Hubble's Evidence for the Big Bang | Instructor Guide

Students will explore data from real galaxies to assemble evidence for the expansion of the Universe.

Prerequisites

- Light spectra, including graphs of intensity vs. wavelength.
- Linear (y vs x) graphs and slope.
- Basic measurement statistics, like mean and standard deviation.

Resources for Review

- Doppler Shift

Overview

- Students will consider what the velocity vs. distance graph should look like for 3 different types of universes - a static universe, a universe with random motion, and an expanding universe.
- In an online interactive environment, students will collect evidence by:
  - using actual spectral data to calculate the recession velocities of the galaxies
  - using a "standard ruler" approach to estimate distances to the galaxies
- After they have collected the data, students will plot the galaxy velocities and distances to determine what type of model Universe is supported by their data.

Grade Level: 9-12

Suggested Time

One or two 50-minute class periods

Multimedia Resources

- Hubble and the Big Bang WorldWide Telescope Interactive

Materials

- Activity sheet - Hubble's Evidence for the Big Bang

Lesson Plan

The following represents one manner in which the materials could be organized into a lesson:

Focus Question:
- How does characterizing how galaxies move today tell us about the history of our Universe?

Learning Objective:
- SWBAT collect and graph velocity and distance data for a set of galaxies, and argue that their data set provides evidence for the Big Bang theory of an expanding Universe.

Activity Outline:
1. **Engage**
    a. Invite students to share their ideas about these questions:
        i. Where did the Universe come from?
        ii. Has it always been like it is today?
        iii. What evidence do scientists have about our Universe's history?

    b. Share and discuss past ideas about how galaxies in the Universe move.
        i. Galaxies appear as fuzzy blobs in the sky. 100 years ago, astronomers had a debate about whether these objects were part of our own galaxy, or whether they were far away "island universes." The debate was resolved after astronomer Henrietta Leavitt discovered an important property of Cepheid variable stars, which provided proof that the "island universes" (now known as galaxies) are much farther away than anything we knew about before. At first, scientists (including Albert Einstein) commonly assumed that the Universe was static, and that galaxies don't move.
        ii. Around the same time, an American astronomer named Vesto Slipher made spectral measurements of the light from galaxies and noticed that the light is doppler-shifted, showing that the galaxies are moving, not static. More of the galaxies he observed were moving away from us than towards us, but other than that, there was no particular pattern to his measurements.
        iii. Also during this time, physicists Alexander Friedmann and Georges Lemaitre independently used Einstein's theory of relativity to show that the Universe might be expanding.

c. Edwin Hubble used Cepheid variable stars to measure distances to galaxies and combined his data with Slipher's measurements of galaxy velocities, plotting their velocities vs. distance on a graph.

d. Let's consider what a velocity vs. distance graph might look like for the scenarios we discussed. Before we jump to galaxies, we can look at more concrete examples to help students better understand what is happening in each situation. Hand out the activity sheets and have students work on the 1st page (velocity vs. distance plots) in a think-pair-share.
   i. Analogy for a static universe: You are standing still in a park with 5 trees. Sketch a graph of velocity vs. distance for the trees relative to you.
   ii. Analogy for a universe with random motion: You are at a shopping mall with 5 friends. You are waiting in a sitting area while the others shop at different stores. Graph the velocity vs. distance for your friends relative to you.
   iii. Analogy for an expanding universe: You and 5 other people are standing close together in a line. Imagine that the people in front of you start running a race, but each person in the line runs faster than the person behind them.
      1. After they have been running for a while, graph the velocity vs. distance for the runners at a particular moment, relative to you.
      2. At this moment, what does the line of runners look like compared to at the start of the race?

e. Review as a class what each type of graph should look like (see answer key).

f. Now let's return to the galaxies. In this activity, students will need to measure velocity and distance to the galaxies. You can ask students for their ideas on how to do this.

