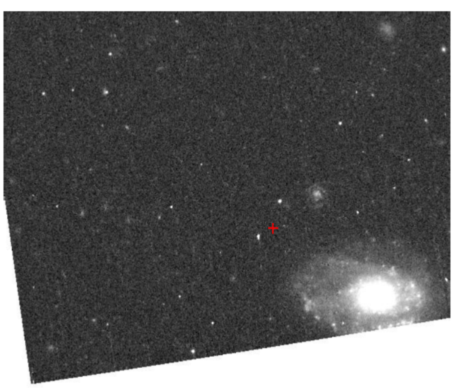
   c. Suppose that at some time long ago, all the galaxies were so close together that they were essentially at the same location. How could we use the Hubble Constant to estimate how long ago this was? ***Since the units of the Hubble constant are just the reciprocal time units, this shows that the Hubble Constant is simply the expansion rate. So the reciprocal would be the time that the universe has been expanding.***

   d. Estimate the age of the universe in units of years, using the Hubble Constant. Compare this value to the "commonly accepted" value of 13.7 billion years. ***Using 68 km/s/Mpc as the Hubble Constant, this is equivalent to 2.2×10^{-18} s^{-1}. The reciprocal of this is 4.5×10^{17} seconds which is (dividing by 60 s, 60 min, 24 hr and 365 d) 14 billion years, fairly close to the accepted value of 13.7 billion years.***

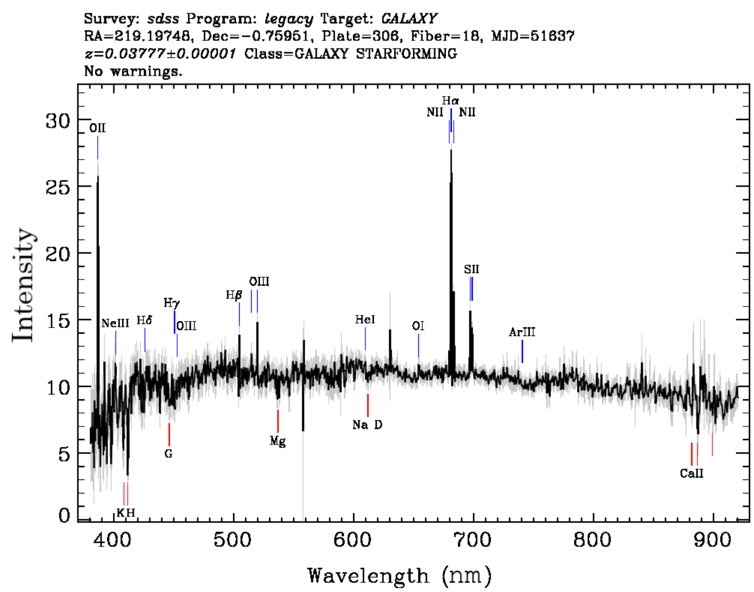
Galaxy A



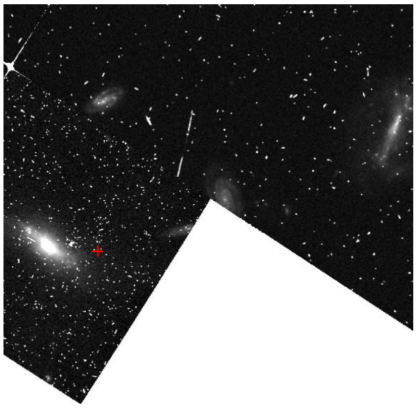
Above: Galaxy A, distance 72 Million Light Years



