A Brief Guide to Our Cosmic Context

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last modified 11/21/08

Whirlpool Galaxy (M51) - S. Beckwith (STScI)

There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened.
— Douglas Adams, *The Hitchhiker's Guide to the Galaxy*

Introduction

Cosmology is the science of the very big picture. It addresses some of the grandest questions we can ask, such as:

• *What does the universe look like on the largest distance scales?* Do planets and stars go on forever, or do they come to an end somewhere? If they end, is there empty space beyond them, or does space itself come to an end? How far apart are the things we can see in the universe?

• *What is the history of everything we see around us?* You know that you have a history – stages in your life that led to the person you are today. But how far back does history extend? Where did the Earth come from, and the stars we see in the night sky, and the elements (like carbon and oxygen) that make up the cells in your body?

• *What is the universe made of?* On Earth we know there are a few basic building blocks (such as electrons, protons, and neutrons) that are the ingredients for everything we see. Is the rest of the universe composed of the same building blocks, or do things have a completely different composition other places in the universe?

Thanks to modern science and technology, we have pretty good answers to these kinds of questions. So we can put together a reasonable picture of the cosmic context from which we emerged to wonder about where it all came from.

We'll begin with a survey of how far away different things in the universe are from us. In order to describe the huge distances we'll encounter, we need a unit called a **light year**. Despite the word "year" in its name, a light year measures *distance*, not time. It is the distance a flash of light (traveling 300,000 km/s) covers in one year (about 10 trillion km, in case you were wondering).

A Tour of the Universe

Imagine yourself looking out at the ocean from a beach. Think of how big the Earth looks from this perspective. For reference, the diameter of Earth is about 13,000 km. Light can cover more than 23 times this distance in one second. The same flash of light takes a little over a second to reach our Moon, about 8 minutes to reach the Sun, and about 5 hours to get to Pluto.

The stars are also suns, but so far away that they appear as tiny points of light. It takes light over 4 years to get to the next closest star beyond our Sun. There are at least 200 billion stars collected together into the "island" of stars we inhabit, called the Milky Way Galaxy (Figure 1). Our Galaxy is about 100,000 light years across.

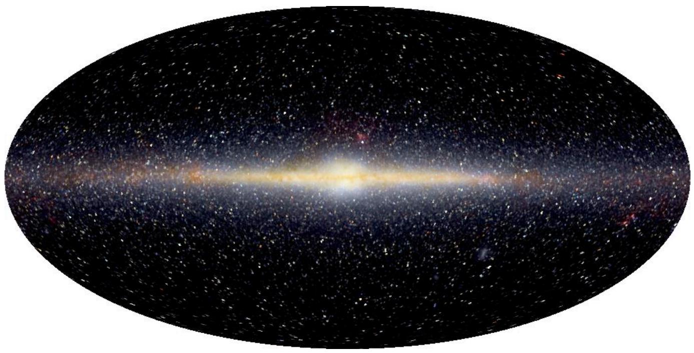

Figure 1 – This all-sky panorama view is a picture of our Milky way galaxy (seen from our point of view of course, inside the disk-shaped island of stars). [Image from http://antwrp.gsfc.nasa.gov/apod/image/9712/milkyway_cobe_big.jpg]

It turns out that there are hundreds of billions (at least) of these islands (galaxies) scattered throughout the universe, each containing hundreds of billions of stars. One of our nearest neighbors, the Andromeda Galaxy, is about 2.5 million light years away. Another relatively close neighbor, the Whirlpool Galaxy, is about 31 million light years away (shown in the image at the start of this guide). Our Galaxy would look something like this if we could see it face on from a distance, rather than edge on from within.

Astronomers have taken pictures of millions of these galaxies. A small sample is the Hubble Deep Field showing hundreds of galaxies within a region of sky much smaller than the full Moon.

