How big and how old is the universe?

The purpose of this exploration is for students to gather and interpret evidence bearing on the questions, "How large and how old is the universe?"

In Part 1 of the exploration, students use the telescopes to take images of galaxies far beyond our own Milky Way galaxy. In Part 2, students estimate the distances to these galaxies, based on measurements of their images. In Part 3, students look for a pattern to the motions of their galaxies; they construct a graph that combines their results from Part 2 with published data on the speeds of their galaxies.

In discussing and interpreting their images and data, students arrive at several important ideas:

- The universe is observed to be filled with galaxies all the way out to the telescope's limit of detection.
- The telescope is a "time machine": It takes so long for light to get to us, that we see the galaxies not as they are now but as they were in the past.
- The galaxies are moving away from us and from each other. Based on the pattern of their motion, we conclude that billions of years ago, the matter in the universe was extremely densely packed together.

GRADE LEVEL:
8-12

TIME OF YEAR:
Anytime

SCIENCE STANDARDS:
Origin of the universe
Science as inquiry

MATERIALS NEEDED:
✔Online telescopes (or use archived images.)
✔ MOImage, software provided
✔ Overhead transparency (provided)
✔ Printer (optional)

TIME NEEDED:
2-3 class periods

TEXTBOOK LINK:
Hewitt, *Conceptual Physics, 8th Ed.* Ch. 8, Gravity, p. 160

Background

How large is the universe?

What is "the universe" and how far does it extend? For most of human history, the universe was what you saw when you looked at the night sky: Thousands of stars, whose patterns never changed from generation to generation. The Sun, Moon, planets, and an occasional comet wandered across this fixed background of stars. A mysterious white band—the Milky Way, or Via Galactica—stretched across the sky. That was it.

When the telescope was invented in the early 1600's, Galileo discovered that the Milky Way is a made of countless stars, most of them too faint or too distant to be seen by the naked eye. Suddenly, the universe was a bigger place. For the next 300 years, this vast "city of stars" was thought to be the whole universe. It came to be known as the Milky Way galaxy, from the Greek word *galactos*, meaning milk.

Henrietta Leavitt developed a method used to determine distances to stars and nearby galaxies.

As telescopes grew more powerful, astronomers discovered other galaxies beyond our own. At first, these were seen as faint, fuzzy patches of light throughout the sky. The 18th-century astronomer, Charles Messier, cataloged more than 100 of these objects, which were called "nebulae," from the word for fuzzy. Messier was looking for comets; he was disappointed that these fuzzy objects did not move across the sky as comets should. In fact, he created his catalog so that other comet-hunters would not waste their time looking at these objects. Other astronomers cataloged thousands more of these fuzzy patches of light.

At the beginning of the twentieth century, no one knew whether these nebulae were part of our Milky Way galaxy or whether they lay beyond our galaxy. At the time, most astronomers still believed that our galaxy was the whole universe.

By the 1920s, astronomers were able to show that these fuzzy patches of light were galaxies beyond our Milky Way galaxy. Using the technique of spectroscopy, developed in the nineteenth century, the astronomers were able to detect and characterize starlight coming from these galaxies.

Today, astronomers have charted hundreds of billions of galaxies, scattered in every direction in space. There is no sign that the number of galaxies decreases as one looks further from Earth.

Could the universe be *infinitely* large? Are there *infinitely* many galaxies? If not, where do the galaxies stop and what lies beyond them? No one knows. Our view of the universe is limited not by technology, but by nature itself: The problem is that light takes *time* to travel vast distances through the universe. Therefore we see the universe as it *was in the past*, not as it is in the present. For example, the light that reaches our telescopes today, from very distant galaxies, is light that was emitted billions of years ago and has been traveling through space all that time. The image we see shows how these distant galaxies looked billions of years ago. The further out we try to look, the further back in time we are seeing. Eventually, we reach a distance beyond which we see no visible light: Light has not had enough time, since the beginning of the universe, to reach us yet.

In summary, we have a magnificent view of the universe. We can see vast distances, and huge numbers of galaxies, each containing huge numbers of stars and planets. And nature allows us to see all the way back in time to the Big Bang (see below). But we are limited to viewing only a portion of creation directly. Today, only our imaginations can take us beyond that limit.

The Big Bang and the Origin of the Universe

Throughout history, cultures around the world have created beautiful stories, myths, and legends about the origin of the universe. These stories are variations on three themes: The universe was created from nothing; the universe always existed; or the universe went through cycles of creation and destruction. But the beauty and enduring qualities of these stories could not alter the fact that the origin of the universe has remained one of the great mysteries of all time.

Today, we still don't know for certain whether the universe as a whole has existed forever, or whether it was created from nothing, or whether it goes through cycles of creation and destruction. However, we do know that our *observable* universe—the portion of the universe that we can see from Earth—went through an extraordinary event known as the Big Bang.

Here is a summary of what we know about the Big Bang and its aftermath: About 14 billion years ago, all of the matter we see today was packed into a volume the size of a grapefruit. This incredibly hot, dense mass expanded and cooled. Under the tug of gravity, clumps of matter condensed to form the stars and galaxies we see today.

Understanding the Big Bang

In your classroom, you may choose to present only the evidence for the Big Bang, and forego the modern description of how and why the event took place. However, it is important to understand that the Big Bang was *predicted*, on the basis of Albert Einstein's theory of gravity, before evidence for the Big Bang was discovered. Einstein's explanation of the Big Bang is one of the greatest triumphs of science.

Although Einstein's theory of gravity is beyond the scope of this activity, the basic idea behind it is simple. Briefly, Einstein described gravity, not as a force, the way Isaac Newton had, but as a distortion of the space and time that surround us. According to the theory, matter "curves" the space-time around it. Although we cannot see space and time directly, we *can* observe the effect of this distortion, as shown in the pair of illustrations on the next page, which attempts draw this curvature of space-time.

The illustration at the top shows two galaxies and the space-time in which they live, for a fictitious universe in which there is no gravity. (In the diagram, time increases to the right, and space is the direction up and down. The two remaining dimensions of space are omitted for clarity.) According to Einstein, if there is no gravity, then space-time is "flat"—that is, there is no distortion of the underlying space-time. As a consequence, two galaxies that are motionless will stay motionless and the distance between them remains constant as time passes.

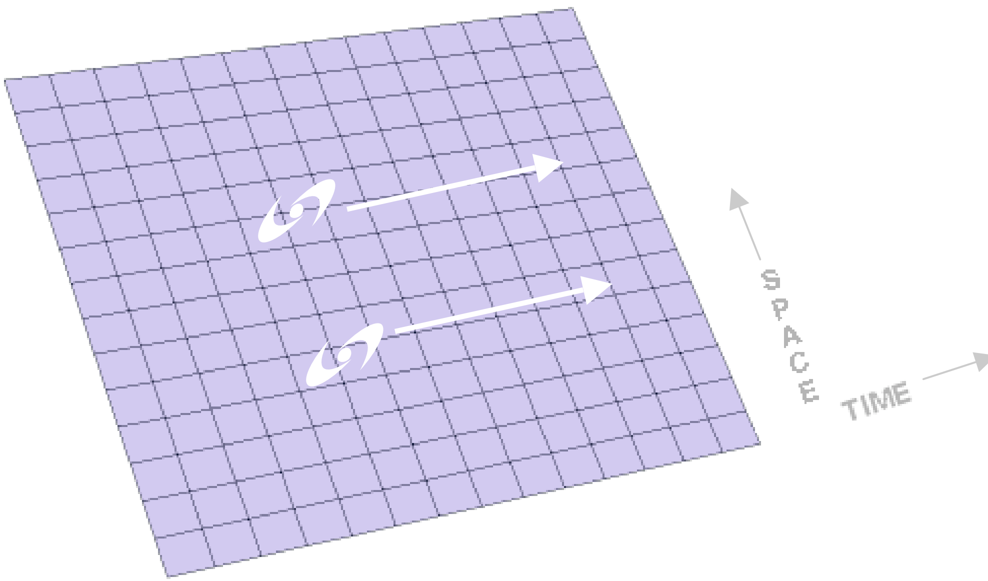
The bottom illustration shows the same two galaxies in a universe filled with matter. According to Einstein's theory, this matter "curves" the underlying space-time as shown. If you follow the two galaxies forward in time, you'll see that they get further apart from each other. If you follow them *backward* in time, you'll see that there was a time in the past when they would have been on top of each other.

This revolutionary way of describing space and time leads to the amazing prediction that galaxies should be flying apart from each other, and that in the past, the matter in the universe was incredibly densely packed. However, by studying the illustration, you can see an even stranger prediction of the theory. Note that neither galaxy moves along the space direction (up and down); that is, each galaxy remains motionless relative to the space around it. Yet as time passes, clearly the galaxies become further apart. This is interpreted as meaning that *new space* is created between the galaxies: space is continually coming into creation as time passes. In the modern view, galaxies are not flying *through* space; rather, new space is welling up between the galaxies (or clusters of galaxies), ever increasing the distance between them. This means that the creation of space did not simply happen in the past; it is an ongoing process taking place even today. In fact, *most* of the volume of the universe was created in the last few billion years.