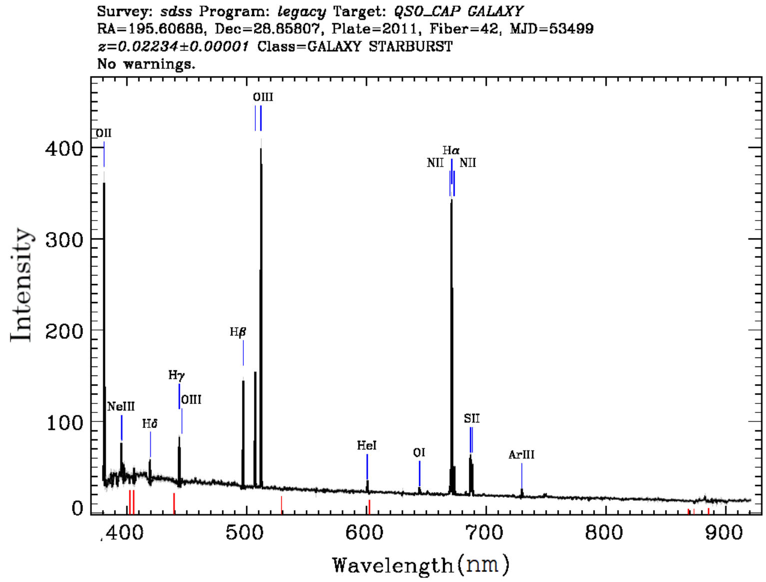
Galaxy B



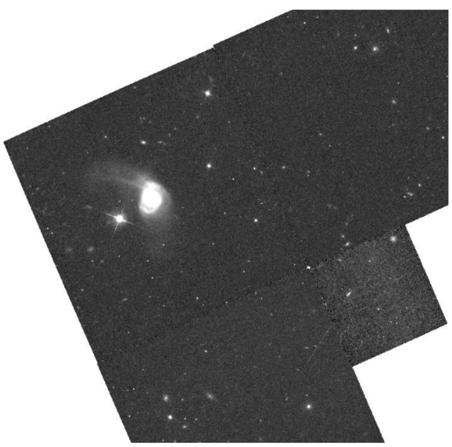
Above: Galaxy B, Distance 557 Million Light Years



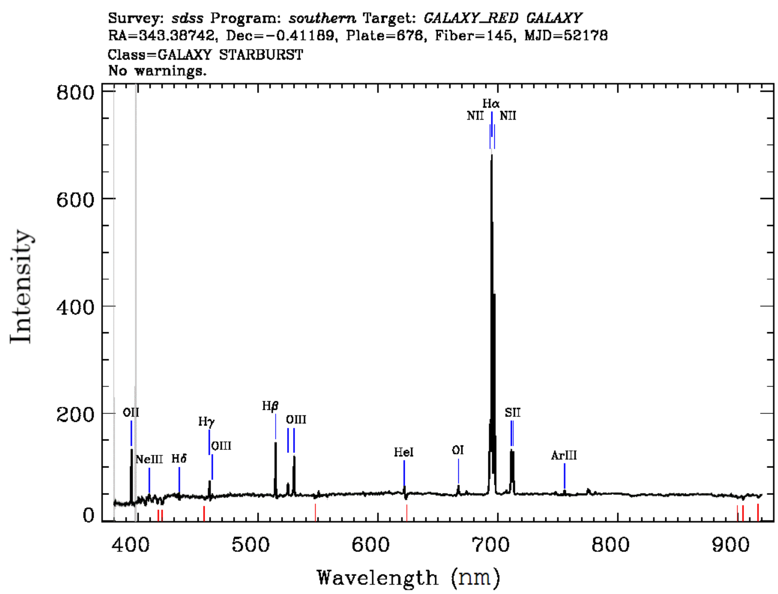
Galaxy C



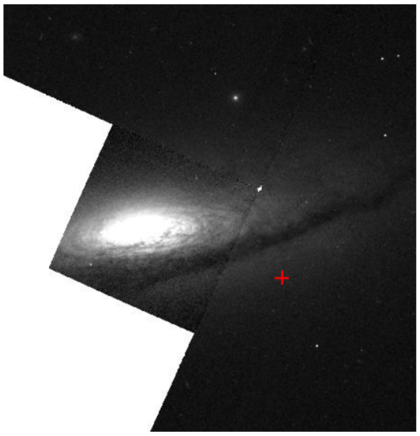
Above: Galaxy C, distance 340 Million Light Years