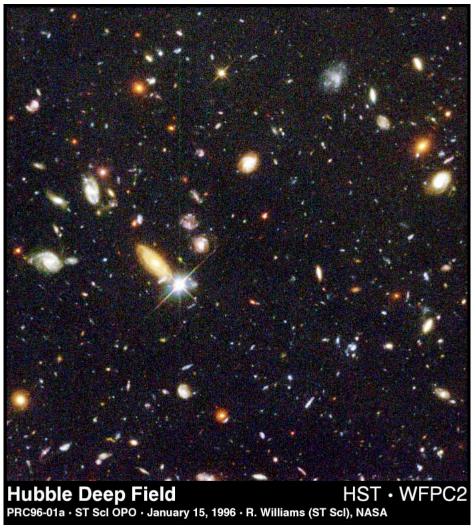

Figure 2 – Several hundred galaxies in a region of the sky 1/30th the diameter of the full Moon. Each splotch of light is a galaxy; some are billions of light years away. [http://hubblesite.org/newscenter/newsdesk/archive/releases/1996/01/image/a]

Summary of Distance Scales

Earth (diameter)	13,000 km
Earth to Moon	384,000 km (1.3 light seconds)
Earth to Sun	8 light minutes
Earth to next star	4.2 light years
Milky Way Galaxy (diameter)	100,000 light years
Earth to Andromeda Galaxy	2.5 million light years
Earth to distant visible galaxies	*billions* of light years

For a more detailed tour of the distances and arrangement of stars and galaxies in our universe, visit http://www.anzwers.org/free/universe/ (seems to work best in Internet Explorer).

Motion and History

The work of astronomers V.M. Slipher, Henrietta Leavitt, Edwin Hubble, Milton Humason, and others led in 1929 to one of the most amazing discoveries in the history of science: most *galaxies in the universe are moving away from us at high speed*. What's more, the farther away they are, the faster they are moving. To give you an idea, it turns out that a galaxy 1 billion light years away is increasing its distance from us at a rate of about 20,000 km/s!

Today astronomers have observed millions of galaxies so we can see a clear, direct relationship between distance and speed. This relationship is known as the Hubble Law, and it has the mathematical form: $v = H_0 \times d$, where v is the speed of the galaxy, d is the distance to the galaxy, and H_0 is a proportionality constant known as the Hubble constant (it indicates how fast galaxies are moving away for a specific distance apart). The best current measurements indicate that H_0 is about 70 (km/s)/Mpc. One Megaparsec (Mpc) is another common distance unit in astronomy, equal to 3.3 million light years. Figure 3 shows the relationship between speed and distance in graphical form, known as a Hubble Diagram.

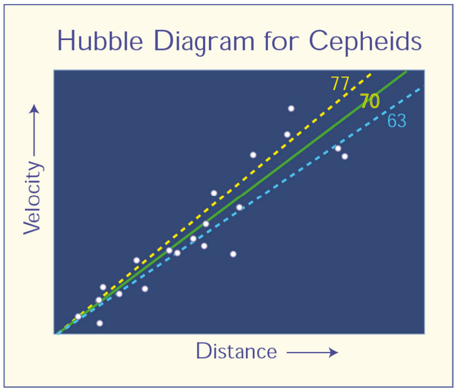

Figure 3 – Hubble Diagram. Points represent distances and velocities of various galaxies. The line that best fits the data has a slope of about 70 (km/s)/Mpc.
[Hubble Space Telescope Key Project; http://hubblesite.org/newscenter/newsdesk/archive/releases/1999/19/image/j]

You can use modern data from the Sloan Digital Sky Survey to make your own Hubble Diagram (http://cas.sdss.org/dr4/en/proj/advanced/hubble/ – this is an advanced, fairly involved activity).

Let's pause a moment to consider what this means. All but the very nearest galaxies are moving away from us, at a rate proportional to their distance away. At first glance this suggests that we are in a special location, since everything is moving away from *us*. But surveying the contents of the universe reveals nothing particularly special about our location. We orbit a fairly typical star among billions, located in a typical galaxy among billions. The answer to this apparent paradox is that space itself is expanding, and simply carrying galaxies along with it! This is a difficult concept to grasp. You can discover the essence of the idea for yourself by drawing dots on a balloon and inflating the balloon. See http://cas.sdss.org/dr4/en/proj/basic/universe/expanding.asp for an activity to illustrate how this produces the same type of distance to speed relationship we see in the Hubble Diagram.

The key point to grasp is that *space expanding* is not the same as galaxies moving *through* space. Galaxies are not moving apart from each other by moving through space; they're being carried along as the space they are embedded in "stretches out" or expands. Figure 4 illustrates this for an imaginary, 2-D universe that's easier to visualize than our real one.

