# 5.4: Evolution of Galaxies and the Universe Itself

**What Do You Think: Change in the Universe**

In the first section of this chapter, we discussed how astronomers measure distances in terms of the time required for light to travel across them. We introduced the idea of the light-minute, the light-hour, and the light-year as distance measurements. This method works because the speed of light is constant. That means light will always travel a certain distance in a given amount of time. For example, in a time interval of one year, light will always travel one light-year, or about 6 trillion miles. In a different time, say one second, light always travels a light second, which is about 300,000 kilometers. We can use the constancy of the speed of light to measure distances this way for any time period we like.

However, the constancy of light speed means that light is not only a useful tool for measuring distances; light can also be used as a sort of time machine. How can we do this? We will explore this idea by using the Sun as an example.

We know that the Sun is about 8 light-minutes away from Earth. In other words, it takes 8 minutes for light to travel from the Sun to Earth. Therefore, we see the Sun as it was 8 minutes ago. If the Sun were to suddenly stop shining, we would not know about it for 8 minutes!

As another example, the closest star to the Sun is Alpha Centauri. It is the brightest star in the southern constellation Centaurus. Light requires four years to reach Earth from Alpha Centauri, so Alpha Centauri is 4 light-years away from us. In addition, we see the star not as it is, but as it was four years ago. Because stars fdo not change very much on a timescale as short as four years, we do not notice the time delay due to the speed of light when we observe nearby stars.

Viewing other galaxies, however, the situation changes. The nearest galaxy to the Milky Way is M31. It is located in the northern constellation Andromeda. Light takes about 2.5 million years to reach us from M31, so M31 is 2.5 million light-years away from us. But just as above, this also means that we see the galaxy M31 not as it is currently, but as it was 2.5 million years ago. That is a very long time for us, but it is not a very long time for a galaxy. Galaxies change on timescales of hundreds of millions of years, not just a few million years.

What happens if we look at even more distant galaxies? The most distant galaxies we observe are not millions of light-years away, they are billions of light-years away. As a result, as we look at galaxies that are more and more distant, we see them as they were hundreds of millions or billions of years ago. Given those long delay times, we begin to see that even galaxies have changed over time.

Distant galaxies, seen as they were when the Universe was younger, tend to be smaller (in size) and less massive (they contain less stuff) than nearby galaxies. They also tend to be bluer and have stronger indications of ongoing and recent star formation than nearby galaxies have. We also see that the shapes of galaxies has changed over time. Very distant galaxies tend to have odd, clumpy shapes. A much larger fraction of nearby galaxies have regular, disk-like shapes (like the Milky Way or Andromeda) or elliptical shapes.

Does this mean that we live in a special part of the Universe where the galaxies are more massive and have more regular shapes? No, it does not. Remember that when we look at distant galaxies, we are really looking back in time, seeing them as they were when the Universe was much younger than it is now. What we are in fact seeing is evidence that galaxies have grown in size and mass, that they have used up some of their star forming fuel, and in many cases, that their shapes have stabilized over time. What would astronomers living in the most distant galaxies see if they observed the Milky Way? They would not see our Galaxy as the large spiral disk we live in today. Instead they would see a small “proto” galaxy, the one that eventually evolved into the Milky Way. That is because the light they would be observing "now" actually left our Galaxy billions of years ago, when it was much younger than it is now. Over the intervening time the light has been traveling across the immense distance between ourselves and the imagined alien astronomers who are only now able to look out toward us, viewing the ancient light as it arrives at their location.

One of the most difficult concepts that students deal with when studying cosmology is the time-machine effect due to the speed of light. We are used to thinking that light travels instantaneously between objects, but that is not true. Even in our normal experience, it takes time for light to travel from one place to another: light takes 1 nanosecond (a billionth of a second) to travel 30 cm, or about a foot. This amount of time is too short for us notice, though it can be measured by electronic circuits. In the study of cosmology, however, the distances are so large that the light travel time becomes quite noticeable. This effect has some advantages, as we are able to view almost the entire history of the Universe by looking at more and more distant objects.

Some of the most impressive observations obtained thus far are from the Hubble Deep Field and Hubble Ultra Deep Field images taken by the Hubble Space Telescope. In each of these, the telescope was pointed for about 10 days at small patches of sky that contained no bright stars. By exposing the telescope’s cameras to these patches of sky for such a long time, the cameras were able to see “deeply” into the Universe, building up the light from very faint, very distant galaxies. Recently, astronomers estimated that one of the galaxies in the Hubble Ultra Deep Field image is 13.2 billion light-years away, seen as it was when the Universe itself was less than half a billion years old. We can imagine a team of alien astronomers in that galaxy, as it exists "now," peering back in our direction and seeing our galaxy at that time, long before humans or the Sun or Earth even existed. This is the time machine afforded us by the finite, and constant, speed of light.