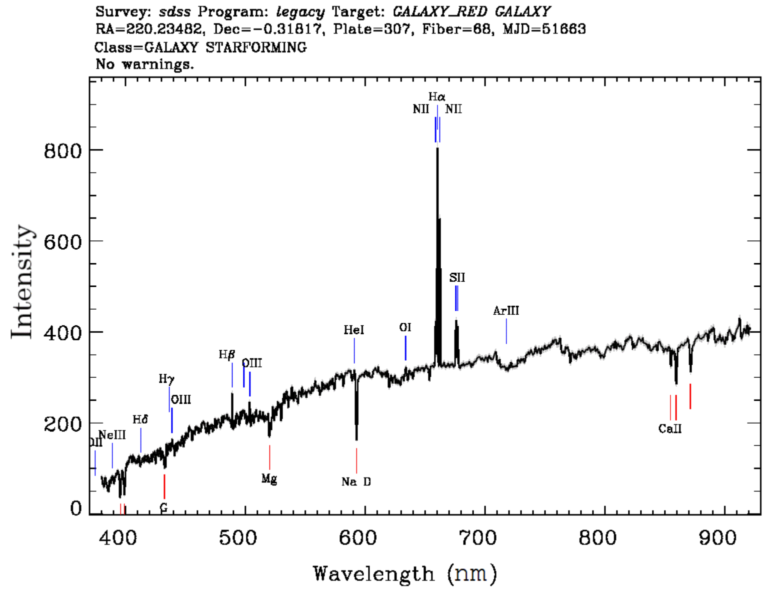
Galaxy D



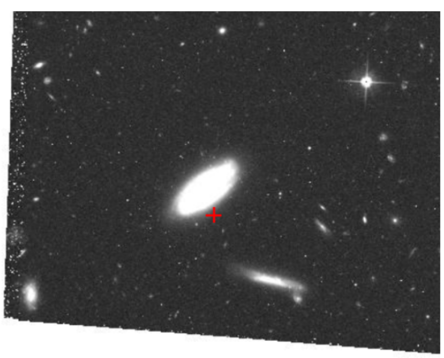
Above: Galaxy D, distance 811 Million Light Years



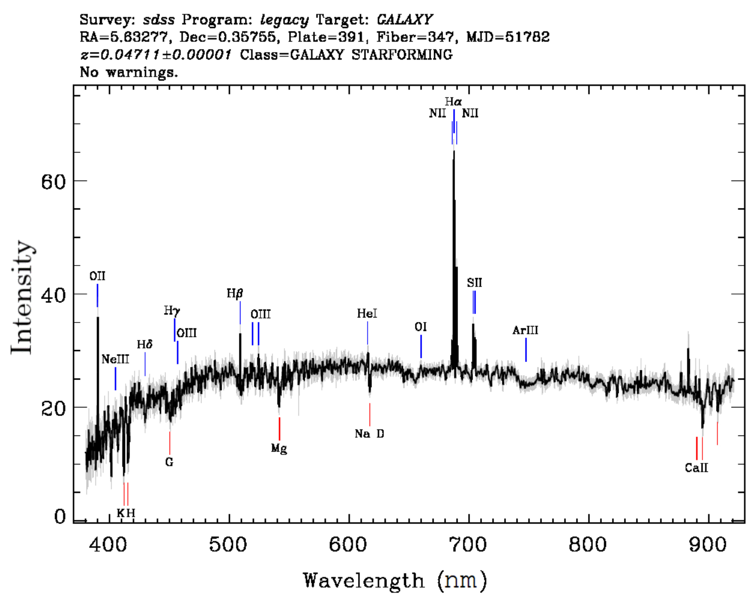
Galaxy E



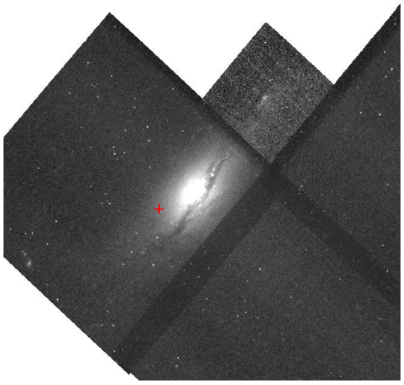
Above: Galaxy E, distance 88 Million Light Years