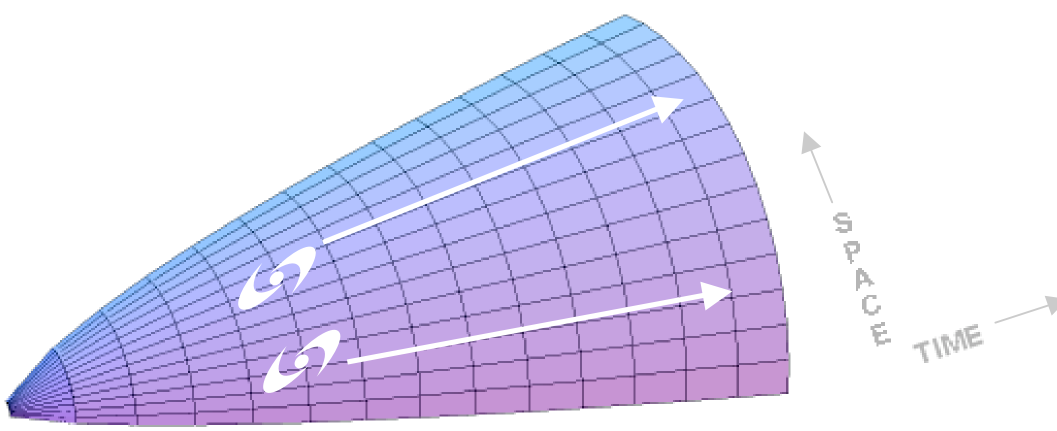
It is important to understand that the Big Bang scenario does *not* describe the origin of the whole universe. It does not describe where space and time came from in the first place, nor does it tell us how and why particles of matter burst into existence.

Ideas about curved space and time are so strange that it takes time to get used to them. The predictions they lead to are even stranger—so strange that even Einstein thought they could not be true. Einstein, like most scientists of the early 20th century, believed that the universe, at the largest scale of structure, remains unchanged from "everlasting to everlasting." The idea of a dynamic universe seemed bizarre. After all, the constellations we observe today were the same thousands of years ago. But a century of evidence proved that the universe is a dynamic place after all.

Why is the universe expanding?: Einstein's prediction

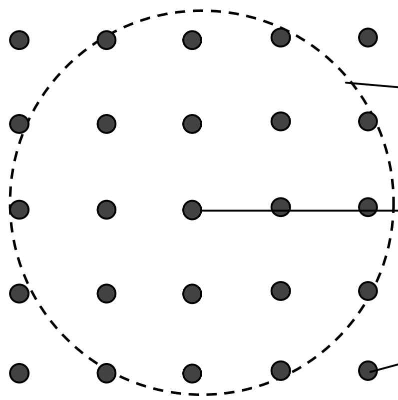


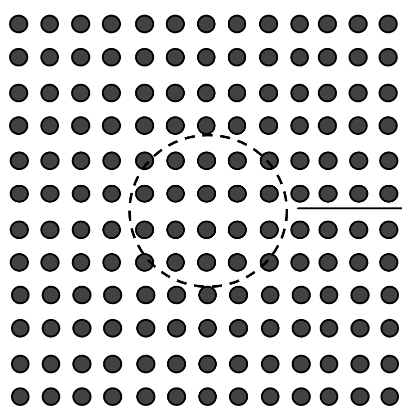
In this "space-time" diagram, two galaxies move in the direction of increasing time. In a universe without gravity, the underlying space-time is "flat." As a consequence, the two galaxies remain the same distance apart. (For simplicity, only one dimension of space is shown.)

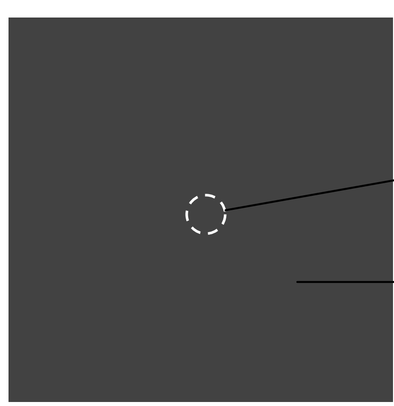


According to Einstein's theory of gravity, matter that fills the universe "curves the geometry of space-time," as shown. Though we can't see space or time directly, we can see the *effects* of this curvature. One effect: galaxies become further apart with time. At first, even Einstein thought this prediction was too strange to be true, but a century of evidence has confirmed the Big Bang scenario.

Visualizing the expanding universe







Evidence for the Big Bang

How do we know that the universe we see today expanded from a hot, dense Big Bang in the past? There are three pillars of evidence:

1. We observe the galaxies moving further apart. This tells us that the galaxies were much closer together in the past. From the speed and directions of the galaxies' motion, we conclude that all the matter in the observable universe would have originated from a tiny region of space about 14 billion years ago.

> In 1929, astronomer Edwin Hubble was the first to discover that the galaxies are receding from Earth, with the fastest galaxies being furthest away. This was a completely unexpected discovery; if anything, the galaxies would be expected to fall towards each other under the influence of gravity. Hubble remained uncomfortable throughout his life with the idea of the Big Bang, even though his work was the first solid evidence for it.
>
> Hubble and his colleagues were able to determine the velocity of a galaxy by measuring a particular, known wavelength of starlight coming from the galaxy, and then observing how much this wavelength was shifted due to the galaxy's motion towards or away from the observer on Earth. (The wavelength of light from receding galaxies is shifted towards the red, while for approaching galaxies it is shifted towards the blue end of the spectrum. A similar technique is used by police to measure the speed of a car, or in sports to measure the speed of a ball.)

2. We can see the ashes left over from the Big Bang. If you have ever been camping, you know how to tell whether someone has occupied a campsite before you: Look for the charred wood and ashes of a previous campfire.

In the same way, astronomers have found the remains of the Big Bang's nuclear fires. These "ashes" consist of simple elements that can only be produced at high density and temperature. These elements are found throughout the universe in the exact proportions predicted from nuclear physics and the Big Bang scenario. This confirms that the early universe was not only very dense, it was also extremely hot.

In the 1940s, the physicist George Gamow and his colleagues were the first to realize that the Big Bang must have been hot as well as dense.

3. We can detect the heat and light left over from the Big Bang. You might think the light from the Big Bang would be long gone. Not so: The Big Bang took place *everywhere* in space, not just at a point. "Big Bang" light from very distant regions of the universe is just arriving at Earth today, from every direction in space. Because the universe has cooled, this light can no longer be seen by eye; it requires special instruments to detect. This light confirms that the universe was once extremely hot.

> In 1964, radio astronomers Arno Penzias and Robert Wilson detected the light left over from the Big Bang, coming from all directions in the sky. Due to the expansion of the universe, the wavelength of this light is in the *microwave*—rather than visible—portion of the spectrum. (It is similar to the waves that fill your microwave oven.) Penzias and Wilson received the Nobel Prize for their work. In 2003, a NASA space probe called WMAP took the most detailed images of this light to date (see below).

These and many other lines of evidence have established that the Big Bang took place as described. In fact, we know what happened during the first second after the Big Bang in greater detail, and with more confidence, than we know what lies just 100 miles beneath our feet, inside the Earth.

Misconceptions about the Big Bang

Misconception: "The universe began as a point." The portion of the universe we observe today ("observable universe") was packed into a very small volume. But the universe as a whole extends beyond what we can see. We do not know how large the universe as a whole was during the Big Bang. (See illustration.)

Misconception: "An explosion caused matter to expand away from a central point." In the modern view, there was no explosion, nor is there a central point from which matter is rushing away. In the modern view, clusters of galaxies are getting further apart because *new space is continuously being created between the galaxies, and has been since the Big Bang.* This new space comes into existence throughout the universe, not just at one point—and it is still taking place today. In fact, most of the space in the observable universe was created only in the last few billion years, not during the Big Bang!

Misconception: "The Big Bang is a theory." The Big Bang scenario is neither a theory nor a model. It is now a firm conclusion, based on nearly a century of evidence. All known observations about the universe are consistent with the Big Bang scenario, and no known observations contradict it.

Misconception: "The Big Bang was the origin of the universe." It is important to understand the the Big Bang scenario does *not* describe the actual origin of the universe. For example, the scenario does not say anything about where space, time, and matter or energy came from in the first place. The scenario does not allow us to peer back in time beyond 14 billion years ago. New theories and evidence are needed to understand what happened before the Big Bang.

Science current events: What came before the Big Bang?

Modern theories of the universe are attempting to predict what came before the Big Bang. These new theories are based on the realization that *even empty space* can have energy of its own—that is, even empty space can "weigh" something! According to the leading theory—called the inflationary universe theory—before the Big Bang there was only empty space, but this space had enormous energy of its own. During the instant of the Big Bang, this energy was converted into the heat, light, and particles that filled the universe.

Scientists do not yet know what this "energy of space" actually is, or how it relates to known forms of energy. However, there is growing evidence that this new theory may be correct. Astronomers have detected a telltale "imprint" of this primordial energy on the light they have imaged from the Big Bang. Also, they have recently confirmed that, even today, empty space contains a small amount of its own energy.

Was the Big Bang unique?

The inflationary universe theory predicts that other Big Bangs may have happened, independently of ours, at other places in the larger universe. We do not know what these other Big Bangs would have been like, nor whether the portions of the universe they produce are even remotely similar to our own. But future developments in physics and astronomy may give us insight into parts of the larger universe that we could never hope to observe directly.

Materials Needed

	For each team of students
	Optional: Rulers for measuring printed images
	For the class
	Internet access to the MicroObservatory online telescopes
	Image-processing software (MOImage) on your local computer
	Printer (black-and-white)
	For the teacher
	Overhead projector
	Overhead transparency of graph[1]
	Optional: Dinner plate or paper plate to model shape of a spiral galaxy

Part 1: What do galaxies look like?

The purpose of this investigation is to use the telescopes to create a gallery of galaxy images similar in shape to our own Milky Way galaxy.

[1] Supplied with *From the Ground Up!* materials.

- The universe is observed to contain galaxies all the way out to the telescope's limit of detection.

Recording Ideas and Discussion

Have students respond to the introductory questions in their Science Journals and discuss some of their responses.

1. What do you think lies beyond our own Milky Way galaxy? Are there galaxies of stars beyond our own? Do you think creatures live there?

