14.3: The Formation and Evolution of Galaxies

Learning Objectives

- You will understand why the different galaxy types look the way they do
- You will know that galaxies collide
- You will understand how the Milky Way formed from the mergers of smaller galaxies

What Do You Think: Why Do Galaxies Look the Way They Do?

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14.3.1: Galaxy Types

The Hubble Ultra-Deep Field (Figure 14.15) combines 800 exposures of an unassuming spot in the sky from NASA's Hubble Space Telescope (HST). Hold your index finger out at arm's length. The angular size of the Moon is about half of the width of your finger. The spot Hubble looked at for just over 11 days is only a tenth of the size of the Moon. Nearly every single blob of light you see in the image is an entire collection of stars, dust, and dark matter with a black hole in the center bound together by gravity —in other words, a galaxy**.** From this image we can start to classify types of galaxies.

Figure 14.15: In 2004 astronomers pointed NASA's Hubble Space Telescope at an empty patch of sky near the constellation Fornax and collected light for over 11 days. This image shows approximately 10,000 galaxies of various ages, sizes, shapes, and colors. Credit: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

Classifying Galaxies

Classification is often the first step toward scientific discovery. When confronted with a collection of data they do not understand, scientists try to organize the data by searching for patterns or trends that can give clues about the physical processes that affect the data.

In this activity you will analyze images of 16 nearby galaxies taken by the Hubble Space Telescope. You will attempt to organize them according to their shapes, colors, and one more characteristic of your choosing.

Play Activity

A. Shape

In this part you will examine the 16 images and classify them according to their shapes.

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B. Color

In this part you will examine the 16 images again and classify them according to their colors.

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C. Your choice

In this part you will examine the 16 images again and classify them according to a characteristic of your choosing. **Do not use size!**

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D. Comparing categories

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The structure or morphology of galaxies can be categorized as being either spiral, elliptical, or irregular. You might have chosen to use those terms or something similar in the previous activity. Edwin Hubble was the first person to classify galaxies in much the same manner. He noticed a correlation when comparing galaxy morphology and color. A correlation does not necessarily imply that one thing caused the other, but it does hint that the two properties are related. Elliptical galaxies tend to be red, while spirals and irregular galaxies tend to have more blue stars. Hubble developed a detailed morphological classification scheme known as the Hubble tuning-fork diagram shown in Figure 14.16.

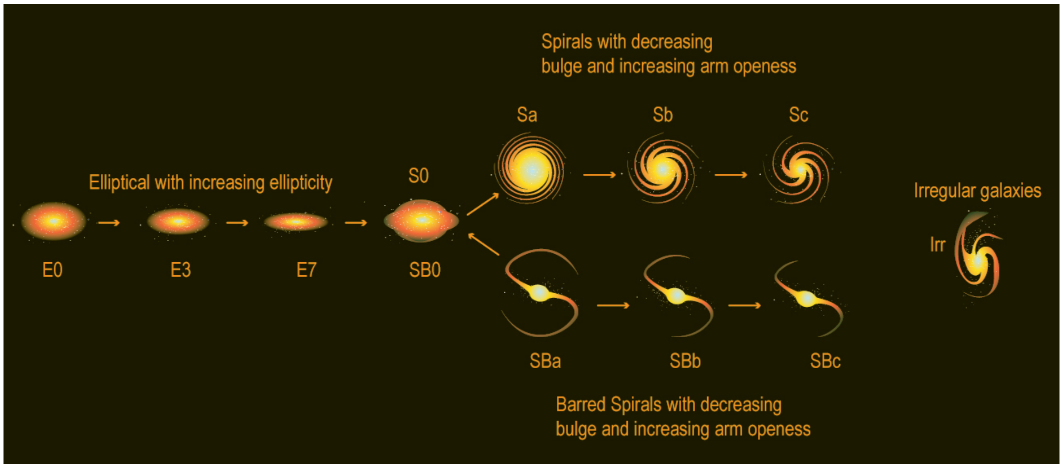


Figure 14.16: Edwin Hubble's tuning fork diagram divides galaxies into three groups: elliptical, spiral, and irregular galaxies. Elliptical galaxies are classified by how round or flat they look. Spiral galaxies are classified by how tightly the arms are arranged and whether or not the galaxy appears to have a central bar. Irregular galaxies are neither spiral nor elliptical and can have any number of shapes. Credit: NASA/SSU/Aurore Simonnet

These three broad categories can be further subdivided based on visual appearance. Hubble noticed that some spiral galaxies have a bright line, or bar, running through them. He called them barred spiral galaxies. Those without bars he simply denoted as spiral galaxies. Spiral galaxies are further classified by how tightly their arms are wound and the brightness of the central bulge. Elliptical galaxies are classified by how round or elliptical they appear. A transitional galaxy type, named lenticular is somewhere between highly squished ellipticals and disks. These lenticular galaxies have a central bulge but no spiral arms.