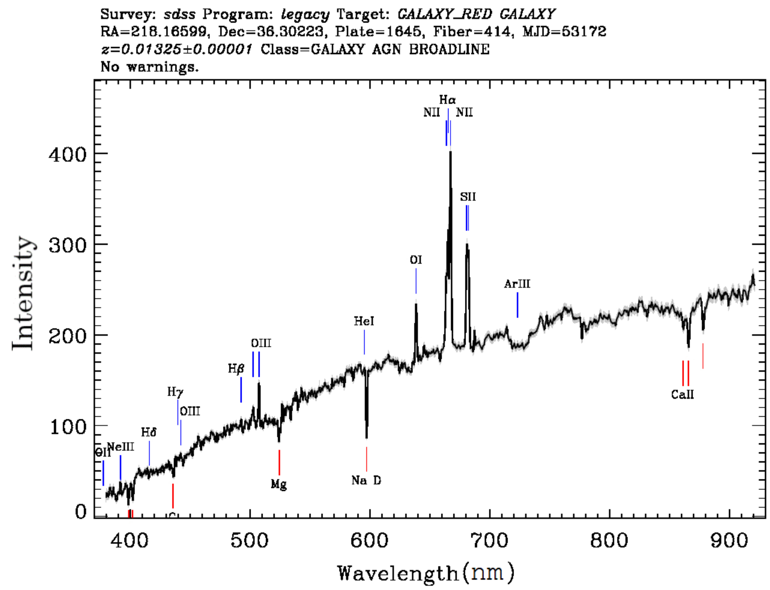
Galaxy F



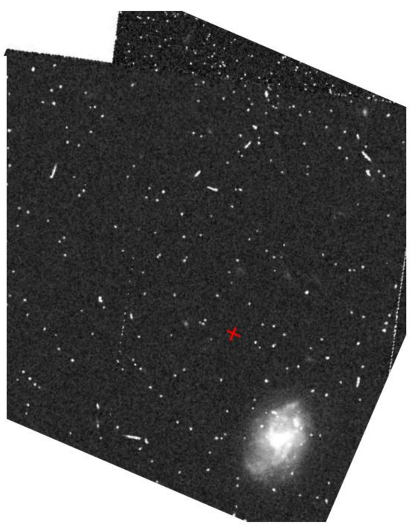
Above: Galaxy F, distance 715 Million Light Years



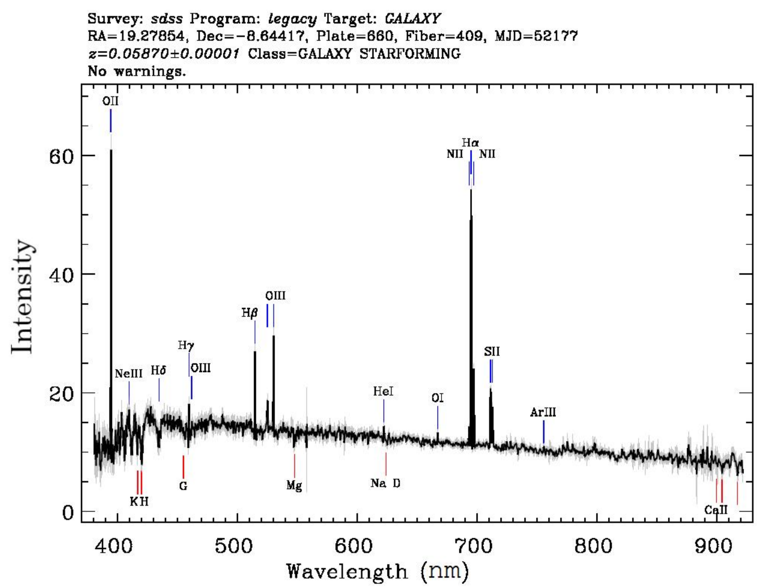
Galaxy G



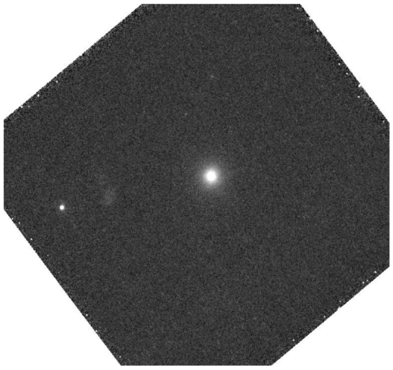
Above: Galaxy G, distance 205 Million Light Years