2. Do you think space goes on forever? If so, could it be filled with galaxies like our own?

3. Do you think the universe always existed? If not, what came before? What are your questions about the universe?

Many students' responses will be drawn from their experiences with science fiction, with religion and spirituality, with mythology, and from their own imaginations. Accept all answers as ideas that students may re-examine as they do the following explorations.

Procedure

Students work in groups of three or four. Each group is responsible for imaging four galaxies—one galaxy chosen from each of the four galaxy sets listed on the "'Scope It Out!" page. (This ensures that every team will be working with galaxies which span a range of distances.)

> **Note:** It doesn't matter if different groups work with some of the same galaxies. But collectively, the class should work with most or all of the galaxies on the list, so that there is a sufficient amount of data to construct the graph in Part 3.

If a chosen galaxy is not visible at this time of year, students may download an image of the galaxy from the Image Archive at the "From the Ground Up!" Web site.

http://cfa-www.harvard.edu/webscope

Students using archived images will still have to use the MicroObservatory Image Processing program to adjust the contrast of the images and to measure the size of the galaxies. Students may also choose to image a galaxy not on the list, provided it is a spiral galaxy similar in shape to our Milky Way galaxy.

Have students take images, and measure the width of their galaxies in pixels, using the procedure listed in their Science Journals:

1. **Choose the galaxies** that your team will image: Your team will be responsible for imaging four galaxies: one from each of the four sets of galaxies listed on the "Scope it Out" page. If a galaxy you have selected is *not* in the night sky tonight (i.e., wrong season for viewing), then you may use an image of the galaxy from the Image Archive instead.

IMPORTANT: Check with the teams to make sure that, together, the teams will image as many *different* galaxies from the list as possible. But it does not matter if more than one team images the same galaxy.

2. **Log on to the telescope** and use the suggested settings on the "Scope it Out" page to take your images.

   Discuss with your team: *Does it matter whether all your images are taken with the same exposure time? How would different exposure times affect your images?*

NOTE: Have students use a consistent exposure time (e.g., 60 seconds) for all their images. The longer the exposure time, the more of a galaxy is revealed in the image. To make a fair comparison of the angular widths of the galaxies, students should use one exposure time.

3. **Download your images** from the telescope Web site as soon after they are taken as you can. Download your images in the

FITS image format, following the instructions on the Web page.

Download: When you find the image on your computer, download it in the FITS format. (To do this, click and hold on the “Save as FITS file” option just above your image.) Choose “Save as SOURCE” rather than as TEXT.

4. **Name each image file** with the name of the galaxy, so that you can easily tell which galaxy is which. If needed, rename the image file to include the name of the galaxy.

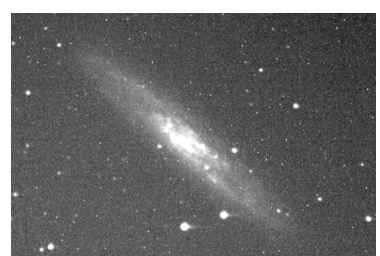
5. **Process your images** using the image-processing software on your computer. Open the image. Under the **Process** menu, select **Adjust Image** and process until you are satisfied with the result. Try to bring out the faint outer part of the galaxy as best as you can; otherwise, the galaxy will look smaller, and therefore further away, than it really is.

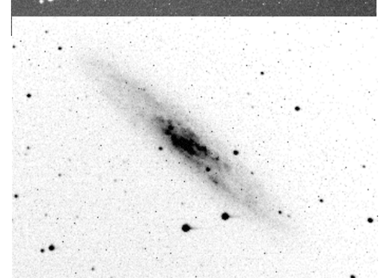
6. **Measure the size of each galaxy**. When you are satisfied that your image shows the whole galaxy, measure the width of the galaxy as follows: Position the cursor at one end of the galaxy. Click and hold, while dragging the cursor across the longest part of the galaxy. The width of the galaxy, in pixels, appears in the information box at the top of the image.

7. **Record the galaxy size on the DATA PAGE.** You'll need this measurement to determine the distance to the galaxy in Part 2 of the challenge.

8. **Save your processed image** as a GIF file. Make sure it is labeled with the name of the galaxy.

   Important: Be sure to download your image promptly. Save it in both formats. Name the file and keep it. Process the image and print the image.





9. **Print your images** at normal size (100%). **TIP:** Instead of printing a white galaxy on a black background, you can INVERT your image in your image-processing program. This produces a grey or black galaxy on a white background. It looks interesting, is easier to see, and saves your printer's

ink! (Under the **Process** menu, select **Invert**. Then save the inverted image as a GIF file.)

Interpreting Images and Discussion

1. Use a paper plate or dinner plate to model what a spiral galaxy looks like when seen from different angles. Ask students to examine their galaxy images and try to determine from what perspective they are viewing each of their galaxies—i.e., edge-on, face-on, at an angle to the plane of the galaxy, etc.

   The center of most galaxies contains a noticeable bulge; the concentration of stars is highest here. Galaxies also contain large amounts of dust, which students may see as dark lanes silhouetted against a background of stars. This dust and gas is the raw material from which new stars will form.

2. Have students respond to the questions in "Reflecting on your images" and record their answers in their science journals. Discuss the following questions with students.

   Why do you think you can't make out the individual stars in your images of galaxies?

   How does the width of the widest galaxy in your images compare to the width of a full Moon image? If galaxies are so wide, then why don't you see galaxies when you look at the night sky?

   How do the shapes of your galaxies compare with the spiral shape of our Milky Way galaxy?

   Do you think that the galaxies you imaged could contain life? Intelligent life? Could there be someone—or something—in one of your galaxies looking back at the Milky Way galaxy with a telescope... asking the same questions?

You can't make out individual stars in your images of galaxies because they are too far away and therefore too faint. But students should appreciate that galaxies are in fact huge collections of stars and their planets, and presumably, other life forms.

We don't see galaxies when we look at the night sky because they are too faint — not because they are too small. In fact, the Andromeda galaxy, a neighboring galaxy, has an angular size several times wider than the full moon! If they weren't too faint to see, several galaxies would be the largest objects in the sky!

We don't know, of course, whether there is life in other galaxies. Many astronomers think, however, that galaxies similar to our own Milky Way are likely to harbor life.

Part 2: How large is the universe?

The purpose of this part of the investigation is to determine the distance to the galaxies that students imaged in part 1, and thereby set a minimum size for the universe.

- Galaxies are so far away that their light takes many millions of years to reach Earth. We see the galaxies as they were in the past, not as they are now.

- The number of galaxies does not appear to decrease at great distances. The universe of galaxies continues beyond what we can observe directly with telescopes, but we do not know how far, or whether the universe is infinitely large.

Sorting galaxy images

Have the class line up all of their galaxy images, on a table-top or on the wall, in order of decreasing size. The largest images of galaxies go on the left; the smallest images of galaxies go on the right.

Ask the class, which of the galaxies do they think are furthest away? Why? Most students will identify the smallest galaxies as the furthest. Ask students, how do we know the smallest galaxies are not just small, rather than distant? Perhaps there are other clues that tell us these galaxies are distant—they may be fuzzy or faint. But it is not easy to tell for certain what is near and what is far, unless we know the size of the object!

Note: If you have not previously carried out the *Distance to a Star* activity (Exploration 4) with your class, you may want to briefly discuss three different ways that astronomers use to determine distances to objects (though it is not essential for this activity):

- **Parallax**. As you change your point of view, objects that are closer appear to move more than distant objects. This method is practical only for relatively nearby stars.
- **Brightness**. As a source of light gets further away, it appears dimmer. (You've used this method in the investigation, **"To the Stars!"**)
- **Angular Size**. As an object gets further away, it appears smaller; i.e., its angular size decreases.

Students will use the last of these methods — angular size — for estimating the distances to their galaxies.

Determining galaxy distances

Explain to students that in this activity, we are going to *assume* that each of the galaxies is the same size—namely, the size of our own Milky Way galaxy. If students have carried out Exploration 4, *To the Stars!*, they will already have found that even "nearby" stars are 50 to 150 light-years away. The size of our whole Milky Way galaxy of stars is much larger than this: about 100,000 light-years across.

> **Assumption:** In this activity, we will *assume* that each galaxy in students' images is the size of our own Milky Way galaxy—100,000 light-years wide.

> This turns out to be a reasonable assumption: astronomers have found, from a variety of evidence, that most spiral galaxies are *roughly* the same size, i.e., within a factor of two or so of each other.

The *light-year* was introduced in Exploration 4 as a unit of distance. Remind students that galaxies are so far away that measuring distance in miles or kilometers would be a burden. Astronomers use the *light-year*, which is distance light travels in one year. It is equal to about 6 trillion miles.

Misconception alert: The *light-year* is a unit of distance, but it sounds like a unit of time. Have students imagine what it would be like to "ride" a beam of light for a whole year. The distance they would have traveled on that beam of light is a light-year.

Ask students, if someone at one end of a galaxy signals with a light-beam to someone at the other end of the galaxy, how long would it take for the signal to get all the way across the galaxy?

> If the galaxy is 100,000 light-years across, then it will take 100,000 years for the light to cross the galaxy. Galaxies are immense objects!

Calculating galaxy distances

Each team is now in a position to calculate the distance to each of its galaxies: They know the actual size of each galaxy (100,000 light-years). They know the width of each galaxy, in pixels. All that remains is for them to

- *Convert the angular width of their galaxies from pixels to degrees*: One pixel of a zoomed-out image is 0.0014 degrees; for a zoomed-in image, one pixel is 0.0007 degrees.

- *Use the "rule of 57"*: An object that is 1 degree wide is 57 times further than it is wide. Narrower objects are proportionally further. (See *A Wrangle with Angles.*)

As an example, take the spiral galaxy shown here.

Actual width = 100,000 light-years (our assumption).

