Hubble’s Law: The Expanding Universe

(credit: NIRCam E/PO team, J. Donley, D. McCarthy)

Overview:

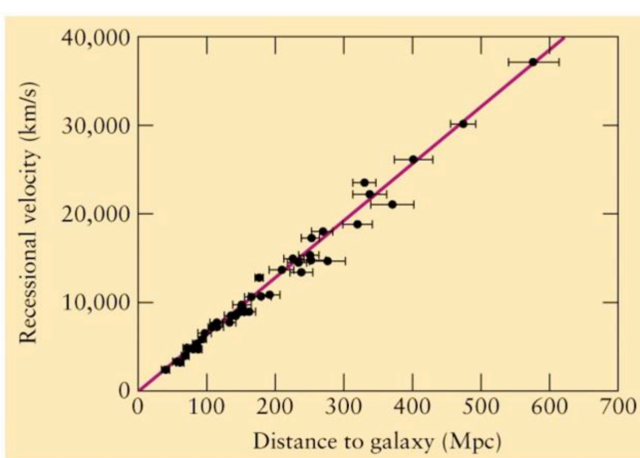
These activities allow students to understand the “expanding Universe” using familiar examples of cars along a highway, enlargements made with a copy machine, and a toy slinky.

Background:

In the early1900s, Harvard astronomer Henrietta Leavitt (one of the first female astronomers) measured the brightness of stars in a class known as Cepheid variables, which are bright, young stars with masses 5 to 20 times our own Sun. She discovered that these stars reveal their true brightness by the way their light varies, and that this makes them reliable markers for measuring astronomical distances.

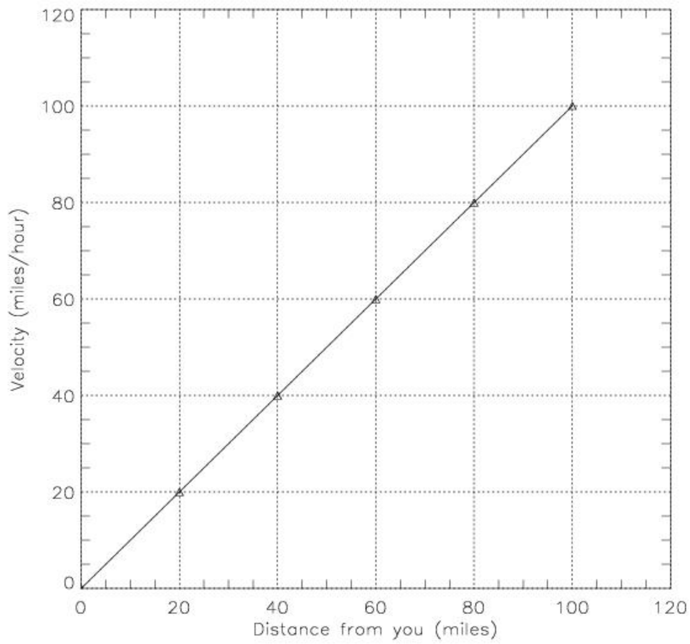
Astronomers Vesto Slipher (Arizona) and Edwin Hubble (California) used Cepheid variable stars observed in other galaxies to discover that the more distant a galaxy is from Earth, the faster it moves away. **In fact, almost all galaxies in the Universe are moving away from us and there is a proportionality between the distance to a galaxy and its velocity.** This relationship is called the Hubble Law, and is shown in the plot below. The ratio of velocity to distance is known as the Hubble Constant, H_o.

Hubble's observations led to the realization that space itself is expanding, carrying all galaxies with it, and that all galaxies were closer together in the past. This leads to a concept for the origin of the Universe called the Big Bang theory. The theory says that the Universe could have begun in an extremely hot and dense form and has been expanding ever since. The age of the Universe is estimated to be equal to the inverse of the Hubble Constant. The current estimate of the Hubble Constant suggests that the Universe is about 13.7 billion years (13,700,000,000 years) old.



Activity #1: Beginning Level

Imagine you are an alien who just arrived at Earth and saw funny things called cars moving along Interstate #10 away from Tucson towards Phoenix. You quickly measure the speeds of five cars and their distances from Tucson. Interestingly, all the cars are moving away from Tucson. You plot your measurements as follows:



Answer the following questions:

1. What does this plot tell you about the cars?
2. Could all of the cars have left Tucson at the same time?
3. If you assume that none of the cars has changed speed since the start, how long ago did they leave?
4. What is the ratio of the cars' velocities to their distances (the slope of the plot shown above)? What are its units?
5. What is the ratio of the distances to the velocities (1/slope)? What are its units? How does this value compare to your answer from question 3?

