Modeling the Expanding Universe

Activity H9

Grade Level: 8–12

Source: This activity is produced by the Universe Forum at NASA's Office of Space Science, along with their Structure and Evolution of the Universe (SEU) Education partners. It is a professional development experience for teachers of grades 8 to 12. See: http://www.cfa.harvard.edu/seuforum/mtu/

What's This Activity About?

This is another sequence of activities (like H8) to help students understand the expansion of the universe. It involves activities to help them picture the expansion and others to help them understand how Hubble discovered the pattern of galaxy Doppler shifts that provide evidence for the expansion.

What Will Students Do?

First they use an elastic band with spots to study expansion. Then they watch as two transparencies with galaxies show how expansion proceeds. Next they learn how to use spectra of galaxies to measure the Doppler Shift (or red shift) and graph the velocity of four galaxies against distance to discover Hubble's Law.

Tips and Suggestions

- Both activities H8 and this one are designed to take students step by step over the reasoning that leads us to the notion of the expanding universe and the Big Bang. You may want to look at both of them and decide which sequence is best for your students.
- You may want to consult or give out the background articles on galaxies and the universe from *The Universe at Your Fingertips* disk.

What Will Students Learn?

Concepts

- Expanding universe
- Doppler shift/red shift
- Galaxy spectra

Inquiry Skills

- Exploring
- Modeling
- Measuring
- Describing
- Graphing
- Reasoning
- Visualizing
- Inferring

Big Ideas

- Patterns of change
- Models and simulations
- Evolution

MODELING THE EXPANDING UNIVERSE

Exhibit Connections: Cosmic Calendar, The Big Bang

Goal
 • to visualize a universe expanding in all directions

Materials
This activity has several parts. Materials for each part are listed separately.

Background
Before 1917, many scientists thought the universe always existed. But Einstein's revolutionary theory of gravity changed all the rules. It opened up the mind-boggling possibility that space itself— the permanence of which had never been questioned—might actually be expanding. If space is expanding, the universe we inhabit today could once have been infinitely smaller.

In 1929, astronomer Edwin Hubble made the amazing discovery that distant galaxies are speeding away from us. This means that the galaxies we see today were once much closer together—originating from a tiny region of space.

The origin of the universe remains one of the greatest questions in science. Current scientific evidence supports the Big Bang model, which states that 12 to 15 billion years ago, the entire universe began expanding from a very hot, very dense state. This sudden expansion is known as the Big Bang.

What does it mean to say the universe is expanding? The Big Bang was an expansion of space itself. Every part of space participated in it. Space is not simply emptiness; it's a real, stretch-able, flexible thing. Galaxies are moving away from us because space is expanding. Galaxies are moving *with* space, not *through* space!* The models in this activity demonstrate how the motions of the galaxies reveal the continuing expansion of the universe.

In the 1920s, Edwin Hubble measured the motion of galaxies. By measuring a galaxy's distance from us and how fast that galaxy is receding (its recession velocity), he found a simple relation-ship: double the distance, double the velocity; triple the distance, triple the velocity. This is Hubble's Law. In equation form, it is written:

$$v = H \times d$$
Recession velocity = Hubble's constant x distance from us

The slope of the graph of distance vs. velocity represents the **Hubble Constant** for the universe.

The Hubble Constant describes how fast the universe is expanding. By measuring the rate of expansion, the size and age of the universe can be calculated. Interpreting recent observation-al results from space-borne and ground-based telescopes, scientists have determined different values of Hubble's constant. Determining the precise value of the Hubble constant is key to understanding the origin of the universe, and there are several factors that affect this determi-nation. For example, the universe may not have been expanding at the same rate throughout time; that is, the expansion itself may be accelerating. Questions like these make the age of the universe a hot topic—one of the most controversial in the study of cosmology. The age of the universe is currently estimated to be between 12 and 15 billion years.

* There is also a local motion through space as galaxies interact with their neighbors, but on larger scales, the expansion of space dominates.

Suggestions for Introducing the Activity

Gather students' ideas and questions about the Big Bang. What caused the Big Bang? Was there anything before the Big Bang? What evidence do we have of the Big Bang? When we say the universe is expanding, what exactly is expanding? Students should also discuss models and the inherent flaws of any model.

In this activity, students will be using rulers to measure distances between hypothetical galaxies and using these distances to calculate the velocities of these galaxies. Astronomers do not have rulers in space, but the relationship between distance and velocity means that they can calculate distances by measuring velocities. Astronomers measure the recession velocities by looking at the spectra of the galaxies. This idea is explored further in **Evidence for the Expanding Universe**.

Part 1. Elastic band model–a one-dimensional model

Materials
- Six-foot length of one inch (or greater) wide elastic ribbon, or exercise band or bungee cord
- approximately 1/2-inch round stickers
- stapler
- tape measure
- white board or chalk board

Procedure
- Prepare the model of the universe. Stickers represent galaxies in space. The elastic band represents space.
- Start from the center and place the stickers evenly along the elastic at approximately one-inch intervals. Staple the stickers to keep them from slipping.

- Ask two students to each take an end of the elastic and hold it taut without stretching against the board. On the board, mark the points of the stickers.
- Label one sticker Galaxy A.
- To model the universe expanding, hold Galaxy A still and gradually pull on both ends of the elastic.
- Observe what happens to the distance between the galaxies.
- Measure the distance between the galaxies.
- Now choose a new sticker and label it as Galaxy B. Repeat the process, holding Galaxy B still.

Discussion Notes

Are the galaxies moving away from each other? Is there a center to the expanding universe? Are the galaxies themselves expanding? Is there any pattern to how far apart the galaxies appear to be?

This model shows how galaxies farther away from us appear to be moving faster. That is, the galaxies farthest from the reference galaxy move a greater distance in the same amount of time. Because velocity equals distance divided by time, a larger distance over a constant time corresponds to a higher velocity.

Part 2. Galaxy fields–a two-dimensional model

Materials
- Student Worksheet Galaxy Field A Transparency
- Student Worksheet Galaxy Field B Transparency
- Overhead projector
- transparency markers
- ruler

Procedure
- Project Student Worksheet Galaxy Field A Transparency for everyone to observe. This is a picture of an imaginary field of galaxies taken at one moment in time.
- Lay Student Worksheet Galaxy Field B Transparency over A. Imagine this represents the same galaxy field one second later. Choose one galaxy (it is easier to choose a large dot) and match up Worksheets A and B. It is important to keep the Worksheets square and not rotate either one, as you do this.
- What can you observe about how the other galaxies appear to have moved? (It should look as if all the galaxies are moving away from this point).
- Now choose a different point on Worksheet B to align with Worksheet A. Observe the pattern again. (It should look again as if everything is moving away from this point.)

Discussion Notes
Are we at the center of the universe? Is there a center? Is there an edge? In the universe every galaxy is moving away from every other galaxy. There is no center. From the point of view of any galaxy, that galaxy appears to be the center of the expansion. This observation is similar to observations made by a person in a moving car. Objects outside the car may appear to be moving away, but the person inside the car does not experience the sensation of movement.

Part 3. Measuring the relative motion of galaxies

In this model the imaginary galaxy fields on Student Worksheets Labeled Galaxy Fields 1 and 2 show only a few galaxies. Students will measure the distance the galaxies appear to have moved in one second.

Materials
Each student, or small group of students, should have:
- Student Worksheet Labeled Galaxy Field 1
- Student Worksheet Labeled Galaxy Field 2, copied onto transparency
- Expanding Universe Student Worksheet
- transparency marker
- ruler

Procedure
- Each student chooses a different galaxy and locates it in the galaxy field on Student Worksheet Labeled Galaxy Field 1. Remember, this is just an idealized map. Real galaxies are neither sized this regularly nor spread this regularly throughout the universe.
- Lay Worksheet 2 over Worksheet 1 and align the two using the letter of your galaxy. This simulates one second of universal galaxy motion. Your galaxy should not appear to have moved from the top sheet to the bottom sheet.
- What can you observe about how the other galaxies appear to have moved?
- Use a transparency marker to draw an arrow from each galaxy's position at time 00:00:00 to where it has moved one second later. Record your observations and graph your data on the Expanding Universe Student Worksheet.
- Collect all the copies of the Worksheet 2 transparencies. Pile the transparencies on top of each other. You should notice that students have drawn arrows in different directions for the same galaxy. Is it possible for something to move at different speeds and direction at the same time? Is one set of data right and another wrong?