Hubble believed galaxies evolved from left to right in his tuning-fork diagram. We now understand this is wrong. There is no demonstrable way to make an elliptical galaxy spin up enough to form spiral arms. There is, however, a possibility that multiple spiral or irregular galaxies could collide and form a massive elliptical galaxy. Galaxy collisions are a natural consequence of gravitational interaction. In fact, astronomers have seen many examples of interacting galaxies (Figure 14.17).

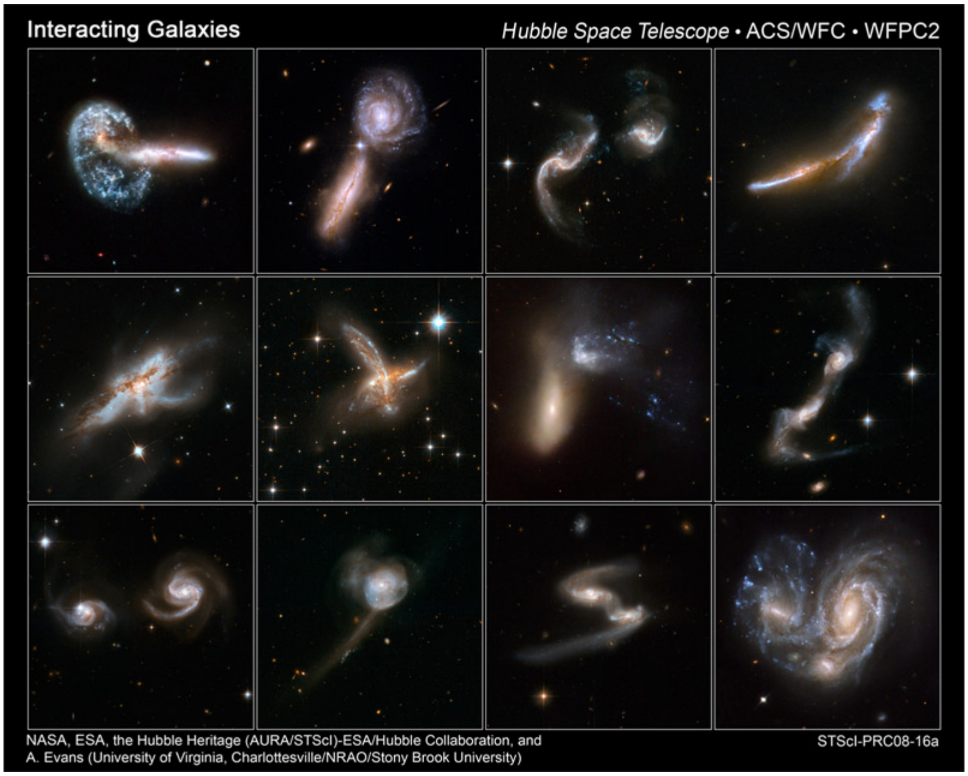
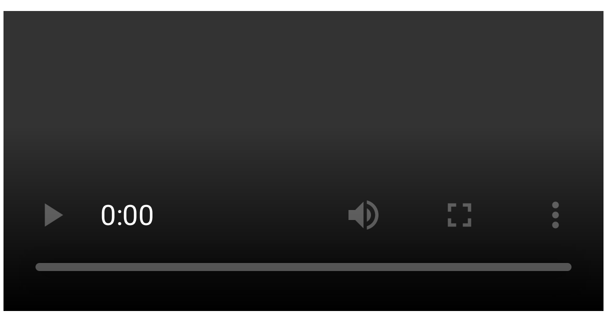


Figure 14.17: These groups of galaxies are all undergoing gravitational interactions. Some of these may one day end up as elliptical galaxies. Credit: NASA/ESA/AURA/STScI/A. Evans