Prepare students for collecting data in the interactive by reviewing these methods:

g. Velocities: You could make an analogy to a firetruck passing by. As it moves toward you, the pitch of the siren is higher (like a blueshift), and as it moves away from you, the pitch of the siren is lower (like a redshift). If you know the pitch of the firetruck siren when it is still, you will be able to use the pitch of the truck as it is driving to determine how fast it is moving toward or away from you. In the same way, we can use the wavelength of light to measure the speed of the galaxies. (Note that the Doppler shift tells us how fast the object is moving towards or away from us, and does not tell us anything about its side-to-side movement).

i. Atoms absorb and emit light at very specific wavelengths. For example, hydrogen atoms at rest emit light at a series of wavelengths, including what's known as an H-α line at 656.3 nm. (nm stands for "nanometer," which is 1 billion times smaller than a meter).

ii. Astronomers can identify H-α and other lines in a spectrum. If they appear at longer (redder) wavelengths than they do when the object is at rest, that means the object is moving away from us. If they appear at shorter (bluer) wavelengths, that means the object is moving toward us.

iii. To calculate the velocity, use the formula:

$$v = c\left(\frac{\lambda_{\rm obs}}{\lambda_{\rm rest}} - 1\right)$$

v is the galaxy's velocity in km/s
c is the speed of light: 300,000 km/s
$\lambda_{\rm obs}$ is the observed wavelength of H-α in the galaxy's spectrum
$\lambda_{\rm rest}$ is the rest wavelength of H-α: 656.3 nm

iv. Point out that in reality, astronomers use multiple lines to determine a redshift, not just one.

h. Distances: Make an analogy about judging how far away an object like a car is. You have a pretty accurate mental model of how large a car is. The farther away it is, the smaller the car appears. Although galaxies vary in size more than cars do, you can still use their size as a very rough estimator of distance using what astronomers call a "standard ruler" approach.

i. In the online interactive, you will "measure" the size of the galaxy in the sky in fractions of a degree (and arcminutes and arcseconds). (1 degree = 60 arcminutes; and 1 arcminute = 60 arcseconds).

ii. Here are some ways to understand angles in the sky:
   1. The part of the sky directly above you makes an angle of 90 degrees with the horizon. 1 degree in the sky is 1/90th of that arc.
   2. If you hold your thumb out in front of you at arm's length, that will cover about 1 degree in the sky.
   3. The full moon is about 0.5 degree (or 30 arcminutes) in the sky.

iii. You will use a tool in the online interactive to measure the galaxy's "apparent" size, or how big the galaxy appears in the sky. A calculator in the interactive will compare the apparent size you measured with an assumed actual length for that type of galaxy to provide an estimated distance to the galaxy. Note that the given sizes can actually vary by up to a factor of 10 or more, and astronomers use more accurate ways to measure distances to objects in space, but this approach will work well enough to help you distinguish between different universe models based on the galaxy data.

2. **Investigate**
    a. At their computers, have students work individually or in pairs on the web-based *Hubble and the Big Bang* interactive.
    b. Students should use the interactive to calculate velocities and estimate distances for 4 galaxies and enter the results into the table on their worksheet.

        i. If students work in pairs, they could each do the calculations and estimations for 4 different galaxies and combine their data.

        ii. After students have had time to complete measurements for 1-2 galaxies, circle the class back together for a discussion about whether they encountered any difficulties, and whether they have suggestions for their classmates.

            1. Be sure students are filling the viewport with the extent of the ***galaxy***, not the circle that marks the galaxy.
            2. Make sure students note on their worksheet what they are considering the galaxy edge. This is what scientists do: they explain their process (methodology) so that other scientists can repeat their work.
            3. After the discussion, allow students to return to the interactive to complete their measurements.

    c. Students should graph their measured distances and velocities on pg 2 of the activity sheet - on their own with their 4 galaxies, or with a partner including all 8 galaxies between them.

    d. Students should consider which of the universe models is supported by their galaxy data.

        i. Hopefully most students will notice a linear relationship between the galaxy velocity and distance, where galaxies that are farther away from us move away from us at higher speeds (the hallmark of an expanding universe). It may help to have students work in pairs and pool their data.

ii. Have students draw a trendline on their graph. The line should start at the origin, and they can adjust their ruler until roughly the same number of galaxies are on either side of the line.

iii. Have students measure the slope of the trendline and determine the units for the slope. (Students will likely need help with this because the resulting units, km/s/Mpc, are completely unfamiliar to them.)

iv. Explain that the slope they measured represents the rate of expansion of the universe (H_o, pronounced "h-nought"), and is also known as the Hubble constant.