Discussion Notes
Each student's galaxy seems to be the center of the expansion. The only way this could possibly happen is if space itself is expanding because otherwise an object (such as the Sun or the Earth) would have to be moving in two directions at once. The expansion of space is the only way to reconcile the observation that from Earth everything appears to move away from us. Astronomers assume that we are not in a special place in the universe; that our place in the universe is not different from other places. This assumption is called the Cosmological Principle. It suggests that every other place should observe the expansion just as we do—a situation that would be true if space itself were expanding between the galaxies.
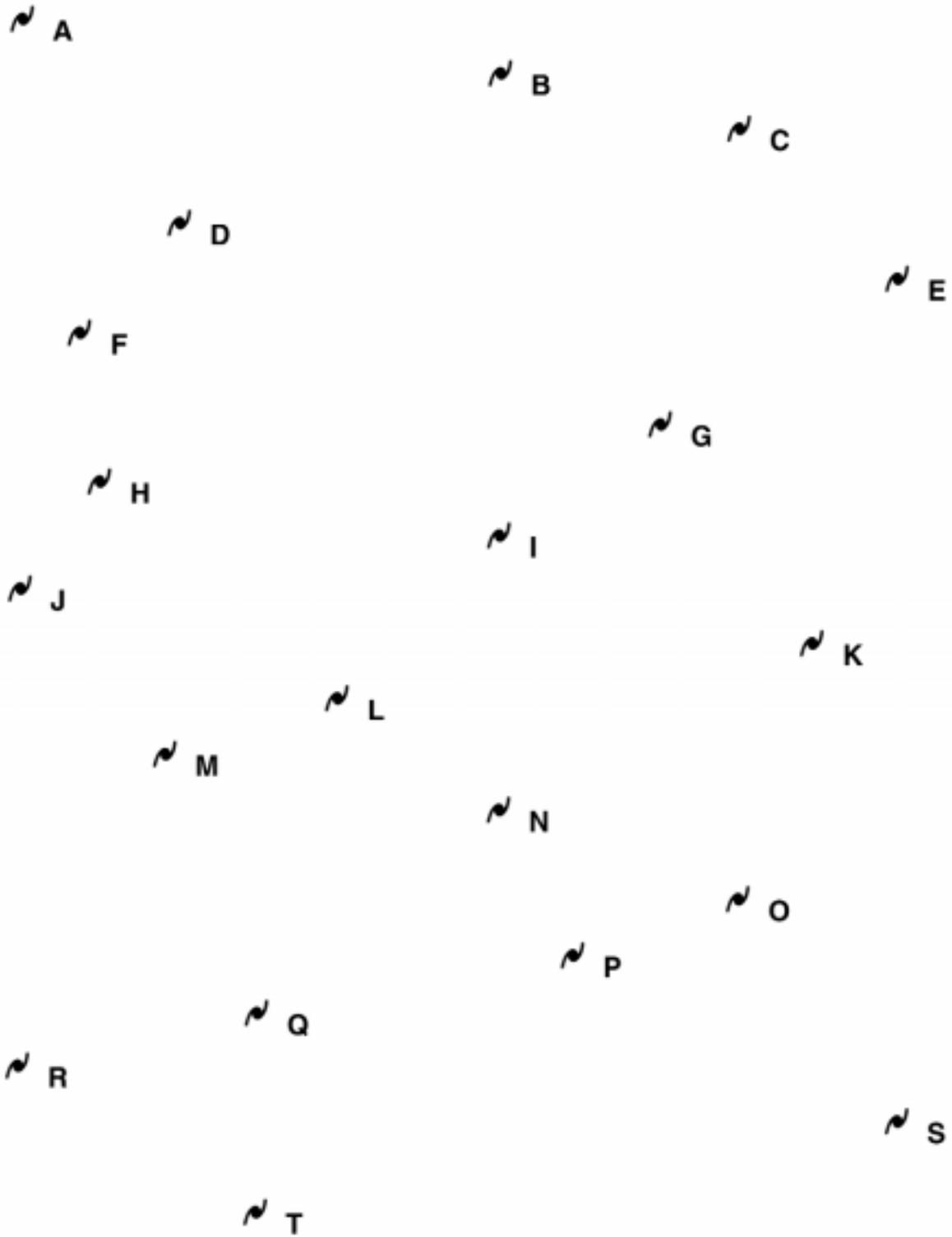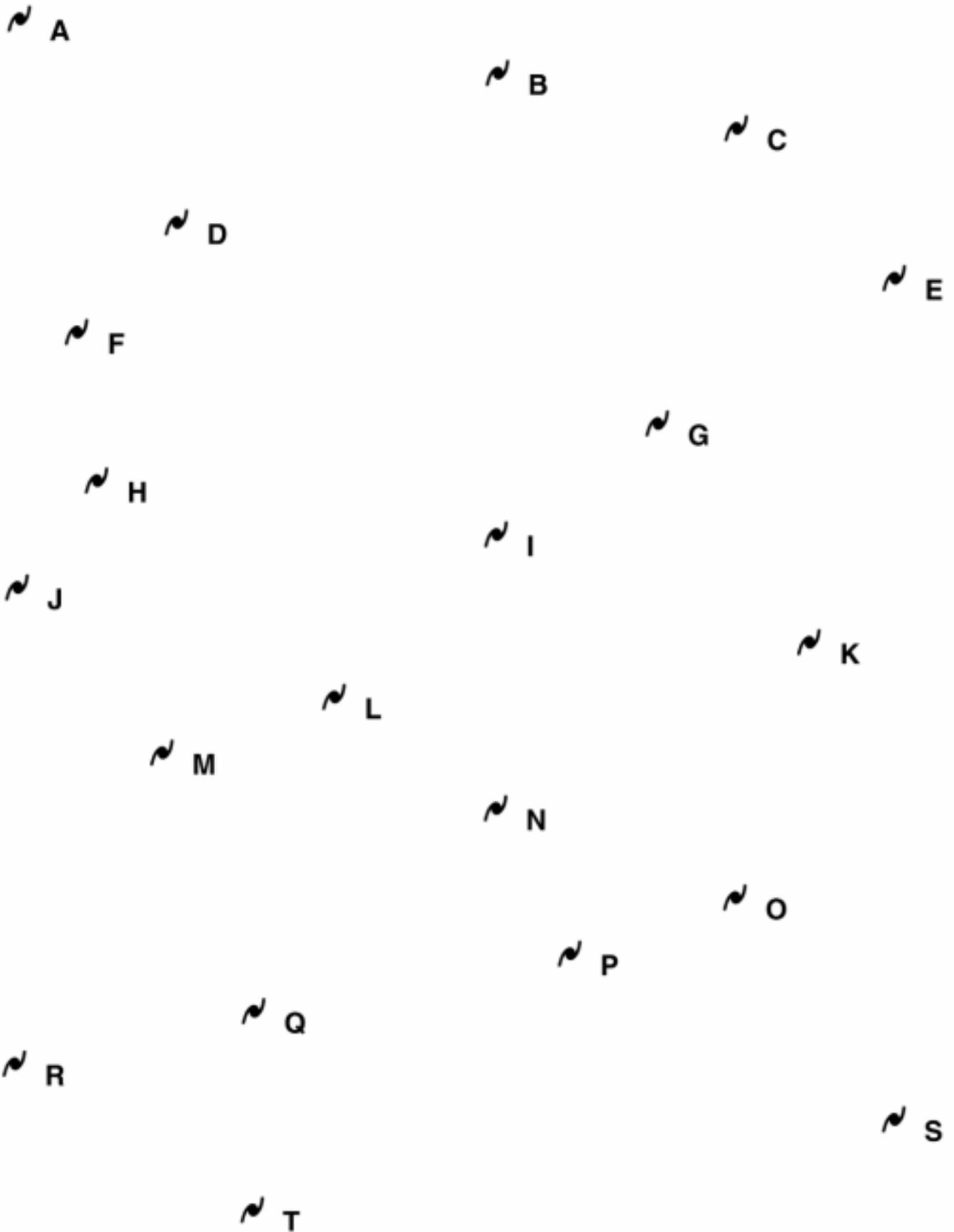
STUDENT WORKSHEET   Galaxy Field A
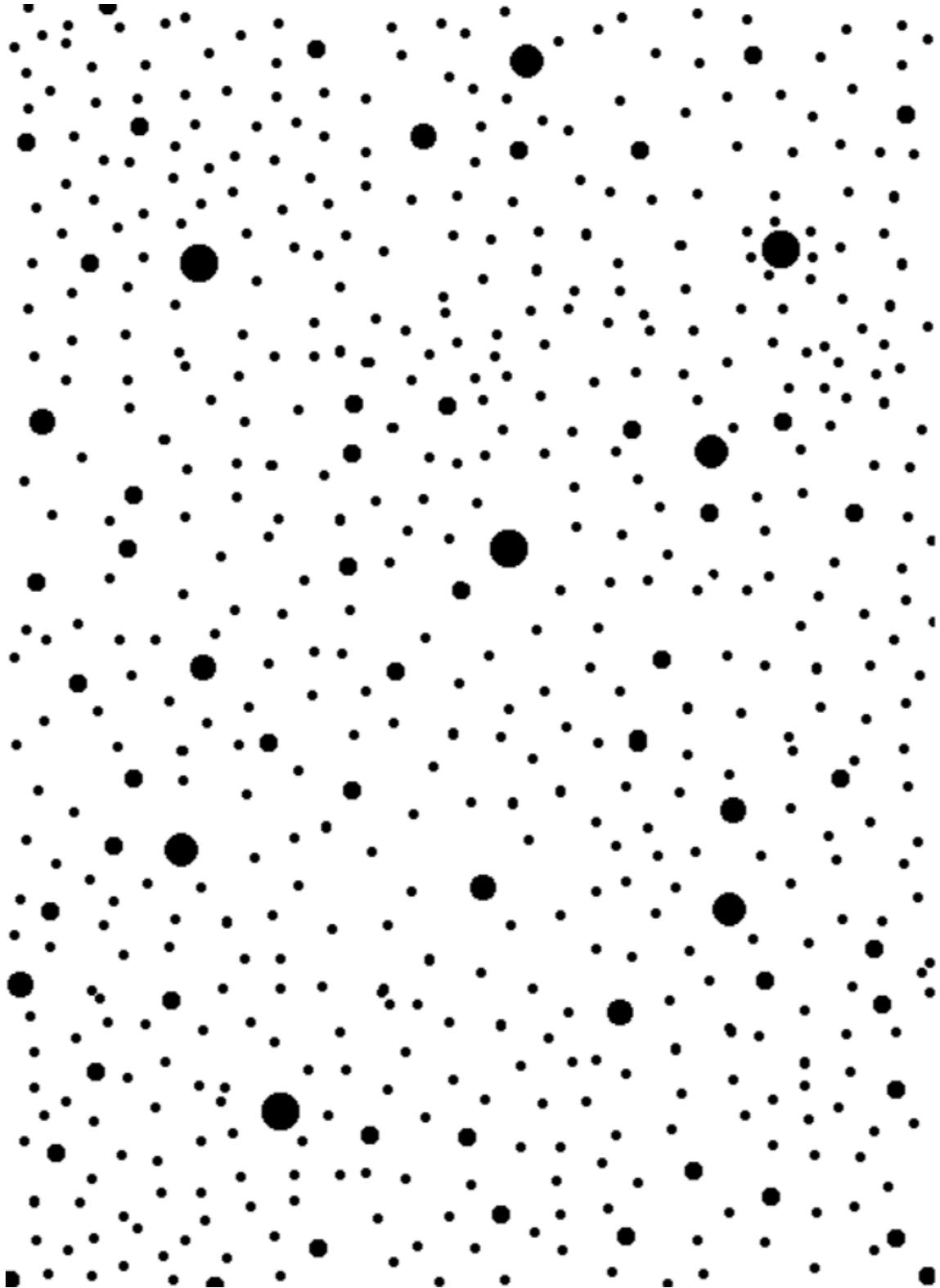
STUDENT WORKSHEET   Labeled Galaxy Field 1
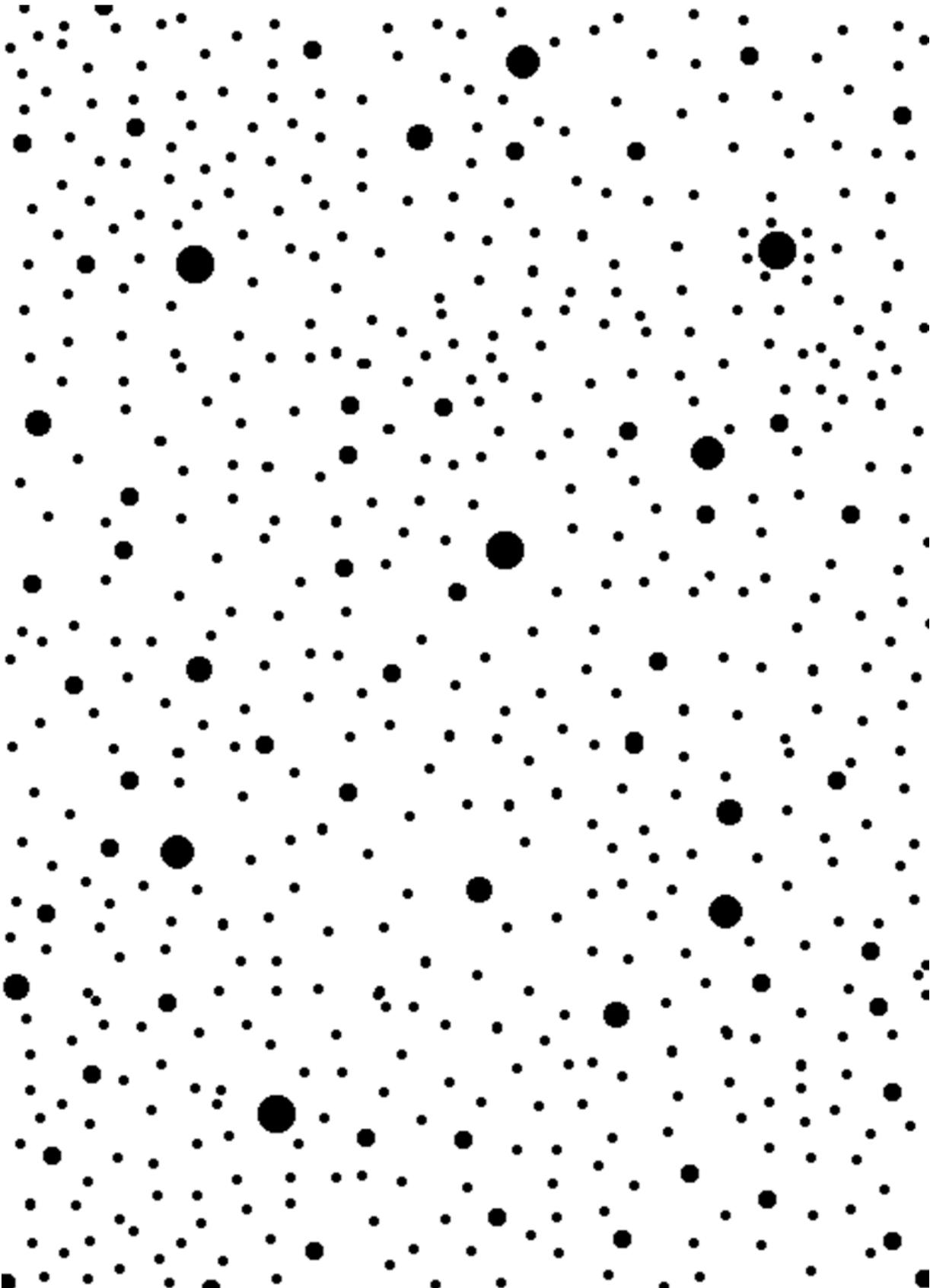
STUDENT WORKSHEET   Labeled Galaxy Field 2