Galaxy collisions can be modeled with simulations such as the one in Animated Figure 14.18. In this simulation, two spiral galaxies pass through each other, yielding a single larger elliptical galaxy at the end of the simulation. In galaxy collisions, the stars and dark matter in each galaxy interact gravitationally. Individual stars are so far apart that they do not actually collide. In fact, a better word for this process than "collision" is "merger." The galaxies do not actually collide during a galaxy collision, but the two interacting systems do eventually merge into one as they settle down. However, there is one component that, if present, does collide: the gas. Collisions between the gas components of the merging galaxies usually triggers huge bursts of new star formation during the interaction.



Animated Figure 14.18: This computer simulation follows two spiral galaxies as they collide and orbit around each other before finally merging. Credit: John Dubinski

The colors of galaxies can be explained by the types of stars they contain. As a galaxy forms, small density perturbations within the gas lead to regions where stars of various masses form. The color of a main sequence star ultimately depends on its mass. Blue stars tend to be more massive than 2 M_{Sun}, stars about the size of the Sun are yellow, and stars much smaller are red. These color differences are a direct result of their surface temperature. Color, temperature, mass, and radius are all intrinsically linked for main sequence stars due to the physics involved; blue stars are hotter, more massive, larger, and die quickly. Red stars are cooler, less massive, smaller, and live longer.

Since blue main sequence stars are also intrinsically brighter. They are so bright, in fact, that they tend to outshine all the red ones within any given group. It is not until a stellar population ages and the blue stars die out that we finally get to see the dimmer red glow of the small long-lived stars. Therefore, the average color of a galaxy is an excellent indicator of how much time has passed since new stars formed. Because stars form from gas, it also tells us how much free gas is available to condense into stars.

Irregular galaxies tend to have the youngest stellar populations. Vast quantities of gas provide the perfect stellar nursery for red, yellow, and blue stars alike. As one star cluster ages and turns more red, another nearby cluster starts anew, causing the galaxy to shine bright blue once again. While irregular galaxies contain stars of all colors, the young blue stars outshine all the others.

Elliptical galaxies are, for the most part, old and devoid of gas. Their reddish colors are dominated by long-lived, red main sequence stars. A majority of the regular matter is locked up in stars. As a result, there is very little ongoing star formation, so only the older, long-lived stars are still present.

Spiral galaxies show a range of star-formation histories and therefore a range of colors. The composite image shown in Figure 14.19 depicts what galaxies similar to the Milky Way would look like farther back in time - so at higher redshifts/lookback times. Notice in the middle, around 9.4 billion years ago, galaxies like ours started to show hints of yellow and red as star formation slowed and their population of massive blue stars began to die off.