3. **Reflect**
   After students have had enough time to collect their data, graph it, and estimate the expansion rate of the universe, bring the class back together for a concluding discussion.
   a. What model universe (static, random, or expanding) did their galaxy data support? How many students in the class had data that supported a static vs. random vs. expanding universe?

      Likely no one's data will support a static universe. Some may support a random-motion universe, but hopefully the majority will get expanding.

   Discuss the model:
   b. How does a linear relationship between velocity and distance tell us that the Universe is expanding? Go back to the example of the runners that start in a line, and each runner runs faster than the person in front of them. At the end of the race the runners will be spread out farther apart from each other, but their relative positions will be the same.

      Now imagine running the race backwards. What happens?
      The stretched out line of runners ends up back where they started, close together, but in the same relative positions.

      Students participate in the following demonstration of this concept:

      - Pick some # of volunteers and put them in single file.
      - Pick any one student to be the Milky Way.
      - Next, move time forward:
        - Classmates one person in front/behind should take one step forward/back; two people in front/behind take two steps forward/back, etc.
      - After a few time steps, the students will be spread out.

- "Rewind time" by taking the same number of steps back. They will all end up back at the same spot.

The same thing is happening in our expanding universe. If the galaxies all started in the same place, and galaxy A is moving twice as fast as galaxy B, it will end up twice as far away as galaxy B. If you "play the movie backwards," all the galaxies we see today will end up where we started, where the Big Bang took place.

Note that there is no "center" to the universe. From our point of view in the Milky Way, almost all galaxies are moving away from us. (The exceptions are a small number of galaxies that are moving toward us because they are close enough for gravity to matter more than the expansion of the universe). An observer in another part of the universe would also observe that almost all galaxies are moving away from them. Neither of us is special and neither of us is a "center" of the universe.

- You can run the student demonstration again, but change who is the Milky Way before rewinding - they will all end up in the same spot, regardless, showing that a linear relationship implies everything in the universe started in the same place in the distant past.

Optional: Complete this hands-on activity to learn more about the expansion of the universe.

c. Allow students to complete Question 7 on the activity sheet, in class, or for homework.

Discuss the data:

d. If you confirm that most students found support for an expanding universe, you can try to understand what happened with the students who found a random motion universe. Ask students for their ideas on what went wrong and how to improve the experiment design to avoid those problems in the future:

    i. We know that all galaxies even within one type can't really be assumed to have the same size. Perhaps some students chose an unlucky subset of galaxies that were very far off from this crude assumption.

       Possible improvement: take measurements for a larger sample of galaxies where this kind of random uncertainties would average out (because some galaxies would be larger than the assumed size and others would be smaller).

    ii. Students may have made mistakes in their measurements

Possible improvement (which is essentially what the class has done): have multiple people conduct the experiment, so you have redundancy and opportunities for comparison. This is why it is helpful for scientists to work in teams to check each other's work, and to try multiple approaches to a problem. For example, when the Event Horizon Telescope team imaged a black hole, they gave the data to multiple sub-teams who worked on the analysis independently and compared their results with each other. This gave them confidence that the results they were reporting were accurate.

e. Students may have trouble determining where the edge of the galaxy begins and the noise in the detector begins. This is a very common issue in astronomy, and it is useful to discuss different ways to handle this. This is also an opportunity to discuss the differences between random and systematic errors in measurements.