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

STUDENT WORKSHEET Expanding Universe

Choose a galaxy on Labeled Galaxy Field 1. Remember, this is just an idealized map. Real galaxies are neither this regularly sized nor spread regularly throughout the universe.

Lay Labeled Galaxy Field 2 Transparency over Labeled Galaxy Field 1 and align the letters of your galaxy. This simulates one second of universal galaxy motion. Align your galaxy so it does not appear to move from the top sheet to the bottom sheet. (Be careful not to rotate the papers.)

What can you observe about how the other galaxies appear to have moved?

What direction are the galaxies moving?

Have all the galaxies moved the same distance?

Using a colored transparency marker, draw arrows on Worksheet 2 to represent the motion of the other galaxies. The arrow should start at the center of each galaxy on Worksheet 1 and end at the center of that same galaxy on Worksheet 2. The arrows represent the direction and speed, or velocity, of motion of the galaxies throughout the universe.

Record how the length and direction of the galactic arrows change with their position relative to your galaxy.

Graph the relationship between the distance of each galaxy from your chosen galaxy and the length of each arrow.

Length of arrow (cm.)

Distance from your chosen galaxy (cm.)
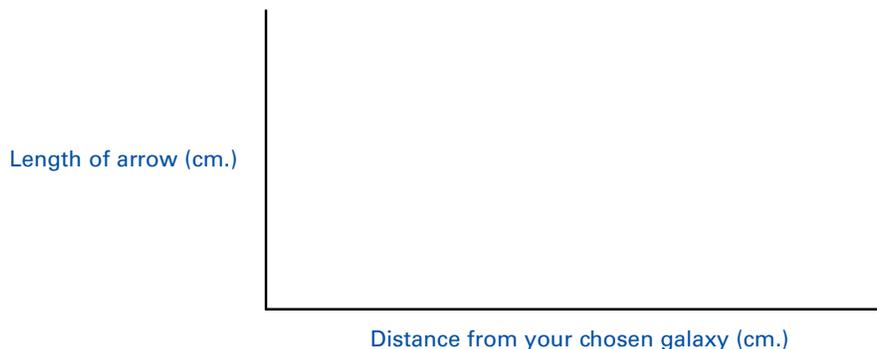
EVIDENCE FOR THE EXPANDING UNIVERSE*

Exhibit Connections: Cosmic Calendar, The Big Bang, Spectra Interactive

Goals
- to become familiar with emission spectra as sources of information
- to use galactic spectra to determine galactic speed

Materials
Each student or small group of students needs a set of student worksheets:

- Looking at Spectra
- Calculating and Graphing Galactic Speed
- Images of Four Galaxies
- Spectra of Galaxies A, B, C, and D

Students should have access to color images of all spectra, including those on the Student Worksheet Looking at Spectra.

Background
The previous activity helps students to visualize a universe expanding in all directions. In this activity, students use astronomical evidence to explore this notion further. How do we know the universe is expanding?

The Big Bang model of the origin of the universe states that the universe originated in a very hot, very dense state 12 to15 billion years ago and has been expanding and cooling ever since. There are three lines of evidence that support this model.

1. We observe that galaxies are moving away from us.

2. We can detect the afterglow from this hot dense state of the early universe. The hot glowing fog that once filled all of space has now cooled to an "invisible" sea of low-energy microwaves (in the radio region of the electromagnetic spectrum). Telescopes sensitive to microwave light detect this afterglow across the entire sky and show that we are bathed in this radiation that dates from when the universe was barely 300,000 years old.

3. Spectroscopic observation of the universe shows its chemical composition to be roughly 75% hydrogen, 25% helium by mass (12 to 1 ratio of hydrogen to helium atoms). The creation of so much helium from hydrogen in nuclear reactions could only have happened if the universe was at some point in time very hot and very dense.

In this activity students examine the first line of evidence, galactic motion. Galaxies are so large, and so far away, that you could never see them move just by looking – even if you looked for a whole lifetime through the most powerful telescope! However, there is a way to detect the motion of a galaxy. By examining the spectrum of light from a galaxy, you can determine whether the galaxy is moving toward or away from us, and how fast. Students will look at optical images of four galaxies. They will then compare the emission spectra from these same four galaxies and measure the wavelength of the red hydrogen line for each galaxy. Because of the Doppler effect, the wavelength will shift as the source travels through space.

Suggestions for Introducing the Activity
Students should already be familiar with the electromagnetic spectrum and understand that atoms emit and absorb light of fixed standard wavelengths. In Part 2, students observe the red-shift of the hydrogen lines in the spectra of galaxies. You may wish to introduce the concept of Doppler shift before completing this activity, or use the activity to motivate a discussion about the relationship between motion and wavelength. For an online tutorial about the Doppler effect, visit cfa-www.harvard.edu/seuforum/galSpeed or www.pbs.org/wgbh/nova/universe/moving.html.

> * This is adapted from an online activity: How Fast Do Galaxies Move? An Interactive Lab. Produced for NASA's Office of Space Science by the Smithsonian Astrophysical Observatory © 2001 Smithsonian Institution. It can be found at: http://cfa-www.harvard.edu/seuforum/galSpeed

Part 1. Looking at Spectra

Atoms emit and absorb light of fixed, standard wavelengths. An emission or absorption spectrum shows a specific pattern of lines that is a kind of "fingerprint," unique to the particular types of molecules. The emission spectrum of glowing hydrogen gas has one bright red line, a fainter blue line, and several other faint lines. The red line for hydrogen has a wavelength of 656 nanometers.

A spectrum of a galaxy is the pattern produced when the light from the galaxy is passed through a prism or similar device. The element hydrogen is the most common element in the universe, and it is plentiful in galaxies. Hydrogen is present in huge clouds of gas that fill some of the space between the stars in a galaxy. The bright red hydrogen line is an easily recognizable feature in many astronomical spectra.

Procedure

- Observe the spectrum of the Sun on the Student Worksheet.
- Observe the spectrum of the fluorescent lamp on the Student Worksheet. Have students record the colors they see and the wavelengths.
- Observe the spectrum of hydrogen gas. Have students record the colors they see and the wavelengths.
- Look again at the spectrum of the Sun and look for dark lines at these recorded wavelengths. Although these absorption lines are not as dramatic as the emission lines in the pure hydrogen spectrum, their presence tells us that the Sun contains hydrogen, and that this hydrogen is absorbing light.
- Observe the spectrum of the sample galaxy on the Student Worksheet. Determine the wavelength of the red hydrogen line in this spectrum. Note that the position of this peak is different from the laboratory sample of hydrogen.
- Discuss why the red hydrogen line would be in a different place.

Part 2. Analyzing Galactic Spectra, Calculating and Graphing Galactic Speed

As students observe the emission spectra from four different galaxies, they will observe that in each spectrum the bright red hydrogen line has shifted from its characteristic wavelength of 656 nanometers, as seen in the laboratory spectrum of hydrogen gas. This shift toward the longer wavelength part of the spectrum, which is the redder end of the spectrum, is called "redshift."

The observed redshift can be used to calculate the galaxy's velocity. The amount of the observed redshift is proportional to the speed of the source (for speeds that are not close to the speed of light). For example, light from a galaxy moving away from us at 10% of the speed of light will be redshifted by 10%. The hydrogen line that was at 656 nanometers will be redshifted by about 65 nanometers to 721 nanometers. (As speeds approach the speed of light, the principles of relativity must be used to explain the relationship between an object's redshift and its speed. However, the speeds of the galaxies in this activity are much less than the speed of light, so the simple proportion described above can be used.)

Using the galactic spectra, students will calculate how fast Galaxies A, B, C, and D are receding from us, and graph that in relation to the galaxy's estimated distance from us.