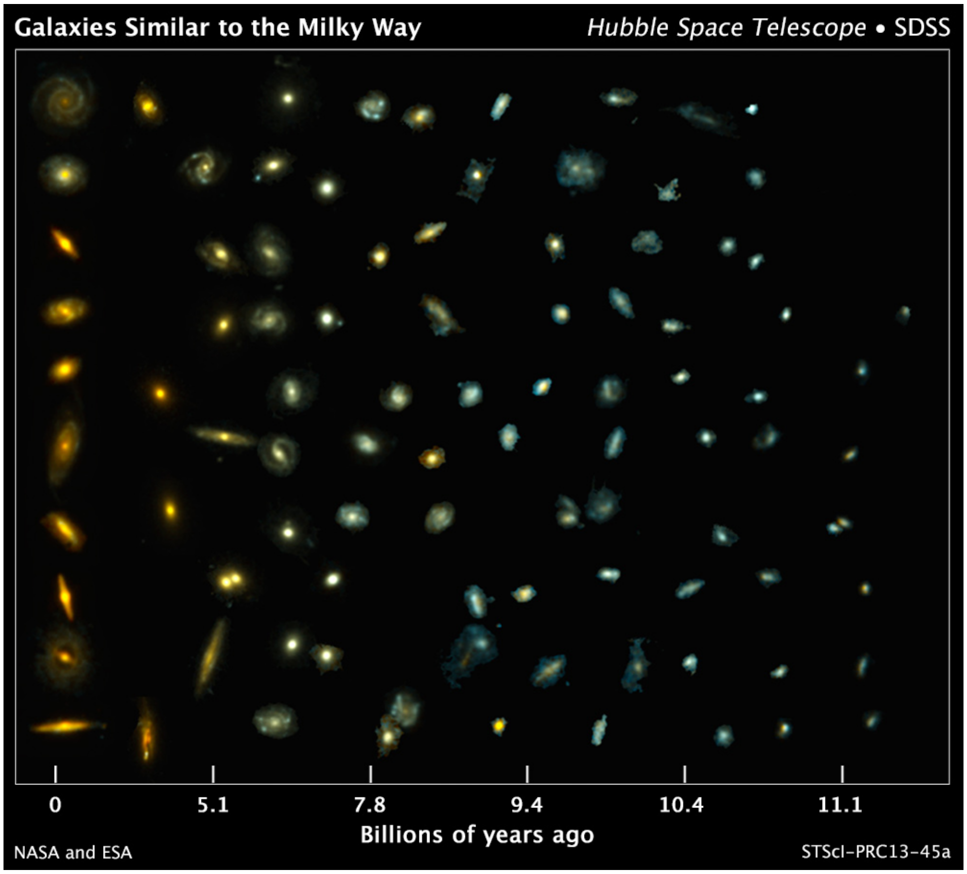


Figure 14.19: This composite image shows examples of galaxies similar to our Milky Way at various stages of construction over a time span of 11 billion years. The galaxies are arranged according to time. Those on the left reside nearby while those on the far right existed when the Universe was about 2 billion years old. The bluish glow from young stars dominates the color of the galaxies on the right. The galaxies at the left are redder from the glow of long-lived red stars. Credit: NASA, ESA, P. van Dokkum (Yale University), S. Patel (Leiden University), and the 3D-HST Team

The Colors of Galaxies

In this activity you will examine a cluster of stars within a galaxy. The slider on the bottom allows you to advance forward in time as the cluster evolves.

Play Activity

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14.3.2: Modeling the Formation of Galaxies

Once again we can compare detailed observations with computer simulations to understand how galaxies, particularly our own Milky Way, formed. From this we know our Galaxy built up over time due to the mergers of many satellite galaxies. These smaller dwarf galaxies collided with the Milky Way and were subsumed into it. In the distant future, the Small and Large Magellanic Clouds, as well as Andromeda, will merge with our Galaxy (Figure 14.20).

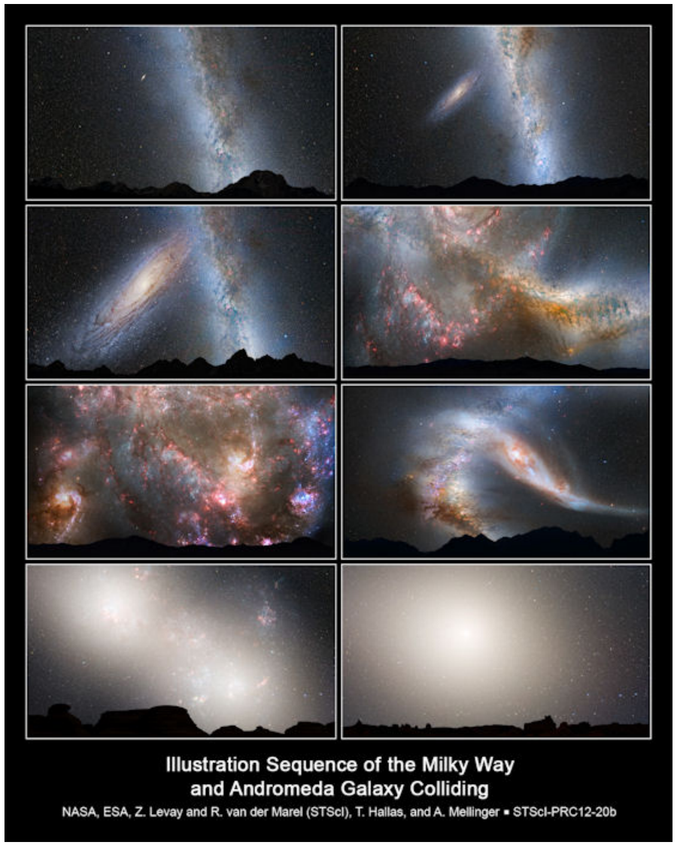


Figure 14.20: This series of photo illustrations shows the predicted merger between the Milky Way and Andromeda as seen from Earth. The first frame is the present day; the last frame is 7 billion years from now. Credit: NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger

We see relics of cannibalized galaxies in the night sky as streams of stars all moving in the same direction or with the similar distances and velocities. Figure 14.21 shows one such observation from the Sloan Digital Sky Survey.