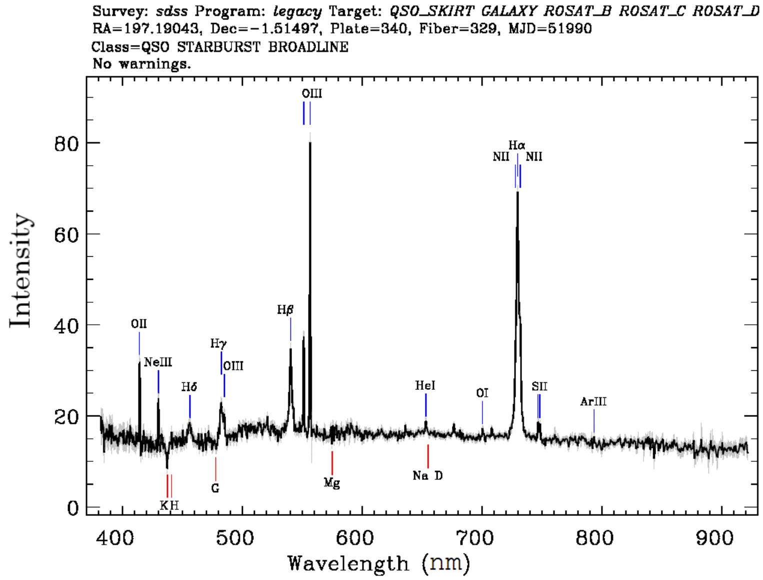
Galaxy H



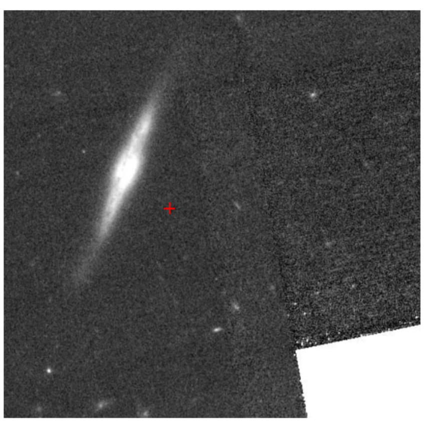
Above: Galaxy H, distance 896 Million Light Years