Our Universe exhibits a similar behavior but instead of cars, astronomers measure the “redshifts” and distances of entire galaxies. One interpretation of a galaxy’s “redshift” is that it is moving away from us through space. However, a more correct, modern interpretation, based on Einstein’s Theory of Relativity, is that **space itself is expanding** and pulling galaxies away from each other just as raisins in a loaf of bread are pulled away from each other while the bread rises when being cooked.

The slope of the straight line in the graph of galaxies on the first page indicates that the Universe could have originated **13.7 billion years ago**, i.e., **space and time had an origin**.

Activity #2: Beginning Level

The following transparency labeled "The Universe One Billion Years Ago" is a fictitious plot of the positions of galaxies in some region of the sky in the past. Each dot represents a galaxy; large dots indicate brighter galaxies. This transparency was enlarged 5% in a standard copy machine to simulate the expansion of space during one billion years of time; it is shown on the next page as "The Universe Today."

Pick a "home" galaxy and carefully overlay the two transparencies on that spot. You should see a pattern like that shown in the last figure below. Notice that all galaxies, except the one you are centered on, is doubled because you are seeing this fictitious Universe ~~are~~ at two different times and the galaxies have moved apart. You should get the impression that all galaxies are moving away from you, faster the farther away.

Do this same experiment using another galaxy as a centerpoint. No matter what galaxy you choose as home, you get the same impression of an expanding Universe. Therefore, astronomers conclude **the Universe has no center**, because everything was once together and space itself has been expanding to pull everything apart over time.

A more advanced extension of this activity:

Using one galaxy as our home, **make your own Hubble Diagram**. Use a ruler as shown below to measure the distance that galaxies have moved in the one billion years between the two transparencies; pretend one inch = 100 million light-years. That distance divided by one billion years represents a speed away from us. Plot that number versus the distance away from home measured in the first transparency. Your plot should display a similar straight line relationship between speed and distance. Use the slope of the line to derive the age of this simulated Universe.

Activity #3: Advanced Level

Required Materials (for each group of ~3):

1 Slinky
1 metric ruler
5-10 pieces of string
pen/pencil
1 copy of these instructions
1 calculator for challenge sections

Directions:

1. In this activity, you are going to create a model of the expanding Universe.
2. Tie 5-10 pieces of string to different parts of the Slinky. In this activity, the Slinky represents the Universe, and the pieces of string are galaxies in the Universe.
   Q: What is a galaxy? How does it relate to a star, or to a solar system? What is the name of our galaxy? Can you draw what it might look like from far away?
   [You cannot stick a question in the middle of a set of directions. Either have it

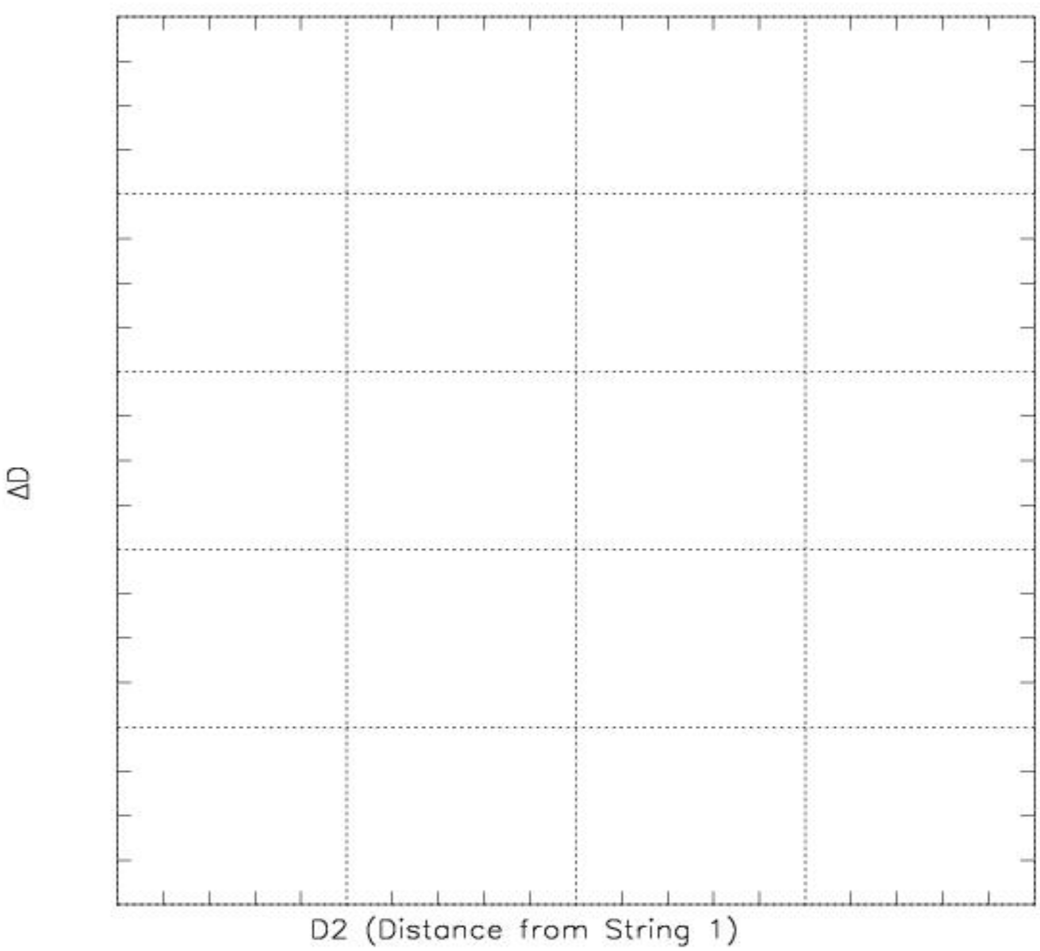
before the directions or after the questions. Probably best before. Call it "Prior Knowledge."]