Procedure

- Give each student or small group of students optical images of the four galaxies, A, B, C, and D.
- Tell students to assume that these four galaxies are all approximately the same actual size.
- Ask students to arrange the four galaxies in order of distance from the earth. Discuss what evidence they used for their choices.
- Label the graph on the student worksheet by writing the letters of the galaxies in order of their estimated distance along the x- axis.
- Give each student or small group of students the spectra of the four galaxies, A, B, C, and D.
- Determine the wavelength of the red hydrogen line in the spectra from galaxies, A, B, C and D. Record these on the worksheet.
- Compare the wavelength of the red hydrogen line in each galactic spectrum to the laboratory sample of hydrogen gas. By how much has the line been shifted? What fraction of the original wavelength is it? At what fraction of the speed of light is the galaxy moving?
- Calculate the recession velocity of the four galaxies using the Student Worksheet.
- Plot the velocity data on the y-axis of the graph on the Student Worksheet.

Discussion Notes

In the 1920s, Edwin Hubble measured redshifts to determine the velocities of galaxies. He found that there was a linear relationship between a galaxy's distance from us and how fast that galaxy is receding (its recession velocity). This simple relationship can be described in equation form, where the slope of the graph of distance vs. velocity represents the Hubble Constant for the universe.

$$v = H \times d$$

Recession velocity = Hubble's constant x distance from us

This equation, known as Hubble's Law, states that a galaxy at double the distance will have double the velocity; at triple the distance, it will have triple the velocity. Hubble's Law is important in understanding the age and size of the universe, and is described further in the background information for the previous activity, Modeling the Expanding Universe.

Suggested Answers

These notes provide answers to some of the questions on the Student Worksheets and can be used to help guide a class discussion.

In Part 1, when looking at the pure hydrogen spectrum, students should measure peaks at 656 nanometers, 486 nanometers, and 434 nanometers. Although this third line is not visible in the color image, it can be measured on the graph. All three of these lines appear in the spectrum of the Sun and may be easier to find in the graph than in the color image.

In Part 2, we have assumed all the galaxies are all the same actual size. Therefore, Galaxy B, which appears largest in the optical image, is presumed to be closest to us. Accordingly, the smallest image (C) is farthest away. In order from closest to farthest, the galaxies are B, D, A, and then C.

Galaxy B is about 210 Mly (million light years) from the Milky Way.

Spectrum B shows the hydrogen line at 666 nanometers. This is redshifted 10 nanometers, or 1.5 %, from its original location of 656 nanometers. Therefore, the velocity of Galaxy B is 0.015 times the speed of light (300,000 km/s), which equals about 4,500 km/s. Students may measure the redshift to be between 5 and 13 nanometers, which corresponds to a recession velocity between 4,350km/s and 6,000 km/s.

Astronomers calculate the recession velocity of Galaxy B to be 4350 km/s.

Galaxy D is about 750 Mly from the Milky Way.

Spectrum D shows the hydrogen line at 690 nanometers. This is redshifted 34 nanometers, or 5 %, from its original location of 656 nanometers. Therefore, the velocity of Galaxy D is 0.05 times the speed of light (300,000 km/s), which equals about 15,000 km/s. Students may measure the redshift to be between 29 and 39 nanometers, which corresponds to a recession velocity between 13,000 km/s and 18,000 km/s.

Astronomers calculate the recession velocity of Galaxy D to be 15,400 km/s.

Galaxy A is about 1,520 Mly from the Milky Way.

Spectrum A shows the hydrogen line at 724 nanometers. This is redshifted 68 nanometers, or 10 %, from its original location of 656 nanometers. Therefore, the velocity of Galaxy A is 0.10 times the speed of light (300,000 km/s), which equals about 30,000 km/s. Students may measure the redshift to be between 65 and 73 nanometers, which corresponds to a recession velocity between 29,000 km/s and 34,000 km/s.

Astronomers calculate the recession velocity of Galaxy A to be 31,400 km/s.

Galaxy C is about 2,260 Mly from the Milky Way.

Spectrum C shows the hydrogen line at 752 nanometers. This is redshifted 96 nanometers, or 15 %, from its original location of 656 nanometers. Therefore, the velocity of Galaxy C is 0.15 times the speed of light (300,000 km/s), which equals about 45,000 km/s. Students may measure the redshift to be between 94 and 102 nanometers, which corresponds to a recession velocity between 42,000 km/s and 47,000 km/s.
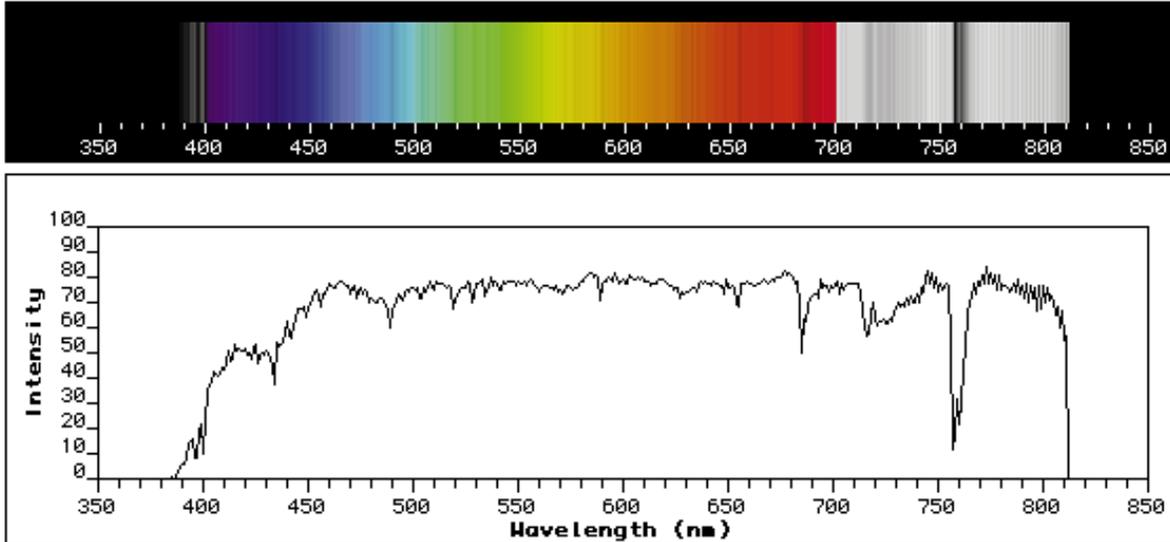
Astronomers calculate the recession velocity of Galaxy C to be 44,700 km/s.

Sample Graph

Galaxy Distance vs. Speed
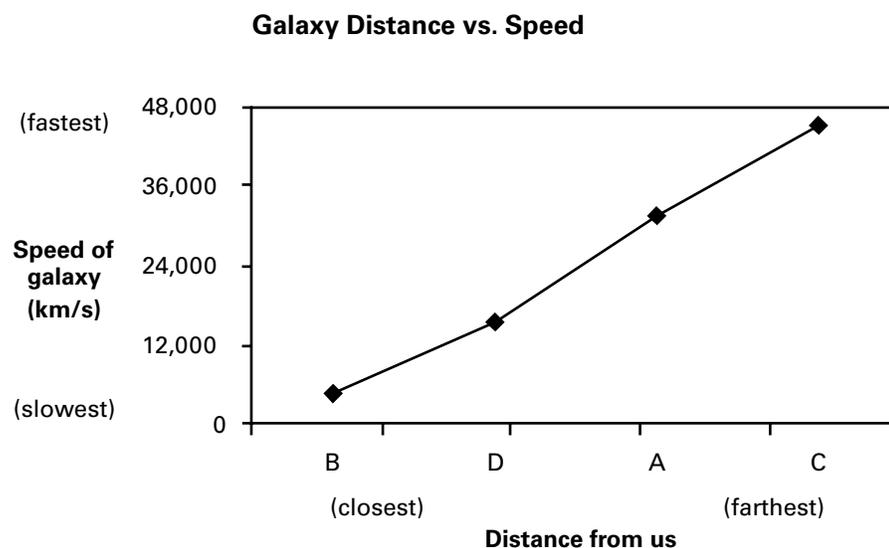
STUDENT WORKSHEET   Looking at Spectra

The Sun

This is the spectrum of the Sun. The pattern is created by passing light from the Sun through a glass prism, which separates the light into its component colors. In addition to the familiar rainbow of colors, notice the dark lines. These lines are produced by atoms in the Sun's atmosphere that absorb certain wavelengths of light. This dark-line pattern is called an absorption spectrum. Note that the pattern extends past the red, into the infrared region. Infrared light is not visible to our eyes. It is colored grey in this image. The grey area to the left of the blue is part of the ultraviolet region of the spectrum.