Width in pixels = 100 pixels

Angular width = 100 pixels x 0.0014 degrees per pixel = 0.14 degree.

If the galaxy spanned 1 degree it would be 57 x 100,000 light-years = 5.7 million light-years away.

But it is less than a degree wide, and therefore proportionally farther:

Distance = 5.7 million x (1 degree/ 0.14 degree) = 40 million light-years away.

Have students record on the DATA PAGE the distance they find for each of their galaxies.

Interpreting Results and Discussion

Have students discuss the questions with their teams and record their responses in their science journals. Then discuss students' responses.

Infinite universe?

1. What's the furthest distance (roughly) that you could hope to see a galaxy with the MicroObservatory telescopes? (Assume that the smallest object you can RELIABLY see in an image is about 2 pixels wide for a zoomed-out image.)

2. What, if anything, can you conclude about the size of the universe as a whole?

If a galaxy were two pixels wide in a zoomed-out image, how far would it be? Using the same approach as in the sample calculation above:

Actual width = 100,000 light-years (our assumption).

Width in pixels = 2 pixels

Angular width = 2 pixels x 0.0014 degrees per pixel = 0.0028 degree.

If the galaxy spanned 1 degree it would be 57 x 100,000 light-years = 5.7 million light-years away.

But it is less than a degree wide, and therefore proportionally farther:

Distance = 5.7 million x (1 degree/ 0.0028 degree) = 2.0 billion light-years away.

In practice, galaxies this far would require a long exposure time and would be difficult to image. However, the MicroObservatory telescopes have imaged galaxies that are about 1 billion light-years from Earth.

Misconception alert: Galaxies on a sphere? Many students believe, erroneously, that the galaxies in the universe are arranged on the surface of a giant sphere. Unfortunately, this misconception is reinforced by many standard classroom activities, such as blowing up a balloon to represent the expansion of the universe. The image of the big bang as an explosion (also erroneous!) leads many students to picture the galaxies as shards on the surface of an expanding sphere. Astronomers sometimes speak of "bubbles and voids" when speaking of the arrangement of galaxies in space, but even this is probably unnecessarily confusing at this level.

In reality, galaxies are distributed throughout three-dimensional space, "all the way out". It is important that students examine their prior conceptions about this, before beginning the investigation.

Frozen in time?

3. If a galaxy were moving sideways at almost the speed of light, could you ever hope to SEE its motion by taking several images of the galaxy days apart — or even months or years apart? About how long would it take for a galaxy to move even 1 pixel in your image?

You could never hope to see a galaxy move in your lifetime using the MicroObservatory (or any) telescope. Suppose the galaxy in your image is 100 pixels wide, say. For a galaxy that is 100,000 light-years across, then each pixel in your galaxy image represents a width of 1000 light-years — an incredibly large distance. So if a galaxy were moving sideways in the field of view at the speed of light, it would take 1000 years to move just one pixel! We see the galaxies essentially *frozen in time*!

Although astronomers can't see galaxies move directly, they can measure the motions of galaxies indirectly (see part 3).

Telescope as time machine?

4. About how long does it take light from each of your galaxies to reach Earth?

5. Do your galaxy images show the galaxies as they look NOW or as they looked in the past? Why?

6. What was happening on Earth when the light you captured in each galaxy image set out on its long journey to Earth?

The distance to students' galaxies will range from about 2 million to 200 million light-years from Earth. Therefore light from these galaxies will have taken between 2 million and 200 million years to reach Earth! The images we take today show us how the galaxies looked in the past, not how they look now.

Emphasize that light travels in a continuous stream from source (galaxy) to Earth. Light is leaving the galaxy right now, but that light won't reach Earth until millions of years from now.

Students' images are truly images of the past! The image show how the galaxies LOOKED millions of years ago, when the light the formed the image first left the galaxy.

By connecting galaxies to ancient events on Earth, you can help students construct a concrete framework for appreciating long time scales. Here is one timeline:

Years Ago	What was happening on Earth?
3 million	Early humans walked upright, left footprints in volcanic ash in Kenya.
6 million	Last common ancestor of humans and chimpanzees.
10 million	The constellation Orion appears in the night sky as the stars in Orion's belt form from clouds of dust and gas.
65 million	Asteroid hit Earth, left giant crater off the coast of Mexico and worlwide layer of the element iridium. Dinosaurs and many other species disappear, early mammals dominate.
100 million	Dinosaurs rule the Earth. Many species of ants have already appeared.
200 million	Half of all species suddenly become extinct. Cause: unknown. The Himalayan mountains are formed as the Indian and Asian landmasses slowly collide.

Part 3: How old is the universe?

The purpose of this part of the challenge is to use data about the motions of the galaxies to draw inferences about what the universe was like in the past.

- Contrary to expectations, almost all the galaxies are moving away from us. The further away the galaxy, the faster it is receding.

- In the past, the galaxies were much closer together.

- About 14 billion years ago, the matter that forms the galaxies we see today would have all been together in a tiny volume.

- In addition to the motion caused by the expansion of the universe, galaxies have slight random motions. A few nearby galaxies are falling towards us, drawn by gravity.

Team discussion and predictions.

Explain to students that one way to explore what the universe might have been like in the past, is to examine the motions of the galaxies. By seeing how the galaxies are moving today, we might be able to infer what the galaxies were doing in the past.

Students work in teams of three or four, as before. Have each of the teams discuss among themselves which of the three possibilities presented here seems most plausible. For each theory, have them infer what the universe would have looked like in the past—that is, where the galaxies would have been relative to where they are today—and what the universe would look like in the future.

> **Possibility 1: Galaxies falling together under gravity.** In the past, the galaxies would have been much further away from each other. In the future, the galaxies would fall together faster and faster and eventually all collide.
>
> Problems with this theory: Why did the galaxies start far apart in the first place? If the galaxies were too far apart, would they have felt each others' pull of gravity?

Possibility 2: Galaxies not moving at all. In the past, the galaxies would have been the same distance apart as they are now. In the future, the galaxies will remain the same distance apart.

Problems with this theory: How can the galaxies be in perfect balance? Would the universe have to be infinite to keep the galaxies from all falling together towards a common center?

Possibility 3: Galaxies moving randomly. In the past, the galaxies might also have been moving randomly. In the future, the galaxies would still be moving randomly.

Problems with this theory: How did the motion start? Wouldn't gravity cause the galaxies to clump as they moved past each other?

By discussing how you might *expect* galaxies to be moving, you lay the groundwork for students to appreciate how truly bizarre their results will turn out: that the galaxies are receding from us. After all, shouldn't we expect gravity to hold things together?

Have students commit to a prediction by entering their predictions and their level of confidence in their predictions. Some students may have heard that the universe is expanding, i.e., that the galaxies are racing apart from each other. They can enter this possibility as "Other Possibility," but it should have the same tentative status as the first three possibilities, namely, as a possibility to be tested by evidence.

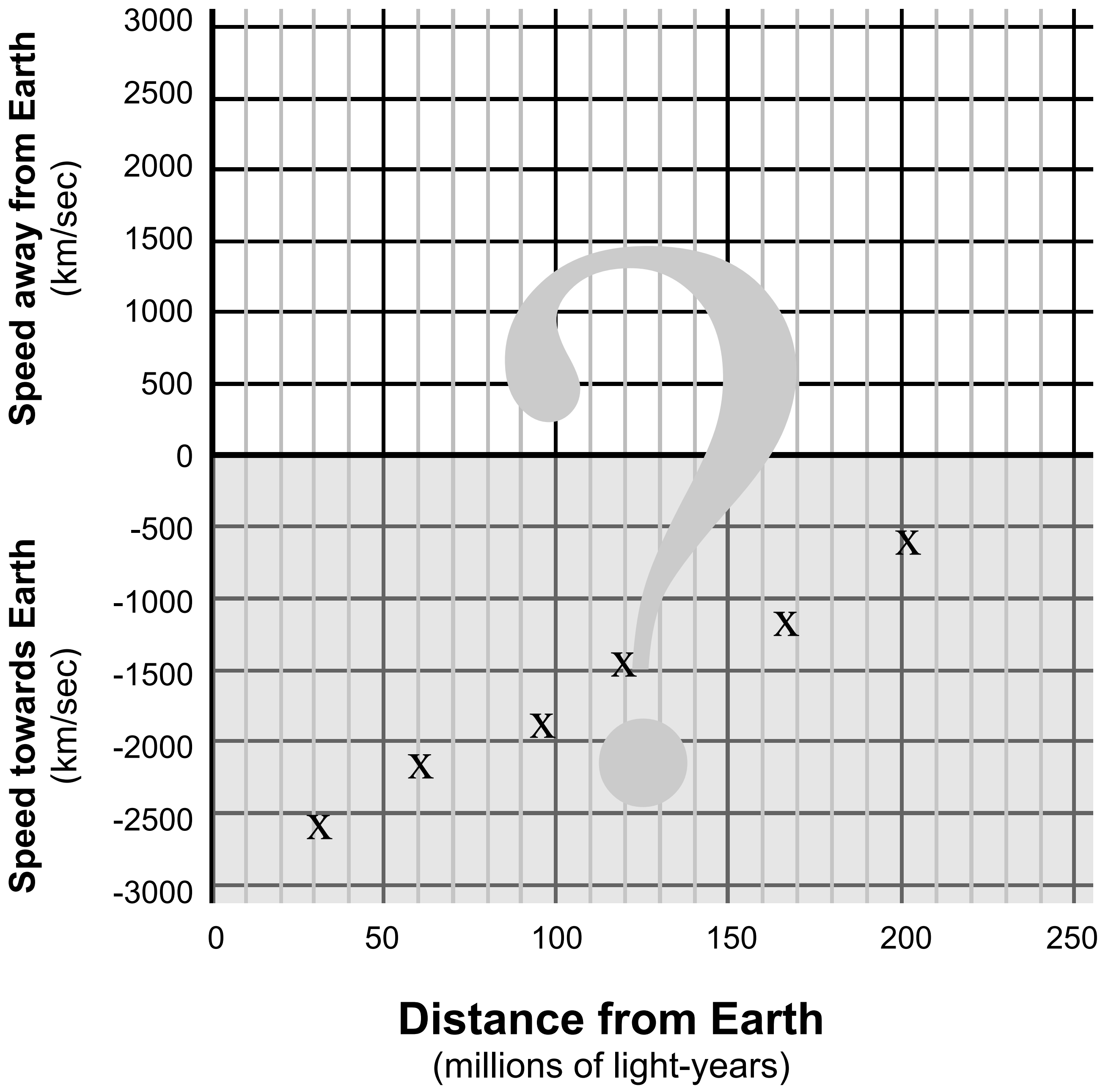
Optional: If you have time, you can discuss what the graph would look like for each of the three possibilities that students have examined. The next few pages show how these graphs might look.