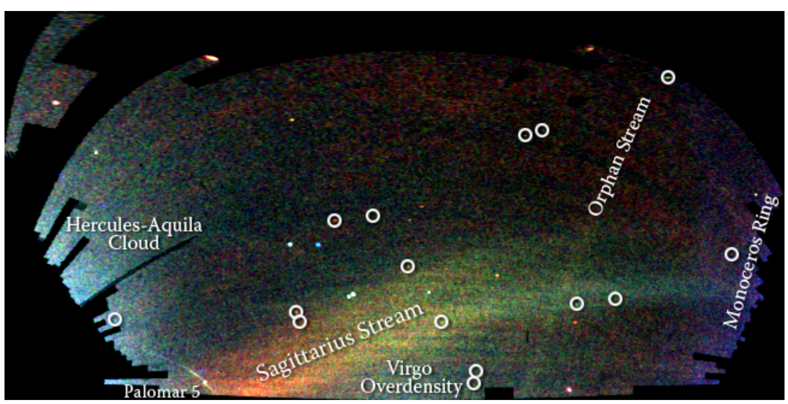
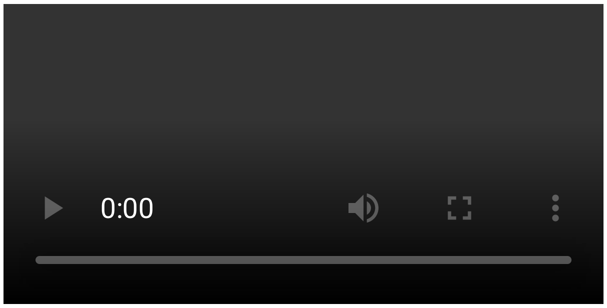


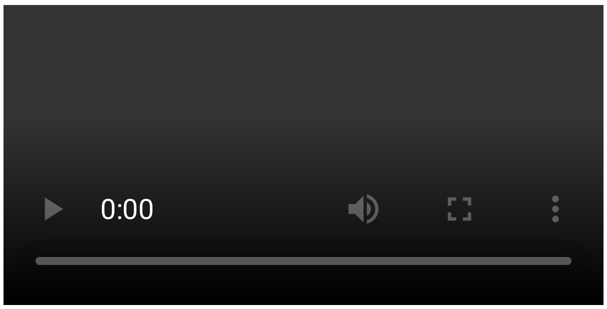
Figure 14.21: This image is a map of stars in the outer regions of the Milky Wave covering about one-quarter of the night sky, as observed by the Sloan Digital Sky Survey. The trails and streams that cross the image are stars torn from disrupted Milky Way satellites. The color corresponds to distance, with red being the most distant and blue being the closest. The circles show the location of several dwarf galaxy satellites. Credit: Vasily Belokurov, SDSS-II Collaboration

The goal of running galaxy computer simulations is to recreate these observations. Astronomers fine tune parameters like the number of dwarf satellites, how often mergers occur, the timing of star formation, and how much star formation affects the overall environment. Combining all of these effects allows astronomers to understand the underlying physical phenomena. The simulation in Animated Figure 14.22 shows one such model run at the University of Zurich. Many small clumps of gas pass by and eventually fall in to the galaxy. In Animated Figure 14.23, we can see what the arrival of the Small and Large Magellanic Clouds to our

Galactic neighborhood would look like if you had very sensitive eyes. In fact, galaxies have such low surface brightness that even the several nearby dwarf galaxies very close to the Milky Way appear to us as indistinguishable from the stars that are part the general Milky Way star field.



Animated Figure 14.22: This movie shows the formation of a spiral galaxy like our own Milky Way. Credit: University of Zurich



Animated Figure 14.23: The movie begins with a picture of the Small and Large Magellanic Clouds, our nearest galactic neighbors, and helps us visualize what they would look like if we could see their dark matter halos. The simulation traces the formation of the Milky Way, highlighting these two dwarf satellite galaxies. Credit: Busha, Kaehler, Marshall, and Wechsler