Fluorescent Lamp
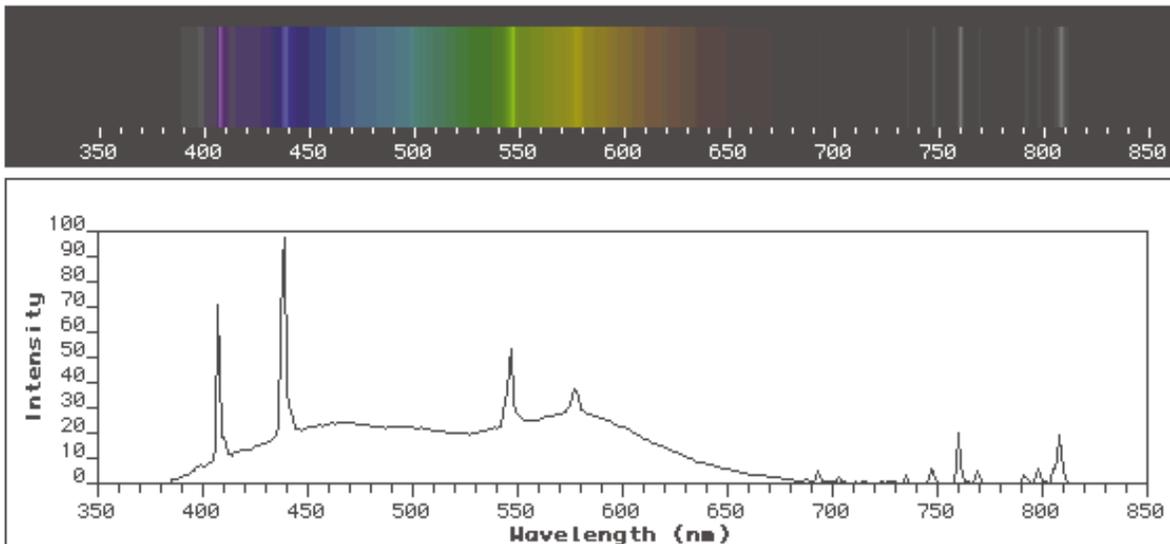
This is the spectrum of a Fluorescent Lamp. Instead of a complete rainbow, we see only certain colors of light. This bright-line pattern is called an emission spectrum. We don't see a full rainbow because rainbows are produced only by light sources that are very hot.

What colors do you see in the Fluorescent Lamp spectrum, and what are their wavelengths?

STUDENT WORKSHEET Looking at Spectra (continued)
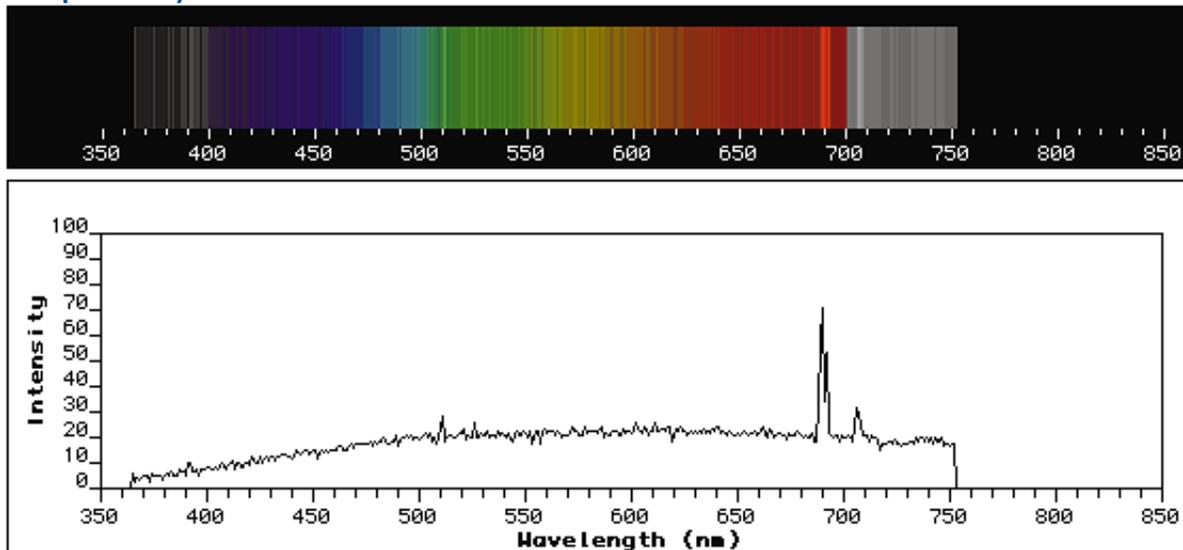
Hydrogen Gas
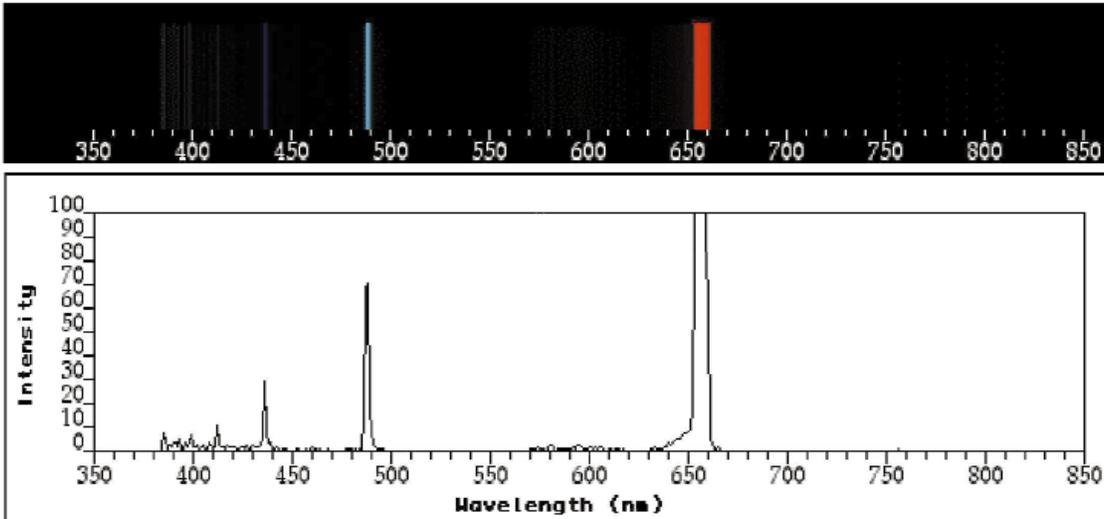
This is the emission spectrum of the element hydrogen. Hydrogen is the simplest chemical element. The pattern was produced by taking the light from a glowing tube of hydrogen gas, and passing the light through a prism.

What colors do you see in the hydrogen spectrum, and what are their wavelengths?

Look for lines at these same wavelengths in the spectrum of the Sun. Which lines can you see?

Sample Galaxy

This is the spectrum of a galaxy. The pattern was produced when the light from this distant galaxy was passed through a device similar to a prism. In addition to the rainbow, there is a bright red line. This line comes from the element hydrogen. Determine the wavelength of the red hydrogen line in the spectrum of the sample galaxy. The peak has been shifted from its characteristic wavelength (as measured above in the hydrogen spectrum) toward the longer wavelength part of the spectrum, which is the redder end of the spectrum. This phenomenon is called a "redshift."

In the sample galaxy, the red hydrogen peak is at _____ nanometers.

STUDENT WORKSHEET Calculating and Graphing Galactic Speed

Look at the optical images of the four galaxies A, B, C, and D. These galaxies, are all approximately the same actual size. Which galaxy do you think is closest to us? Farthest?

_____   _____   _____   _____

Closest   farthest

What evidence did you use in these choices?