3. Lay the Slinky on a flat surface and stretch it out a bit. Measure the distances between your home galaxy (the first piece of string) and each of the other strings. Record your findings on the Table below.
4. Carefully stretch the Slinky about twice as far and measure the new distances between your home galaxy (the first string) and the remaining strings. Record your findings on the Table below.
5. Plot the values of D2 (the distances between the first string (your home galaxy) and the others) and ΔD on the graph above. You will need to choose the scales of the x-axis and y-axis.

String	***Distance from String 1*** ***(Slightly stretched)*** ***(D1)***	***Distance from String 1*** ***(Stretched further)*** ***(D2)***	***ΔD =*** ***(D2-D1)***
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Questions:

1) Compare your graph to the graph of the Hubble Law. How are they similar and different? (Note: if you would like to convert your value of ΔD to a velocity like that of the Hubble Law, you may assume that the expansion you measured took place over 1 second).
2) What does this tell you about the reason for the Hubble Law (the reason that more distant galaxies are moving away from us at larger speeds)?
3) What do you think you would see if instead of measuring the distances from the first string to the others, you measured them from the second, or the third, to the others?
4) Did your strings change in size as the Slinky expanded? Do you think a galaxy would change its size as the Universe expands.



Challenge Section:

Using the first plot of the Hubble Law, on page #1, estimate the recessional velocities and distances of 5 real galaxies. Use each galaxy to estimate the Hubble Constant, H_o, by dividing its velocity by its distance. Record you findings in the Table below.

Galaxy	***Distance (Mpc)***	***Velocity (km/s)***	***H_o***
1			
2			
3			
4			
5			

1. What is the average value of your Hubble Constant?
2. What are the units of the Hubble Constant?
3. How does your value compare to the value astronomers measure today?
4. Can you accurately measure the Hubble Constant from 1 galaxy? What about 5?

Now that you've measured the Hubble Constant, you can calculate the age of the Universe!

1) You will first need to convert the distances you measured above from Mpc (Mega-parsecs) to km (kilometers). 1 Mpc = 3.08×10^{19} km. Write the new values in the Table below.
2) Next, measure the Hubble Constant in units of (1/seconds) by dividing the velocity by the distance.
3) Measure the age of the Universe by taking the inverse of the Hubble Constant ($1/H_o$).

Galaxy	***Distance (km)***	***Velocity (km/s)***	***H_o (1/s)***	***$1/H_o$***
1				
2				
3				
4				
5				

1) What is the average value you measure for the age of the Universe?
   (Hint: 1 year = 3.16×10^7 seconds.)
2) How does this age compare to the value astronomers measure today?

<u>Fun Facts:</u>
Astronomers continue to study Hubble's Law in great detail using the most modern telescopes on Earth and in space.