If galaxies are falling towards us, the data points will almost all lie in the bottom half of the graph. The nearest galaxies would move fastest, since the force of gravity would increase as they got nearer. (Check.)

If the galaxies are not moving at all (universe in balance), the data will all lie along the axis (zero velocity), regardless of their distance from us.

How old is the universe?

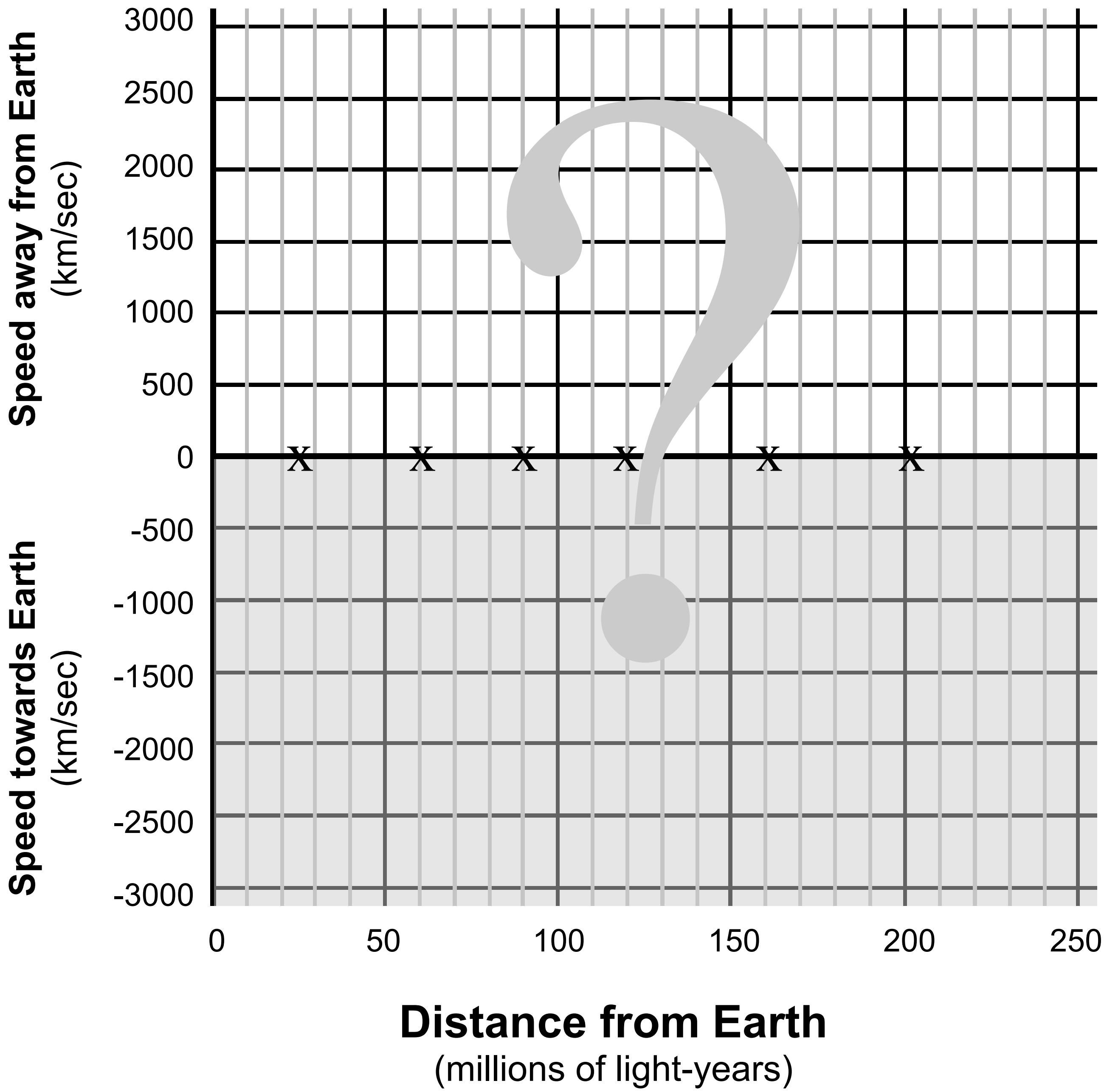
Plot galaxy's speed vs. galaxy's distance from Earth



If the galaxies are all falling towards each other, we might expect a graph like this: Galaxies that are nearer to ours would be falling towards us the fastest, while galaxies farther away would be falling more slowly.

How old is the universe?

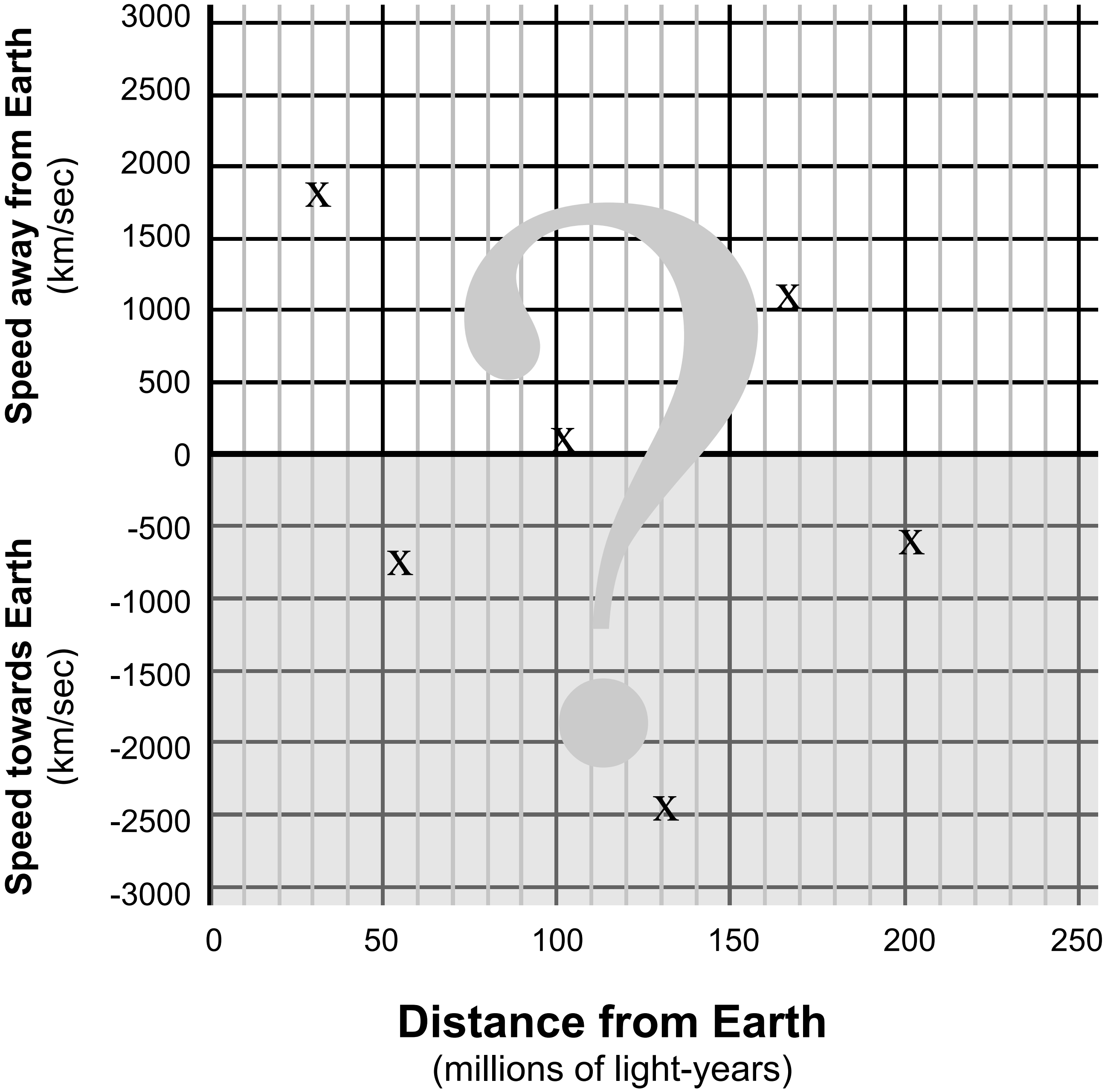
Plot galaxy's speed vs. galaxy's distance from Earth



If the galaxies are not moving at all, we would expect a graph like this one. The galaxy speed is zero, regardless of how near or far the galaxy may be.

How old is the universe?

Plot galaxy's speed vs. galaxy's distance from Earth



If the galaxies are moving randomly, we might expect a graph like this. About half the galaxies are moving towards us and half away from us—but it doesn't matter whether they are near or far: there is no special pattern to the graph.