Label the x-axis of the graph on page 2 with the letter of the galaxies, in order from closest to farthest.

Look at the spectra of the four galaxies A, B, C, and D. Determine the wavelength of the red hydrogen line in each spectra.

Galaxy A: _____ nanometers   Galaxy B: _____ nanometers

Galaxy C: _____ nanometers   Galaxy D: _____ nanometers

The observed redshift is proportional to the speed of the source (for speeds that are not close to the speed of light). For example, for a galaxy moving away from us at 10% of the speed of light, the light will be redshifted by 10%. The hydrogen line that was at 656 nanometers in the laboratory sample of hydrogen gas will be redshifted by about 65 nanometers, and will be observed at 721 nanometers.

By how much has the red hydrogen line been shifted in the spectra of galaxies A, B, C, and D? What fraction of the original wavelength is this? At what fraction of the speed of light is the galaxy moving?

Galaxy A: redshifted _____ nanometers =_____ %   Galaxy B redshifted _____ nanometers =_____ %

Galaxy C: redshifted _____ nanometers =_____ %   Galaxy D redshifted _____ nanometers =_____ %

Calculate the speed of each galaxy as it is receding from us, using the percentages from your answer above. The speed of light is approximately 300,000 kilometers per second (186,000 miles per second).
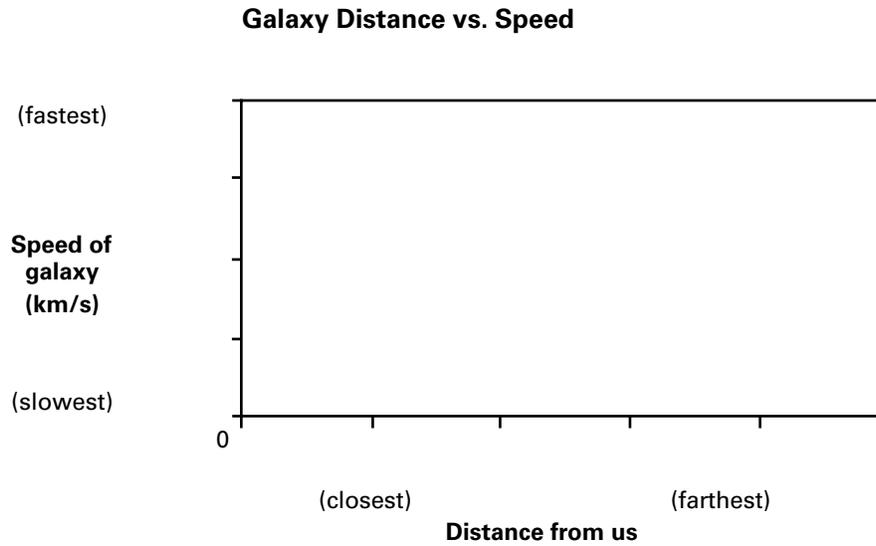
Galaxy A: _____ % x 300,000 km/s = _____   Galaxy B: _____ % x 300,000 km/s = _____

Galaxy C: _____ % x 300,000 km/s = _____   Galaxy D: _____ % x 300,000 km/s = _____

Plot the speeds of Galaxies A, B, C and D on the y-axis of the graph.
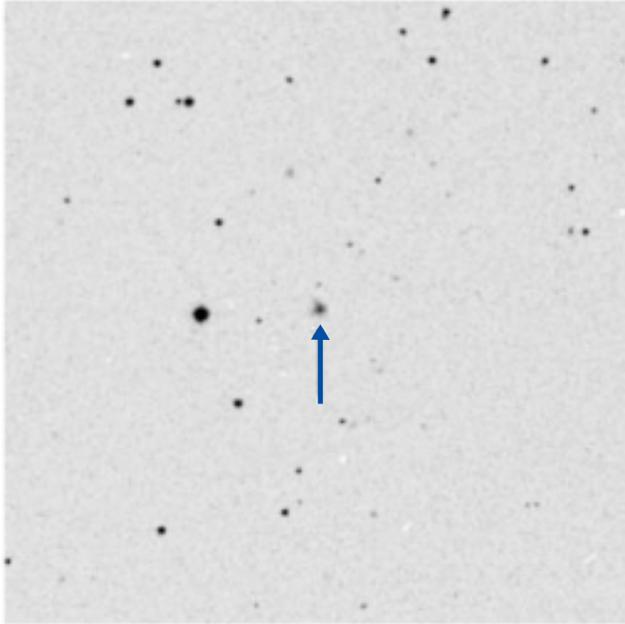
Galaxy Distance vs. Speed

What can you conclude about the relationship between galaxy distance and redshift?
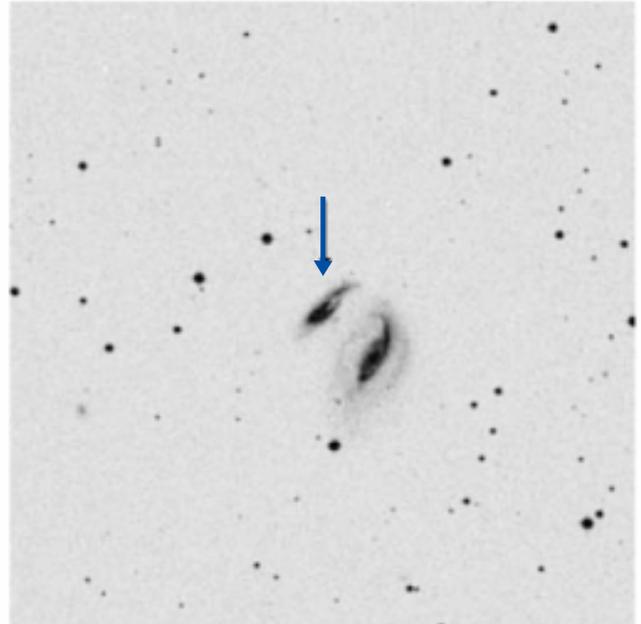
How does this evidence support the theory of an expanding universe?
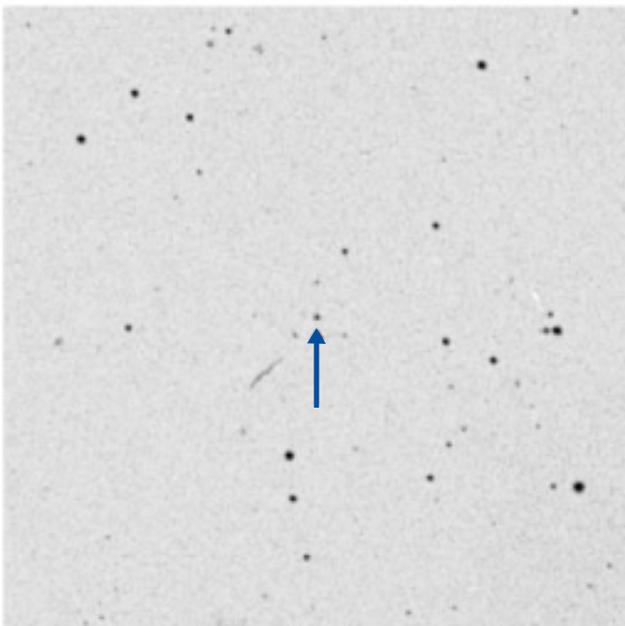
STUDENT WORKSHEET   Images of Four Galaxies
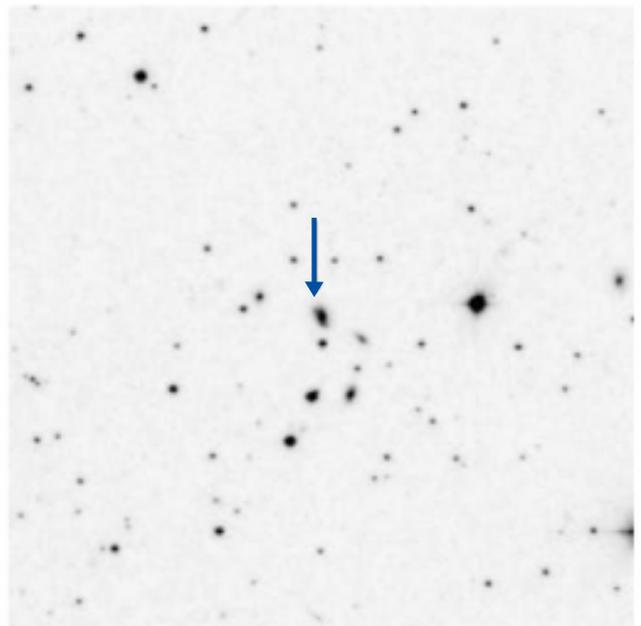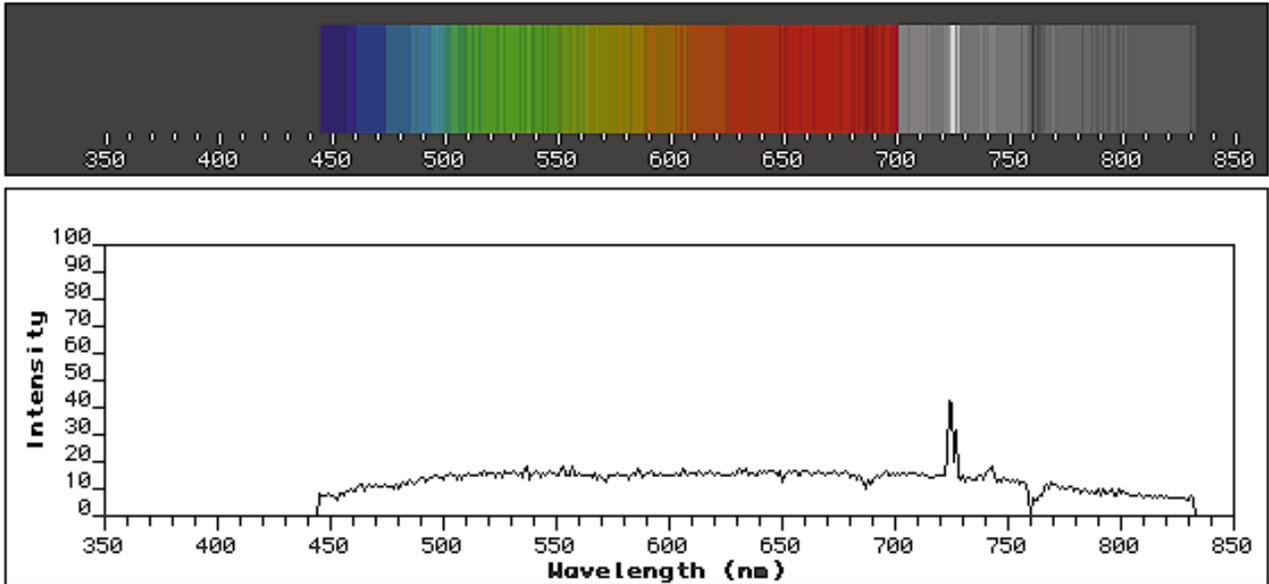
Galaxy A