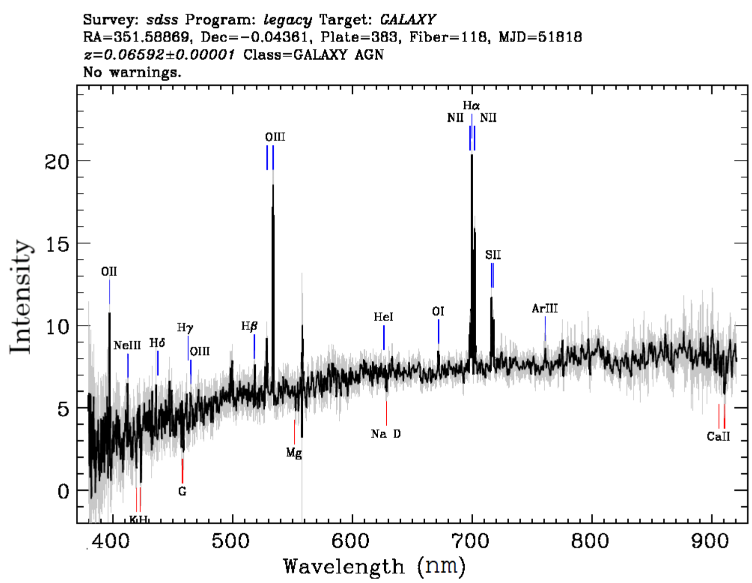
Galaxy I



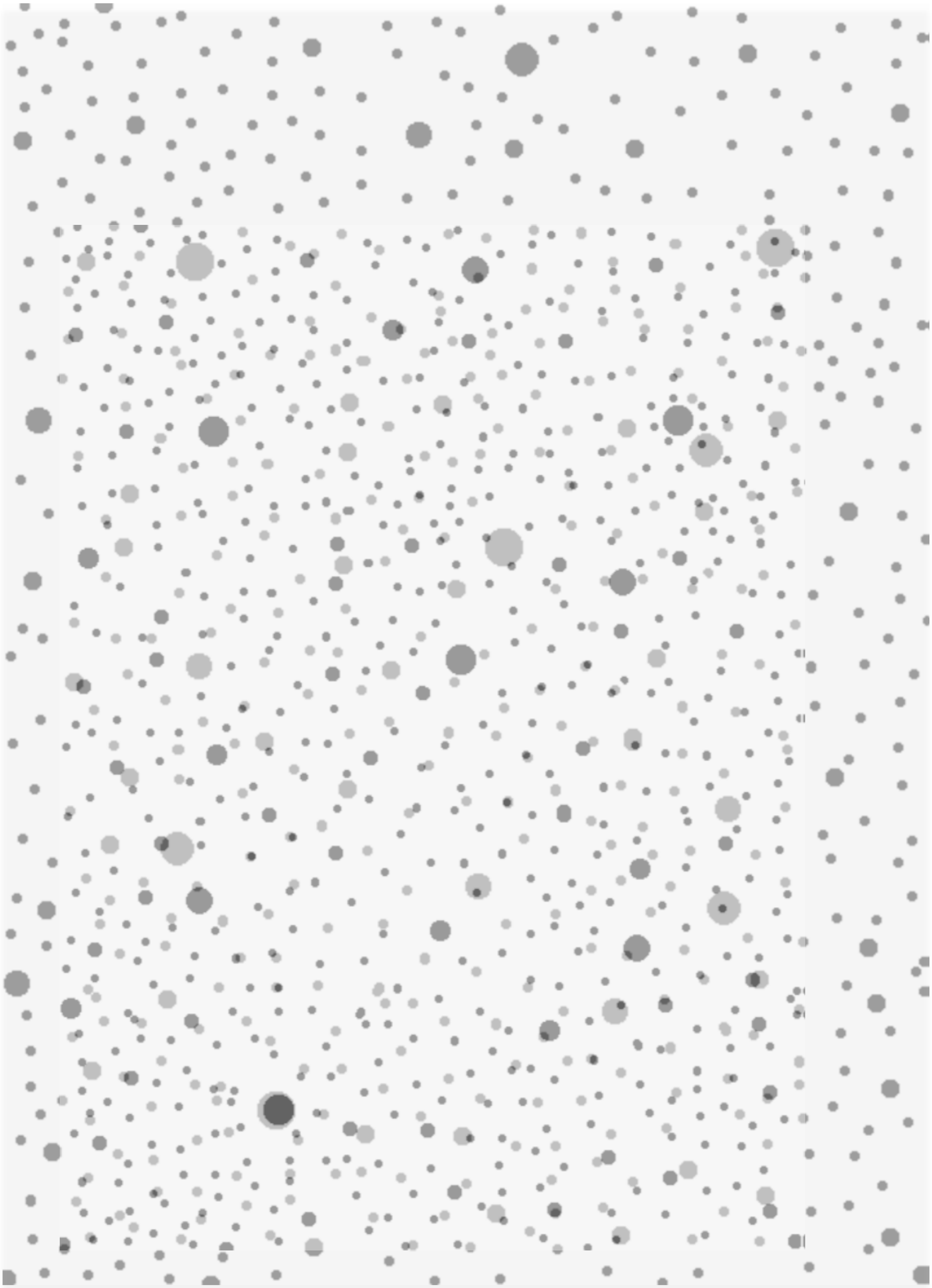
Above: Galaxy I, distance 1526 Million Light Years



Galaxy J



Above: Galaxy J, distance 996 Million Light Years



C. Alternative styles for instructions (3 additional styles)

Style 1: Calculation-heavy and open – No distances provided

1. Below, you are provided with 10 images of galaxies from the Hubble Space Telescope and their spectra. ***Note to teachers: this can be differentiated to a more challenging task by removing the distances, and asking students to use the Cepheid Variable data in the Appendix to calculate distance.***
2. The "redshift" of an object (usually written as ***z***) can be calculated by comparing an expected wavelength λ_e to an observed wavelength λ_o using the following formula:

$$z = \frac{\lambda_e - \lambda_o}{\lambda_e}$$

   You can then convert redshift to a speed, by multiplying by the speed of light c = 299,800,000 m/s.