If the galaxies are moving randomly, the data will be completely scattered, with half the galaxies moving towards us (bottom half of graph) and half the galaxies moving away from us (top half of graph) with random speeds regardless of distance.

Gathering the data

In reflecting on their results in Part 2 above, students found that galaxies are too far to have any hope of directly seeing them move, even with the most powerful telescopes. But astronomers can determine how fast galaxies move, using an indirect method that is similar in principle to how we can clock the speed of baseball pitches, tennis serves, and speeding cars (see box). You can describe this method if you wish. In this part of the exploration, however, students will simply use the published results of astronomers' measurements for the speed of galaxies—and combine these data with their own results for the distances to their galaxies.

1. Explain to students that they are going to look for a pattern to the motions of their galaxies. For each galaxy they have imaged, they are going to use published data to record in their journals how fast that galaxy is moving towards or away from Earth. Then the class is going to create a graph that plots distance to the galaxy, versus speed of the galaxy. Students will then see if a pattern emerges from the graph. Is there any connection between the distance to a galaxy, and its speed or direction?

2. To find out how fast each of their galaxies is moving, students use the published data listed at NASA's Extragalactic Database, on the World Wide Web:

   http://nedwww.ipac.caltech.edu/forms/z.html

   Students input the name of their galaxy, and follow the instructions on the website. Point out to students that for each galaxy, there are several different values for its speed listed. This is a good example that in real science, there are only results, not "answers": Different observers, using different methods, may get different results. The column marked "unc" shows the estimated uncertainty for each measurement. *Students should use the first listing for each galaxy.*

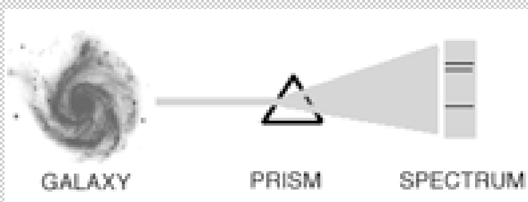
3. Students find and record on their DATA PAGE the speeds for each of their galaxies. **Important:** Remind students to record the SIGN of the speed as well: (By convention, + indicates motion away from us, and - indicates motion towards us.)

SPEEDING TICKET FOR A GALAXY?

How do astronomers measure how fast a galaxy is moving?

They use the Doppler effect. The Doppler effect applies to any object that either emits or reflects sound waves or light waves: If the object is approaching you, the frequency of the waves appears higher; if the object is receding, the frequency appears lower. For a source that emits light, this means that the light appears bluer (higher frequency and higher energy) if the source is approaching, and redder (lower frequency and lower energy) if the source is moving away.

Astronomers pass the light from a galaxy through a prism, dispersing the light into a spectrum. This light comes from the many stars that comprise the galaxy. The spectrum contains lines that are characteristic of the different chemical elements that are found in stars. These lines occur at known frequencies; they serve as markers for frequency. By observing how much these lines are shifted due to the motion of the galaxy, astronomers can deduce how fast the galaxy is approaching or receding from us.



Your students can experience the Doppler effect for sound, by listening to the audio file at:

http://cfa-www.harvard.edu/webscope/doppler

More advanced students can work with actual spectra from galaxies, at the site, "How Fast Do Galaxies Move?" at:

http://cfa-www.harvard.edu/webscope/galaxies

4. Have each team come up one at a time to plot the distance and speed for each of their galaxies. For each galaxy, ask if another team has imaged or measured the same galaxy; if so, have them plot their data at the same time. That way, students can get a feeling for the *precision* of their data—i.e., how similar or varied are measurements on the same object.

5. As more and more data are plotted, ask students if they start to see a pattern emerging. The graph should look something like the sample on the next page.

Troubleshooting: "Why don't all the points lie on a line?"
The points on your graph will NOT all lie on a straight line. But it should be possible to draw a straight line through the collection of points and see the general trend. If not, check these problems:

Use enough data. You'll need to use at least a dozen different galaxies to see the trend in the data.

Use near and far galaxies. If the range of distances is too narrow, you'll be looking at too small a part of the whole curve, and won't see the overall trend.

Use either all "zoomed out" images, or all zoomed-in images, and make sure you use the appropriate scale for the image. If you use a zoomed-in image but mistakenly use the scale for a zoomed-out image, then your galaxy will seem twice as close as it really is.

Making sense: Interpreting the results

The universe is expanding

1. After students have graphed all of their data on the overhead transparency, have them discuss with their teams the questions in this section and record their responses in their journals.

   Is there a pattern to your data? Are most of the galaxies moving towards Earth, or away from Earth? Are you surprised?

   In general, are galaxies that are further away from Earth moving differently from galaxies that are closer? In what way?

   Based on the pattern of motion for the galaxies that you've found, what would the universe have looked like long ago?

   Is this the result you expected to find? (Compare your result with the prediction you made earlier.)

2. Discuss and interpret with students the striking features of the graph:

   Virtually all of the galaxies that students imaged are moving away from Earth. Almost all of the data fall in the upper half of the graph; these galaxies are moving away from Earth. Revisit with students their initial predictions. These results are entirely unexpected!

   Explain to students that this is what we mean when we say "the universe is expanding": the galaxies are moving apart.

   This is a truly amazing result, and one that stunned scientists in the early part of the twentieth century. If gravity attracts, why should the galaxies be moving *apart* from each other? Clearly something out of the ordinary is going on.

The galaxies tend to fall on or near a straight line through the graph. The faster that a galaxy is moving, the further it is from Earth.

With students' consensus, draw the best straight line you can through the points, going through the origin of the graph.

The Art of Science

Scientists look for trends and patterns in their data, but these patterns are rarely exact. If you have time, discuss with students why their galaxies do not all fall on the straight line you have drawn. Factors that might be involved:

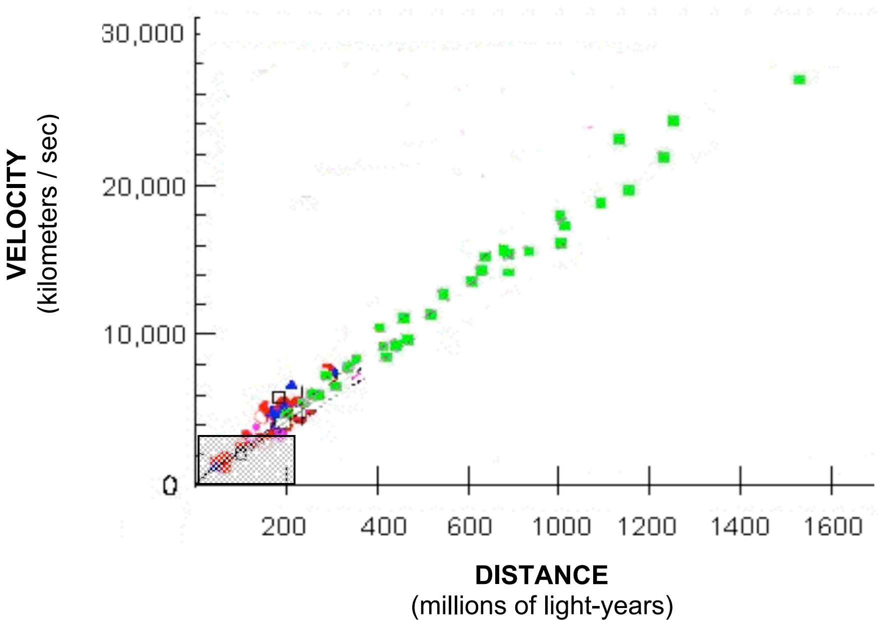
- The *assumption* that the galaxies are all the same size as our Milky Way galaxy is not exactly true. Some galaxies are larger, some may be smaller—so the estimated distances to these galaxies will not be exact.

- Measuring the width of the galaxy is not very precise, because the outer edges of the galaxy are very faint. The more distant and fainter the galaxy, the greater the error in measuring its width.

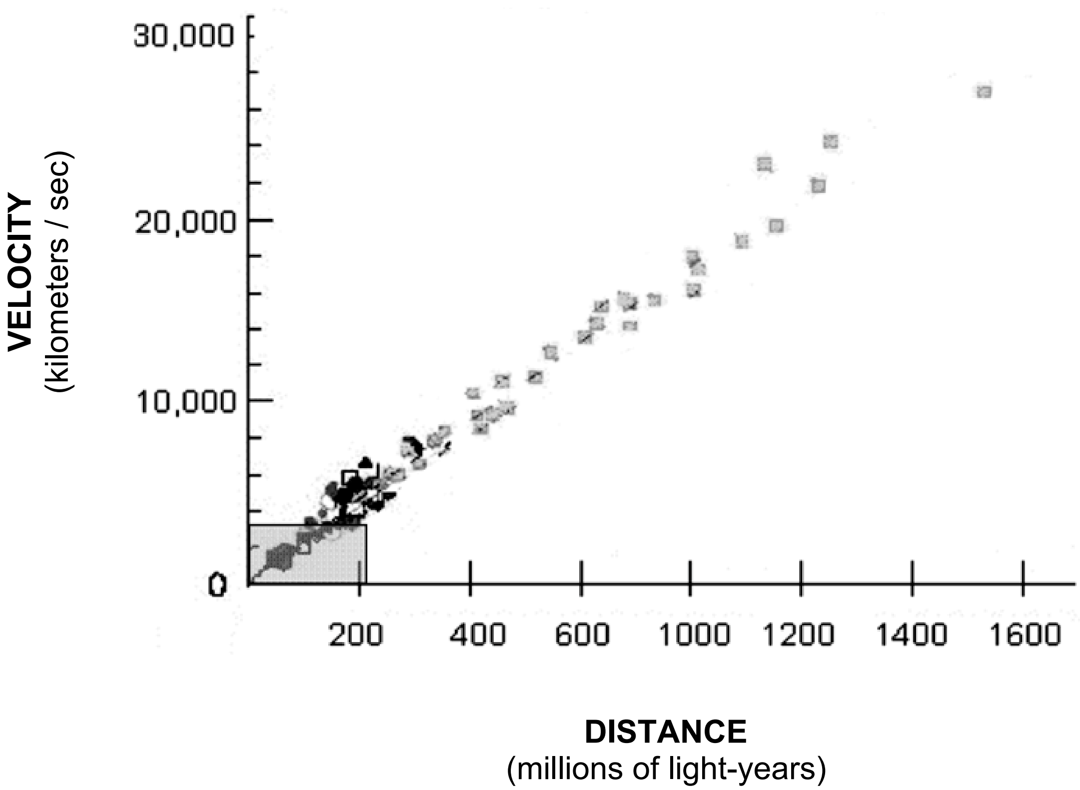
- The motions of the galaxies do not *only* reflect the expansion of the universe. Galaxies that are close to each other are tugged by their mutual gravity. For nearby galaxies especially, this effect is larger than the expansion of the universe. For example, our neighboring galaxy, Andromeda, is falling towards the Milky Way galaxy, drawn by gravity.