   i. If you decided as a class to come up with some consistent way for everyone to "define" a galaxy edge, what are the pros and cons of this approach?
      1. Pros: Your results as a class may have a smaller "spread." This would reduce the **random** error in the class's distance estimations.
      2. Cons: If the class's collective definition is biased in some way, then the whole class average will also be biased. This would increase the **systematic** error in the class's distance estimations.

   ii. If the class decided to let everyone define the "edge" independently, what are the pros and cons of this approach?
      1. Pros: The class's distance estimations will be less susceptible to a **systematic** error if everyone uses their own method to define the galaxy "edge."
      2. Cons: The class's distance estimations will likely have a larger **random** error with everyone using a different approach.

   iii. Discuss: When there is a tradeoff, is it better to try to minimize random errors or systematic errors in an experiment?

   Systematic errors are usually considered more problematic in an experiment because they affect every measurement in the same way. The effects of random errors can be averaged out by taking more measurements.

f. What values did each student or pair of students determine for the expansion rate of the universe (H_o)? You could write all the values on the board and discuss the collective results.

   i. Given that we used a very crude way of estimating distances to the galaxies, how do you expect the class's determination of H_o to compare with scientifically accepted values?
   (For the teacher: As we note further down, Hubble's own measurement was different from today's accepted values by a factor of 7! We expect students' results with this dataset to be closer to the actual value than that. Anything within a factor of 2 in either direction would be reasonable.)

   ii. What was the class average for H_o? What was the range of H_o values obtained by students in the class? How do they compare with the range of scientifically accepted values for H_o (~70 km/s/Mpc).
   iii. If students have studied standard deviations: What was the standard deviation of the class's H_o values? What fraction of the class's measurements was within 1 standard deviation of the class average? What fraction was withing 2 standard deviations? (How do those fractions compare with the 68% and 95% expected values for a normal distribution? If the class's percentages are not in line with those values, what would happen if you combined the measurements of multiple classes?
   iv. You can put the class's measurements into the historical context for scientifically accepted values of H_o:
      1. In 1927, Edwin Hubble measured H_o=500 km/s/Mpc.
      2. In early 1990's there were two prominent groups of scientists working on refining measurements of H_o. One group reported a value of 50 km/s/Mpc, while the other group reported a value of 100 km/s/Mpc.
      3. In 2020, accepted values ranges from 67 km/s/Mpc to 74 km/s/Mpc, depending on the methodology used to measure H_o.

      Students may wonder why Hubble's value of H_o was so different from today's accepted value. There were several factors, but the main one is that astronomers had not correctly calibrated the intrinsic brightness of Cepheid variables, the "standard candles" Hubble used to determine distances to the galaxies he observed. Also, it was difficult to distinguish individual stars in distant galaxies using telescopes available at the time.

Dive Deeper:

- Nova video about Hubble and the expanding universe: this clip has helpful visuals about galaxies, redshift, and expanding universe, but note that it simplifies the history of the discovery and doesn't credit Henrietta Leavitt, who discovered the important relationship between the brightness of a Cepheid variable and the period of its pulsation; Vesto Slipher, whose velocity measurements Hubble used; and Georges Lemaitre, who predicted that an expanding universe should have galaxies with velocities proportional to their distance.

Standards

ESS1.A: The Universe and Its Stars

The Big Bang theory is supported by observations of distant galaxies receding from our own, of the measured composition of stars and non-stellar gases, and of the maps of spectra of the primordial radiation (cosmic microwave background) that still fills the universe. (HS- ESS1-2)

Associated Performance Expectation:

HS-ESS1-2. 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. [Clarification Statement: Emphasis is on the **astronomical evidence of**

1. **the red shift of light from galaxies as an indication that the universe is currently expanding,**
2. the cosmic microwave background as the remnant radiation from the Big Bang, and
3. the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).]

NGSS Practice: Analyzing and Interpreting Data

- Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims.
- Apply concepts of statistics and probability (including determining function fits to data, slope, intercept, and correlation coefficient for linear fits) to scientific and engineering questions and problems, using digital tools when feasible.
- Consider limitations of data analysis (e.g., measurement error, sample selection) when analyzing and interpreting data.