Galaxy B

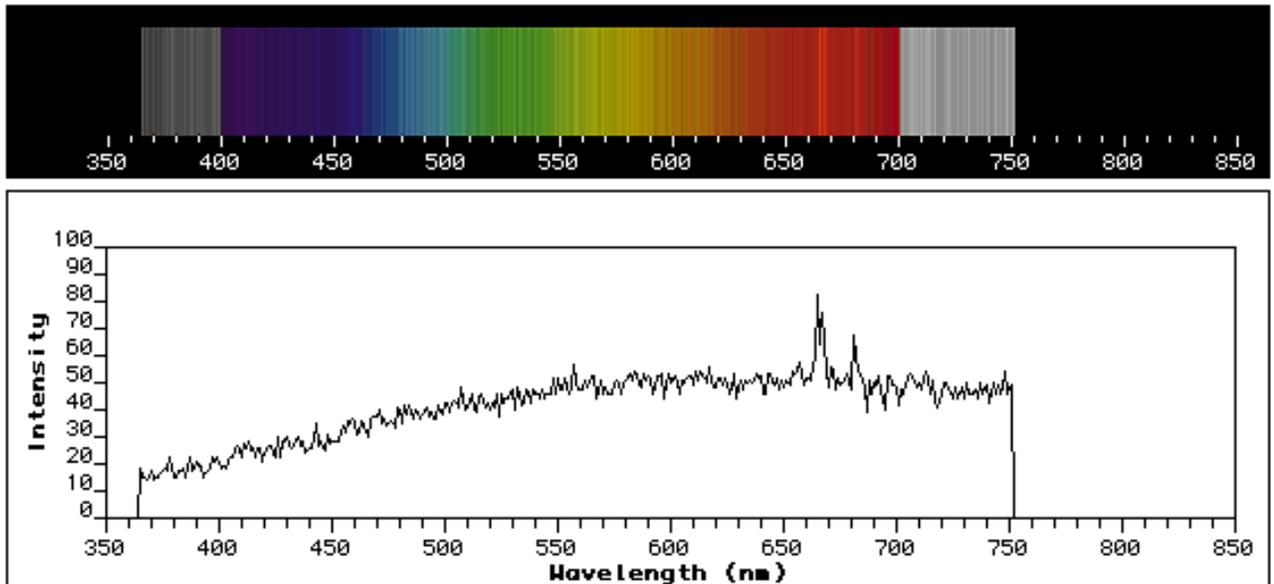**Galaxy C**

Galaxy D

STUDENT WORKSHEET   Spectra of Galaxies A and B
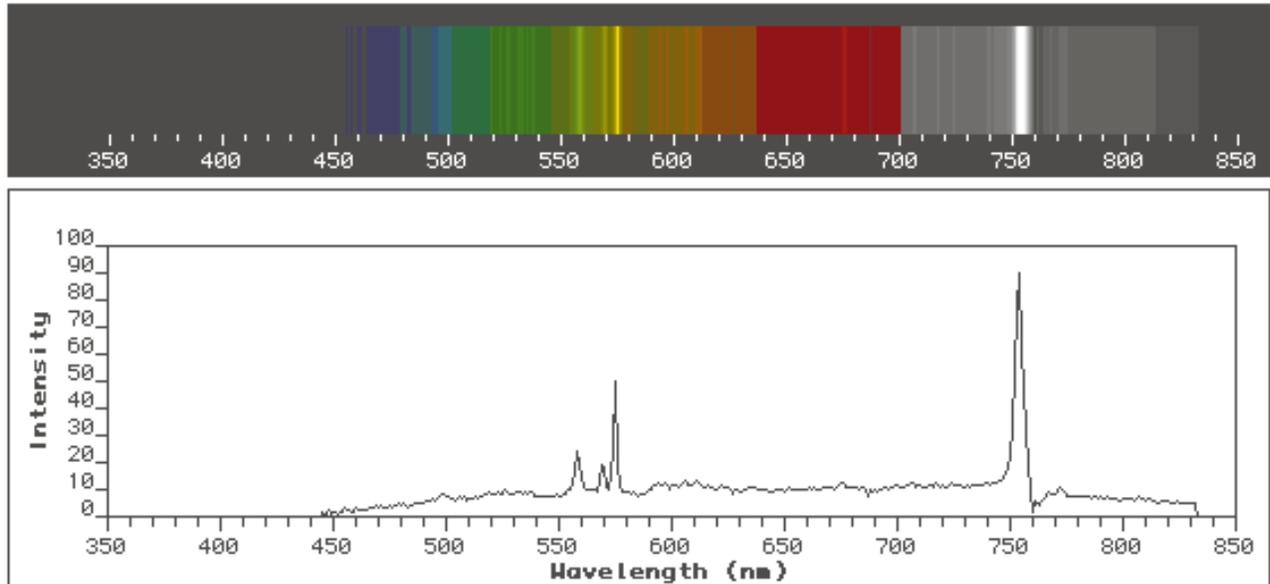
Spectrum of Galaxy A

Spectrum of Galaxy B

Galaxy data courtesy of Emilio Falco, Center for Astrophysics

STUDENT WORKSHEET   Spectra of Galaxies C and D

Spectrum of Galaxy C

Spectrum of Galaxy D