Your students may wonder whether very distant galaxies would follow the same rule. Transparency A shows data from the Hubble Space Telescope Key project, which observed galaxies almost ten times further than MicroObservatory. For comparison, the gray box at lower left of the graph shows the region covered by your students' data. As you can see, even distant galaxies follow the same trend: the further the galaxy, the faster it is receding.

The relationship between a galaxy's distance and its speed away from us holds far beyond what the MicroObservatory telescopes (grey box) can see. Data from the Hubble Space Telescope Key project, courtesy Prof. John Hucra.



Transparency Sheet A



The idea of the Big Bang

3. What does this straight-line pattern mean? Have students discuss the following question with their team and respond in their science journals.

    Imagine a road race in which all the runners run at different speeds. The fastest runners will be further from the starting line than the slower runners. Try using your graph to run the "galaxy race" backwards in time. In the past, where were the galaxies in relation to each other?

   The straight line" relationship between distance and speed means that *at some time in the past, all the galaxies (or the material that makes up the galaxies), were "on top of each other" in some tiny volume of space*!

   Raise with students the question: "What was this event, deep in the past, when all the matter you see today was crammed into some much smaller volume of space?"

   Explain to students that this event is called the Big Bang. It was *Big* because all the matter we see now was very densely packed together. It was a *Bang*, because all these clumps of matter were expanding away from each other.

   Put on hold further questions about the Big Bang until you have discussed the data with students further.

How long ago was the Big Bang?

> Based on the data in your graph, how long ago would the galaxies (or the material they're made of) all have been on top of each other? (Assume that each galaxy has always been moving at the same speed.)

Students can use their data to estimate how long ago the Big Bang took place:

- *Assume* that the galaxies have always been receding from us at the same speed.

- Choose any one of the galaxies that falls near the straight line the class has drawn. Note its distance from our galaxy.

- Divide the galaxy's distance from us by its speed away from us. That tells you how long ago it was in the same spot as our galaxy.

  For example, suppose students determined that the galaxy NGC 2543 is about 200 million light-years from Earth, and is receding from us at about 2400 kilometers / second. Since the speed of light is 300,000 kilometers / second, the galaxy has been traveling for:

Estimated time since the Big Bang, from your results		
time	=	distance to the galaxy/ velocity of the galaxy
	=	<u>200 million light-years</u> 2400 kilometers / sec
	=	<u>200 million yrs x 300,000 km / sec</u> 2400 km / sec
	=	200 million yrs x 125
	=	31 billion years

  Note that you don't have to do this division by brute force. If the galaxy were receding at the speed of light, it would have taken 200 million years to get 200 million light-years away. But since it is traveling at *less than* the speed of light, it must have taken proportionally longer to get where it is.

Thus, according to students' typical data, the galaxies would have all been on top of each other about 31 billion years ago.

How does this estimate compare with the currently accepted scientific value? Astronomers have determined that the Big Bang took place about 14 billion years ago, with an uncertainty of less than a billion years. Students' estimates will be larger than the currently accepted value, for several reasons:

- We assumed that the galaxies have been moving apart at the same speed since the Big Bang. In reality, the galaxies were moving much faster earlier in the history of the universe; they gradually slowed. Taking this into account leads to a smaller age of the universe.

- Students' galaxy images generally only show the brighter, inner portions of the galaxy; the outer edges of a galaxy are very faint. Therefore galaxies will look smaller, and farther away, than they really are. That will lead to an overestimate for the age of the universe: the galaxies are concluded to have been traveling for longer than they really have, to get to where they are today.

Age of the universe?

Astronomers sometimes refer to "the age of the universe" as about 14 billion years. But in reality no knows whether, or for how long, the universe existed *before* the Big Bang. It is more accurate to refer to the "time since the Big Bang."

The observable universe: How big?

You can now revisit with students the question, How large is the observable universe?

Have students discuss with their teams the following questions, and record their responses in their journals.

> *Suppose there are galaxies, say, 200 billion light-years from Earth. Could you see those galaxies, if you had a powerful enough telescope? In thinking about this question, ask yourself, "Has there been enough time since the beginning of the universe for light to travel from those very distant galaxies to the telescope? If not, what would you see when you looked through the all-powerful telescope?*

> We cannot see galaxies beyond a certain distance, no matter how powerful our telescopes. The reason is that light from these galaxies would not have had enough time to get to Earth since the Big Bang. Nature limits our view of the universe to the portion of space from which light has had time to reach us since the Big Bang. The further objects that nature allows us to see are *roughly* 14 billion light-years away (actually more since the universe has been expanding while the light has traveled to us.)

Optional: If you wish, you can discuss with your class a second factor that limits how much of the universe we can observe. Ask your students these questions:

> *How would you use your graph to predict how fast a galaxy is moving away from us, if you know the galaxy's distance?*
>
> *Based on the relationship you found in your graph: How far would a galaxy have to be before it is moving away from us* ***faster than light?*** *(The speed of light is 300,000 kilometers per second.)*

Students have already found that the further a galaxy is from Earth, the *faster* it is receding from us. Some students may ask whether galaxies beyond a certain distance are actually receding faster than light, and if so, whether we could ever see these galaxies.

Amazingly, the answer is yes: Galaxies beyond a certain distance are moving away from us faster than light. In fact, it is thought that most galaxies in the overall universe are moving away from us faster than light.

Faster than light? "I thought nothing can travel faster than light, according to Einstein's theory of relativity?"

Nature's speed limit applies to all known forms of matter and energy, but it doesn't apply to space itself. In the modern view, the universe is expanding because *more space comes into existence between the galaxies*—not because the galaxies themselves are being accelerated through space. Two galaxies that are far enough apart will be separating from each faster than light.

The *slope* of the straight line in the graph tells *how fast a galaxy is receding per unit distance*. (Astronomers call this number the Hubble constant, which tells how fast the universe is expanding.) From the graph, this slope has units of "kilometers per second per million light-years of distance." Depending on your results and how you have drawn the straight line, its slope will be roughly *15 kilometers per second per million light-years*. This means that a galaxy that is a million light-years away will be receding at about 15 kilometers per second. A galaxy that is 3 million light-years away will recede at 45 kilometers per second, and so forth.

To be receding from us at the speed of light (300,000 kilometers per second) a galaxy would have to be this far:

$$\frac{\text{300,000 kilometers per second}}{\text{15 kilometers per second / million light-years}} = \text{20,000 million light-years}$$

Galaxies that are further than about 20,000 million light-years (or 20 billion light-years) are receding from Earth faster than light. These galaxies are invisible to us, because their light never reaches Earth. Therefore, 20 billion light-years is a limit to the size of our observable universe. No matter how powerful our telescopes, we cannot see beyond this limit.

In summary, nature limits our view of the universe in two ways:

- the universe is expanding, so we can't see beyond a certain distance; and

- the universe has a finite age, so we can only see matter whose emitted light has had time to reach us since the Big Bang.

The portion of the universe that nature allows to observe directly is called the *observable universe*.

Wrap-up discussion & Frequently asked questions

1. Summarize, with students, the major results of their investigation: Using the MicroObservatory telescopes, students observed galaxies all the way out to the telescope's limit of detection, beyond which the galaxies are too small or too faint to be seen clearly (about 200 million light-years). The Hubble Space Telescope has imaged galaxies about 50 times further away than this.

   It is possible that there are an infinite number of galaxies, but no one knows, because we can only see a portion of the universe. The light that arrives at our telescopes today has taken millions or even billions of years to get here from distant galaxies. Therefore the images we see show how the galaxies looked in the past: We can see the universe as it used to look.

   The students also showed that galaxies are moving away from us, according to a simple pattern: The more distant that a galaxy is from Earth, the faster it is moving. This leads to the conclusion that all the galaxies started from the same place — that billions of years in the past, the matter in our observable universe was very densely packed together.

2. Ask students what they make of their results. On the one hand, nature puts limits on how much of the universe we can see. On the other hand, nature has given us an extraordinary view, both in space and in time: We can look out at a universe huge enough to stagger the imagination, and we can see all the way back in time to the infancy of our universe. It didn't have to be that way; had the Earth been perpetually cloudy, or if the solar system or galaxy had been too dusty, our view of the universe might have been forever blocked. Fortunately, nature has given us a front-row seat in this great amphitheater of existence.

Frequently asked questions

What was the Big Bang?