1. Hubble's Law has taught us that the Universe is expanding about 7% more every billion years.

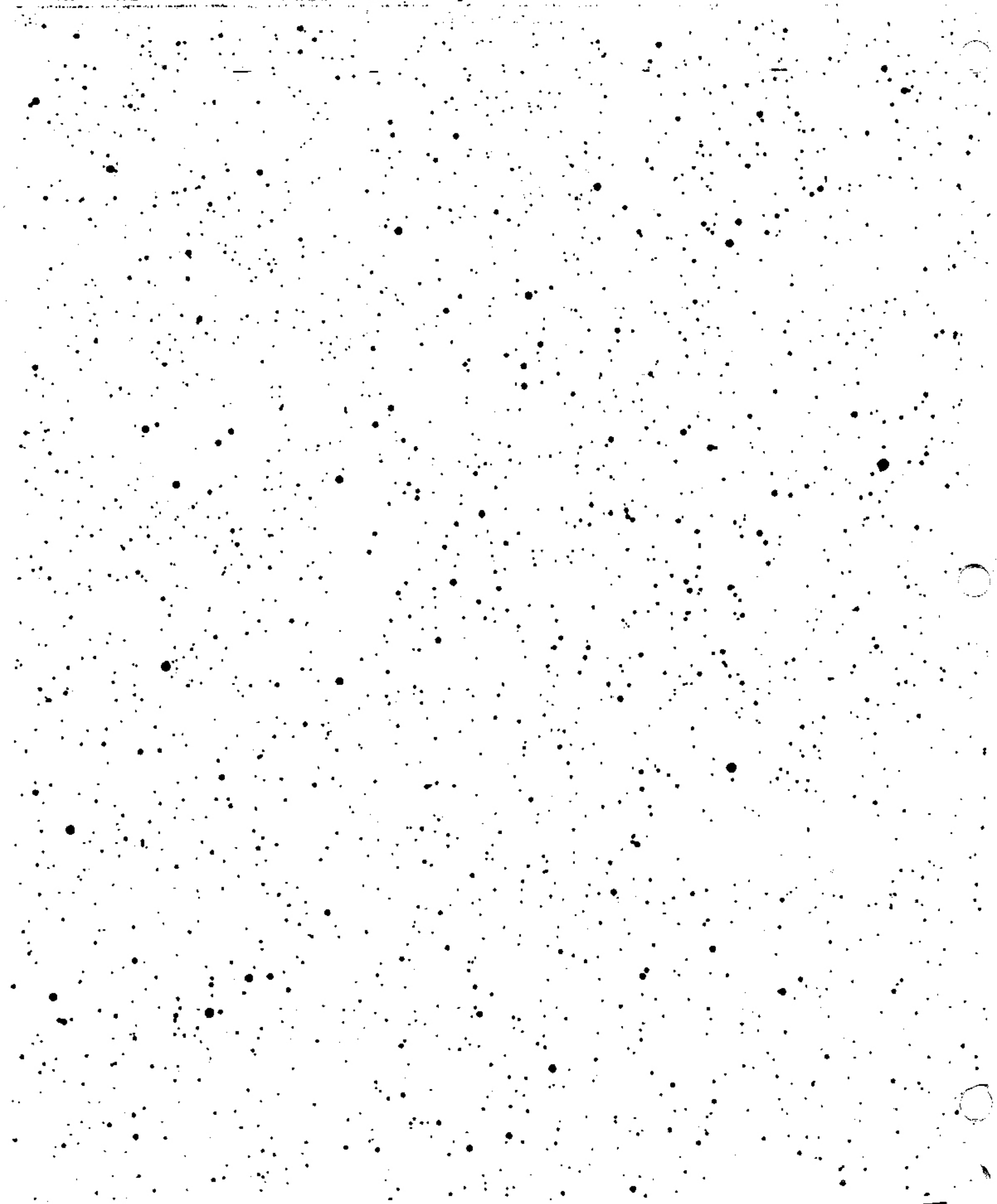
2. Astronomers have observed galaxies as far away as 12 billion light-years, allowing us to study how stars, galaxies, and the Universe worked 12 billion years ago.

3. The James Webb Space Telescope will be launched in the year 2013 and will study the very first stars and galaxies that ever formed in the Universe.

4. Astronomers were surprised recently to learn that the expansion of the Universe is accelerating instead of slowing down. Understanding this mystery will help us understand if the Universe will rip apart or collapse far in the future.

5. When the Universe was very young and hot, it radiated like the surface of a star. Today, this light is detected as microwave radiation, and is responsible for about 1% of the static you see when your television or radio are tuned between channels.

The Universe One Billion Years Ago



The Universe One Billion Years Ago

The Universe Today