In the movie at the beginning of the next section, astronomers’ knowledge of the distances of galaxies in the Hubble Ultra Deep Field has been used to create a “fly-through” video of this region of the sky. This visualization allows us to take a virtual trip into the Universe’s past!

### Hubble Space Telescope Ultra-deep Field Fly-through

Play this video to take a voyage through the Hubble Ultra Deep Field, into the Universe’s past. These deep field images allow us to peer nearly all the way back to the beginning of the Universe. The galaxies you will see at first are closer to us. As the movie plays, it will be going farther away in distance and farther back in time. All of the images and distances have been measured directly with the Hubble Space Telescope.Observations of galaxies can help us learn about the formation and evolution of the Universe itself. The famous astronomer Edwin Hubble (1889–1953) measured the velocities of nearby galaxies by taking spectra of them and measuring the Doppler shift of their spectral lines. Hubble found that nearly all of the galaxies he studied are moving away from us, and the more distant galaxies are moving away from us at faster velocities than the galaxies closer to the Milky Way. This observation, that more distant galaxies have faster velocities away from us, is called Hubble’s law. In a later chapter we will study the details of Hubble’s measurements and other observations since his time that support his results. But an important thing to take away now is that Hubble’s law indicates that the *Universe is expanding!*

This video contains no audio. Video link.

Answer the following:

1.

2.

When you get to the end where there are no more galaxies visible, it is not because you have reached a *place* in the Universe where there are no galaxies, nor is it because the galaxies at those distances are too faint for us to see. It is because you have traveled back to a time in the history of the Universe, more than 13 billion years ago, *before galaxies had formed!*

3.

The idea that the Universe is expanding might be new to you. Or it may be something you have heard about before. Even if you have heard about the expansion, you could be unfamiliar with the astronomical observations that lend weight to this idea. Either way, you might now be wondering: Why is the Universe expanding? Will it continue to expand, or will it stop at some point? These are good questions, the kinds of questions we will investigate further in later chapters. For now, we will take a little closer look at the Universe's past.

## 5.4.1: A Quick Overview of Big Bang Cosmology

Imagine that the Universe is not just expanding now, but that it has been expanding throughout its history. That would mean in the past there was less space between galaxies than there is now, and the farther back into the past we looked, the less space between galaxies we would see. We can keep "rewinding" this scenario until we imagine that all the matter in the Universe today was packed into an extremely dense, very tiny volume. That would have been the earliest stage of an ever-expanding Universe.

What caused the Universe's expansion? Astronomers do not know entirely, but they call the model for how the Universe has changed over time since then the Big Bang Theory, or sometimes the Big Bang Model. Some people colloquially call the early moments of the Universe's existence the "big bang." Perhaps this is to emphasize the fact that the Universe sprang into existence a finite time in the past—13.7 billion years ago—but really, the model explains all of the epochs of time: the past, present, and future of the Universe, not just the earliest moments. Therefore, we will use the phrase Big Bang to mean the model or explanation for how the Universe changes over time.

Using our observations, and explaining them in the context of this model, we can reconstruct the history of the Universe. A brief overview is presented below. We will go into more detail in Module 3.

In the beginning, the Universe was extremely hot and incredibly dense. It contained high-energy photons (light) and other subatomic particles. After about 1 minute, the Universe had cooled considerably from its starting point, but it was still incredibly hot (temperature = 1 billion kelvin). At this stage, the density and temperature in the Universe were both high enough that nuclear fusion could occur, just like at the center of a star today. Protons and neutrons combined to form helium nuclei and a tiny amount of lithium (Figure 5.13). This era, when the lightest elements in the periodic table were created, is known as the era of **Big Bang Nucleosynthesis** (BBN). The heavier elements that we are composed of and depend on, such as oxygen, carbon, and nitrogen, have all been produced in stars after this time. They could not be made in the early Universe, because after about three minutes the ambient temperature and density, though still extremely high by earthly standards, were insufficient to sustain fusion.