The "Big Bang" refers to the earliest known moments of our observable universe. About 14 billion years ago, the contents of our observable universe were packed into a volume about the size of a grapefruit. The universe was then extremely dense, extremely hot, and filled with blinding light. Only a few of the simplest chemical elements existed. As the universe expanded — that is, as clumps of matter grew further apart—the universe cooled. Eventually, matter clumped into the stars and galaxies we observe today.

Is the Big Bang story true, or is it a just a theory?

The Big Bang scenario is now established as actually having happened. It is not a theory or a model.

How do we know the Big Bang scenario is true?

The Big Bang story is based on four pillars of evidence established over the past century:

We observe the galaxies moving further apart. This tells us that matter was much closer together in the past. From the speed and directions of the galaxies' motion, we conclude that they were all together about14 billion years ago.

We can see the ashes left over from the Big Bang. These "ashes" consist of simple elements that can only be produced at high density and temperature. These elements, found throughout the universe in the correct proportions, confirm that the early universe was not only very dense, it was also extremely hot.

We can see the heat and light left over from the Big Bang. The Big Bang took place everywhere in space, not just at a point. "Big Bang" light from very distant regions is just reaching us on Earth today, from every direction in space. Because the universe has cooled, this light can no longer be seen by eye; it requires special instruments to detect. This light confirms that the universe was once extremely hot.

We have a well-tested model that explains the Big Bang in detail. The model is Einstein's theory of gravity. The Big Bang was actually *predicted* before evidence for it was discovered. Over the past century, Einstein's description of gravity has met every test, and is in complete accord with observations of the early universe.

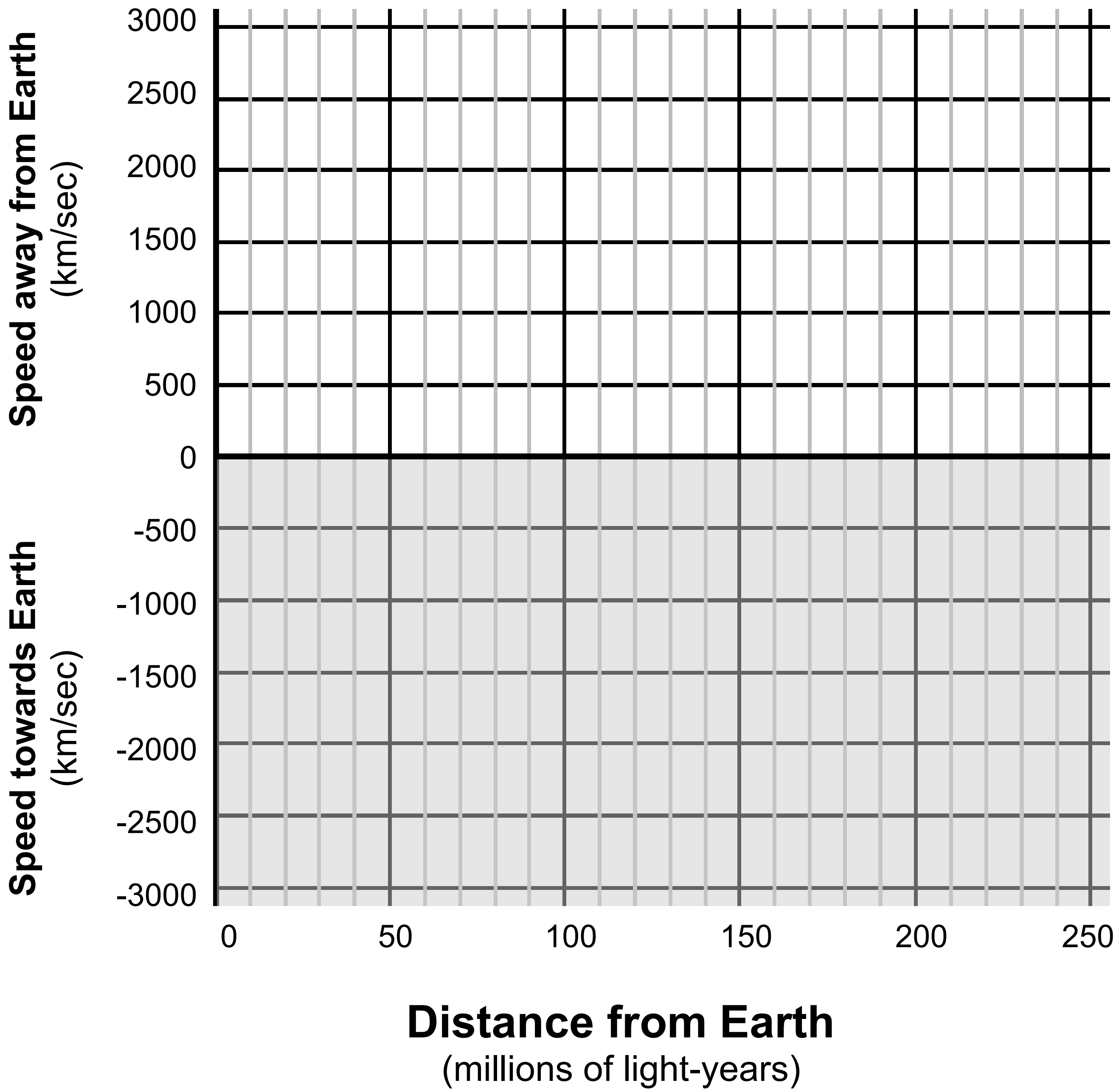
These and many other lines of evidence have established that the Big Bang took place as described. However, the following questions show that the Big Bang is not the whole story of the origin of the universe.

What caused the Big Bang in the first place? What came before the Big Bang?

No one knows yet. The Big Bang scenario does NOT tell us where space, time, and matter came from in the first place. Recent evidence suggests that just before the Big Bang, the universe consisted of space filled with a new, unknown form of energy. Scientists are studying what this energy might be, and how it was converted into the heat, light, and particles of matter that filled our universe during the Big Bang.

How old is the universe?

Plot galaxy's speed vs. galaxy's distance from Earth



How old is the universe?

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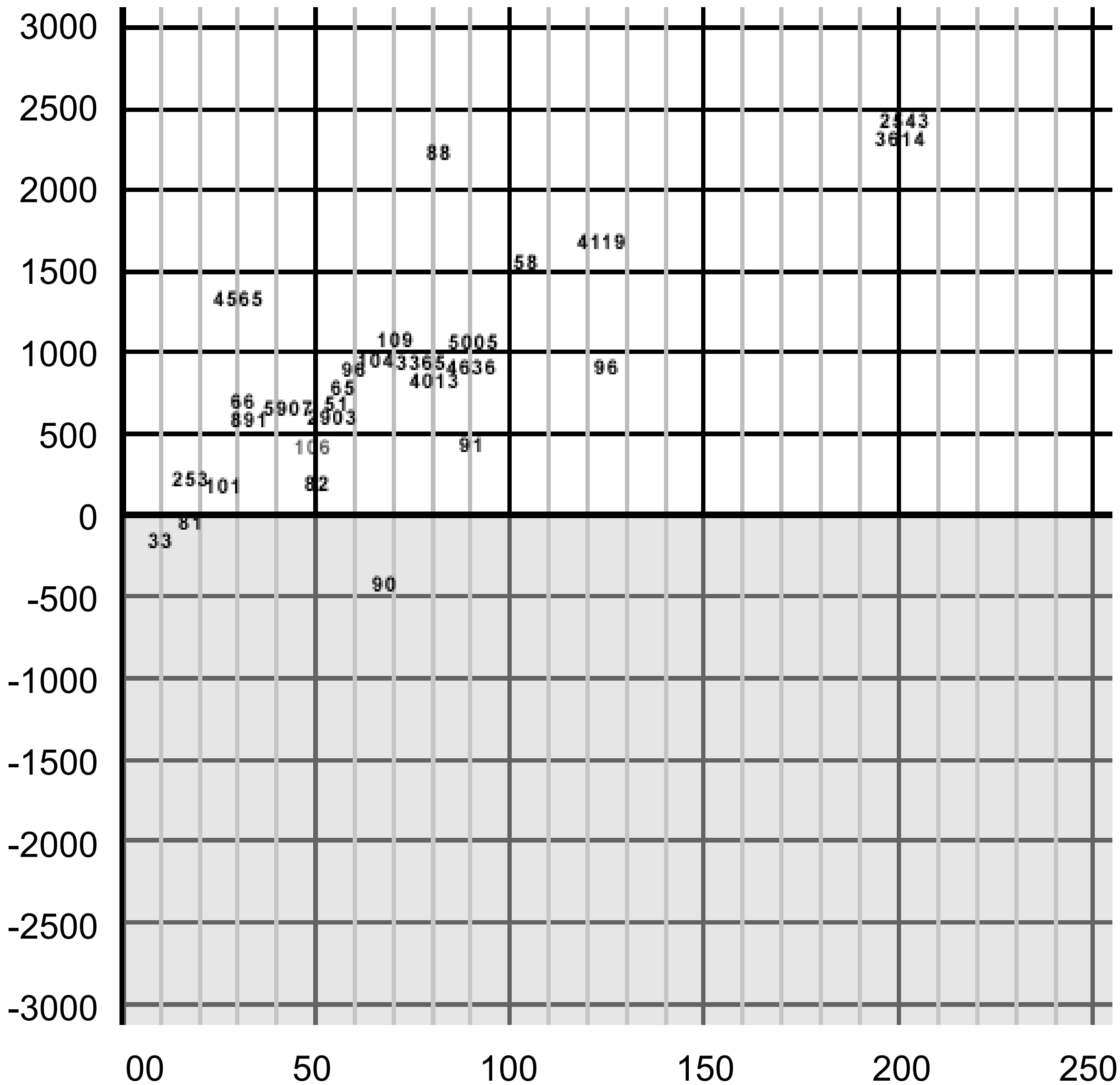

Distance from Earth

(millions of light-years)