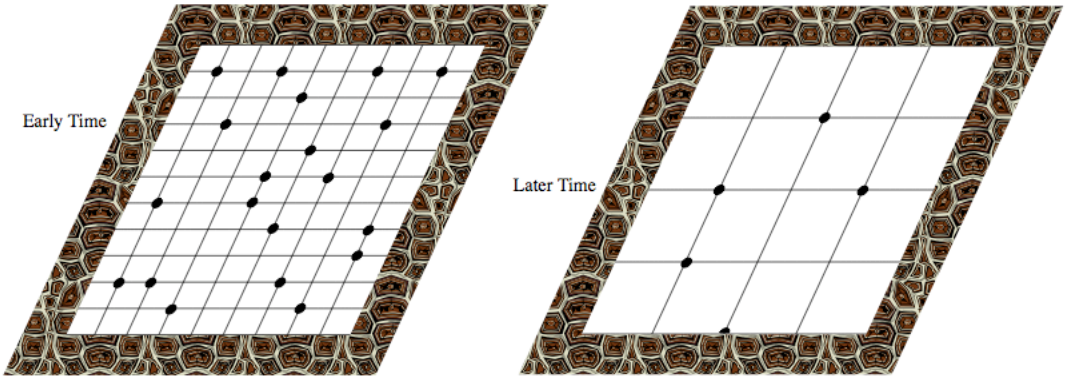

Figure 4 – An expanding universe. This 2-dimensional model illustrates how expansion of space (represented by the grid lines), carries galaxies (dots) along with it, even though here the dots themselves aren't moving through space at all. The 5 dots near the center of the left frame are the only ones still visible in the right frame. The rest have expanded out of view. Notice that there is not necessarily an "edge" (or a center) of the universe. The picture frame highlights a view of one little region of space. Presumably the scene would look much the same if we looked at any other region of the universe.

Of course, if the galaxies are moving apart from each other now, this means that in the past they were closer together. Imagine watching the expansion run backward in time, like playing a movie in reverse. As we go farther and farther back in the history of the universe, galaxies were closer and closer together. Far enough back, we no longer see separate galaxies. Rather, the universe was a hot, dense soup of matter and energy. The name "**big bang**" comes from this recognition that the universe was once hotter and denser than the interior of the Sun, and has been expanding and cooling ever since. So if you cup your hands together, you can hold a little bit of space that was once hotter than the Sun, and glowed with light that might just now be arriving at the detector of a distant observer billions of light years from here, who is also trying to understand the big bang.

By looking at the expansion rate today, astronomers estimate that the universe began in this very hot dense state about 13.7 billion years ago. You can calculate a rough estimate for the "age of the universe" yourself. The Hubble Law tells you that a galaxy 1 Mpc away from you is moving away at a rate of 70 km/s due to the expansion. Assuming this rate was the same in the past, you can use the standard formula time = distance/speed to figure out how long it took to cover 1 Mpc, moving at 70 km/s. (You'll have to convert Mpc into km, and seconds into years to get your answer in years).

This introduction is only a glimpse of your cosmic context. The resources below will help you get started if you'd like to learn more.

Resources for Further Exploration

Cosmology

Duncan, Todd and Craig Tyler. *Your Cosmic Context: An Introduction to Modern Cosmology*. San Francisco: Addison-Wesley, 2009.

Lineweaver, Charles H. and Tamara M. Davis. "Miconceptions about the Big Bang," *Scientific American*, March 2005, pp. 36-45. (A great article answering some of the common misconceptions about the big bang theory of the universe.)

Hubble Space Telescope web site with many incredible images of the universe: http://hubblesite.org/

More in depth tour of distances in the universe: http://www.anzwers.org/free/universe/ (seems to work best in Internet Explorer)

Sloan Digital Sky Survey (images from a survey of over a million galaxies, and several learning activities): http://cas.sdss.org/dr4/en/

Second Law of Thermodynamics and the Arrow of Time

The "second law of thermodynamics" expresses the familiar experience that heat flows from hot things to cold things, and not the other way around. But there is much more to the second law. It is related to our experience that time flows in one direction (the "arrow of time"), and it shows up in the study of black holes and the question of what might have happened "before" the big bang. Here are a couple of references to get you started learning more about the second law of thermodynamics.

Slides from a talk introducing the second law can be found at: http://www.scienceintegration.org/Education/Previous/Lecture1/lecture1.html#secondlaw

An excellent book explaining the second law and the history of its discovery is:
von Baeyer, Hans Christian. *Warmth Disperses and Time Passes: The History of Heat.* New York: Random House, 1998.