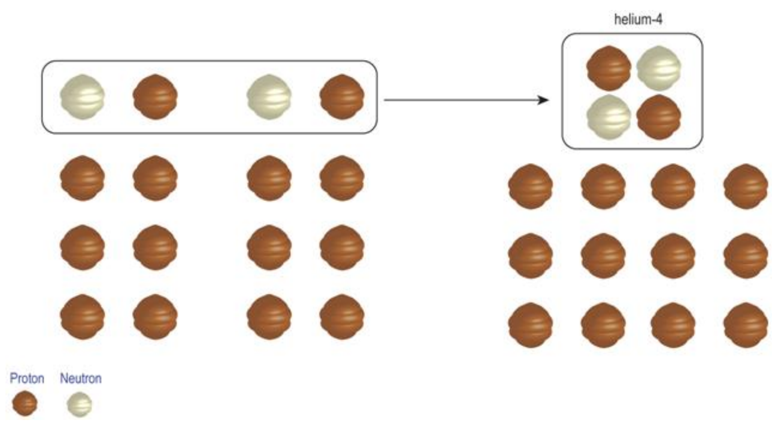


Figure 5.13: When the Universe was a few minutes old, it was the right temperature for nuclear fusion. There were seven protons for every neutron at that time. This led to approximately 25% of the available protons and neutrons forming $^4$He and 75% forming $^1$H. Trace amounts of deuterium ($^2$H), $^3$He, and lithium ($^7$Li) were also created. Protons are represented in the figure as brown particles and neutrons as white particles. Credit: NASA/SSU/Aurore Simmonet

At these early times in the history of the Universe, its temperature was so high that electrons were too energetic to combine with protons or other atomic nuclei. Instead, electrons whizzed around, frequently interacting with photons (light). Because of this, a photon could not travel very far before interacting with an electron, and the Universe was opaque (we would not have been able to see through it). This changed at about 380,000 years after the Universe began, when it had expanded and cooled down to a temperature of 3,000 K. At this point, the cooler temperatures allowed electrons to slow down enough to be captured by atomic nuclei, forming atoms, mostly hydrogen and helium. Because the electrons were now bound in atoms, they no longer interacted with light strongly. Light could then travel freely, and the Universe became transparent.

It is possible to see the light from this era still traveling through space; it is one of the most important lines of observational evidence supporting the Big Bang Model. It was first observed entirely by accident in 1963 by Arno Penzias and Robert Wilson, two astronomers who worked for Bell Labs.

While it was still opaque, the Universe itself behaved as a blackbody. If the Universe had expanded and cooled as we think it has according to the Big Bang, physicists predicted that it should contain a background of radiation that preserved this blackbody character. In particular, the relic radiation should have a temperature of a few kelvin above zero. A blackbody of this temperature would emit light most strongly in the microwave region of the electromagnetic spectrum today. This is exactly what Penzias and Wilson detected, and for which they later won a Nobel Prize. The background signal from the early Universe is called the Cosmic Microwave Background (CMB; Figure 5.14).

Astronomers have continued to study the CMB intensely since its discovery some sixty years ago. They have now measured tiny fluctuations in its temperature. These provide information about which regions of the early Universe were slightly more or less dense than average. The more dense regions are those where galaxies or even clusters of galaxies have since formed. Under the pull of gravity, the atoms that formed in the early Universe have combined to form stars, galaxies, and clusters of galaxies. These objects began forming when the Universe was 400 million years old, and we see them still today.

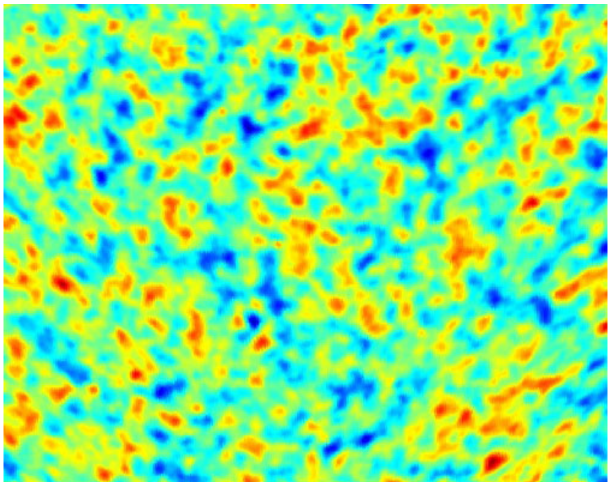

Figure 5.14: An image of the Cosmic Microwave Background (CMB), as measured by the Boomerang Group. Light from the CMB was emitted when the Universe was about 380,000 years old. The blue spots are places that were slightly more dense than average, and the red spots are places that were slightly less dense. Credit: NASA/NSF/Boomerang

This has been only the barest, most general outline of our current understanding of the evolution of the Universe as viewed through the paradigm of the Big Bang Theory of cosmology. We hope you have more questions about this and other topics related to the Big Bang, as well as questions about how the Universe has evolved and what its fate may be. That is the subject of the rest of the modules.