3. Work with your partner to produce a **graph** that illustrates a relationship between the 10 galaxies provided, and be prepared to explain this relationship using evidence from the data provided. Use the data table below to help organize your findings, and add new column(s) if you need to.

Galaxy		
A		
B		
C		
D		
E		
F		
G		
H		
I		
J		

4. Could this graph be used as evidence to support "Hubble's Law?" (you might need to do a bit of reading about this law) Why or why not?

Style 2: ISLE Framework Approach (courtesy of Dr. Marianne Vanier {JHU} via Dr. Eugenia Etkina {Rutgers}; see e.g. https://www.islephysics.net/isle.php)

1. Below are 10 pictures of galaxies from the Hubble Space Telescope. To the right of each picture is the emission spectrum for the galaxy.
2. With your partners, have a look at the information given for each galaxy and discuss of the similarities and differences among them. Can you observe any obvious patterns? Write your observations on your white board (1 marker color per partner).
3. Choose one partner to stay in place with the white board. The other partners should visit other groups to discuss what they have observed and ask questions.

   Can we, as a class, agree on 1 or 2 patterns that are significant and might lead to something?

4. With your partners, design an investigation. Be sure to consider the following:

- What relationship do you want to investigate?
- What are the steps in your investigation?
- What materials will you need to complete these steps?

5. In order to validate your steps, check and compare the method you intend to use with **2 other groups**.
    - Revise your method if needed.
    - If the 2 teams you consult have the exact same method as yours, try to find a 3rd team who does not.
6. At the front of the classroom, on a cart, you should find what you need to complete your list of materials needed. Ask your instructor if you need additional equipment.
7. Scientific Sharing (Class-Wide)
    - Main question: Did you find a pattern in your data?
    - Pattern between…. And……
    - *Teacher leads each team to share one of their results and ask the other teams if their results agree or disagree.*
    - *If the results disagree, the methods or possible 'mistake' can be discussed… without implying that the result from one team is correct and the result from another team is incorrect.*
    - *The goal of this 'scientific sharing' is to make sure that everyone is more or less at the same level and, for those who are not, to give them a bit of help to catch up.*
8. With your partners, discuss the best way to represent your findings. Once an agreement has been reached, create a representation that you will show to the other teams.
9. The NASA newspaper summarizes important findings made in the 1920s by Edwin Hubble. After reading *what you judge are the most important parts of the article*, **explain in your own words what the Hubble Law is**.
10. The Big Bang model of the universe includes the idea that the universe we live in is expanding. In a paragraph or two, explain how the results of your investigation could be used as **evidence** for an expanding universe. Be sure to cite and explain specific evidence to support your answer.

Style 3: Guided Inquiry (works best with laminated copies of the galaxy spectra)

1. Below are 10 pictures of galaxies from the Hubble Space Telescope. To the right of each picture is the emission spectrum for the galaxy.
2. With a partner, first look at the spectral graphs and try to identify a pattern. Once you agree on a pattern, use this pattern to organize the graphs.
3. For each galaxy spectrum:
    a. Using a dry-erase marker and ruler, draw a vertical line on the graph at wavelength 660 nm (as it appears on the baseline galaxy above). This is the expected wavelength for the Hα emission line.
    b. Still using a dry-erase marker and a ruler, draw a vertical line on the graph at the wavelength where the peak for the observed Hα emission line is.
    c. Measure the difference between the expected wavelength and the observed wavelength for the Hα emission line.
    d. Write this difference in the table below.
    e. Repeat for all the spectra until the chart is completed.

Galaxy	Difference between expected and observed Hα lines (nm)	Distance to galaxies (millions of light years)
A		72
B		557
C		340
D		811
E		88
F		715
G		205
H		896
I		1526
J		996

4. Use the table to make a graph. The difference (separation) between expected and observed Hα lines should be on the X-axis, and the distance should be on the Y-axis.
5. Based on your graph, what is the relationship between the distance to a galaxy and the separation between its Hα expected and observed emission lines?