

Gravity, General Relativity, and Dark Matter

CHAPTER

6

For more than seventy-five years, the theories of general relativity and quantum mechanics have done an incredible job of correctly predicting the outcome of innumerable experiments. General relativity is useful for describing gravity and the large things detailed in Chapter 2. Quantum mechanics describes things that are tiny, such as atoms and molecules—the sizes we saw at the end of Chapter 3.

In this chapter, we will focus on gravity. We will start with a useful—albeit incomplete—version of gravity originally put forth by Newton, who was the first to describe how things are attracted to each other because of mass. In doing so, he made us all realize that a rock falls to the surface of the Earth for the same reason that planets go around the Sun.

We will also discuss the modern theory of gravity, known as general relativity, introduced by Einstein. We will need this more precise and accurate description to properly understand not only gravity and the evidence for dark matter, but also other mysteries like black holes and the expansion of the universe.

We begin by examining some highlights of each theory, continue with the experiments in the early part of the last century that confirmed Einstein's more complete description of gravity, and end with the evidence for dark matter.

6.1 NEWTON AND UNIVERSAL GRAVITATION

In the late 1680s, Newton revolutionized physics by providing a new understanding of how things move.¹ We call his description **classical mechanics**. One of the most important things he noted was that a particle—or any other composite

¹ To be fair, many of the ideas were based on the work of others, including Galileo. Of particular importance was the use of mathematics to gain a proper understanding of physical reality. While we are shying away from using mathematics in this text, scientists consider it central to our understanding. They call it the language of nature.

object (like a rock)—always moves in a straight line, and with the same speed, unless there is a **force** to make it slow down, speed up, or change direction.

To help illustrate this idea, we consider some examples.

We start with a rock sliding on the ground. It slows down because of the force of friction. A hockey puck, on the other hand, travels farther because ice has less friction than the ground.

A force can likewise speed things up. Continuing with our puck analogy, a hockey stick can force a puck to accelerate from rest to high speeds. The force of the stick can also change the puck's direction.

A string can exert a force when it is tied around a rock and swung around over your head. The string keeps the rock going in a circle even if the rock stays at the same speed. If you let go, the force of the string will be gone and the rock will fly off. If you are in outer space, it will move in a straight line, keeping the same direction of motion it had at the moment you released it. On Earth this is also true, but it will be simultaneously falling. Another example of this phenomenon is experienced every time the tires on your car push against the road and speed you up, slow you down, or allow you to turn a corner.

Perhaps the most well known of Newton's contributions is in the area of gravity. He described gravity as a force. In his description, *all* things with mass are attracted to each other; it is what makes apples fall to the Earth and the Moon to circle around it² (see Figure 6.1). This is a remarkable idea. No matter how big or small the object; no matter how far away things are from each other, they all feel the “pull” of gravity. As far as Newton could tell, this should be true everywhere in the universe. Thus, he named this description **universal gravitation**.

Newton's gravitational theory effectively explains many things, such as why the Moon orbits the Earth and how the Earth orbits the Sun. If there were no gravity, the Moon would simply fly off into space, as shown in the figure. The force of gravity also causes the other planets—as well as things like comets and asteroids—to go around the Sun. And although it's not perfect, this theory is also remarkably accurate at predicting the speed at which these objects move.

² The Moon is being pulled into the Earth, and that is what makes it go in a circle. This is, in many ways, the same way the rock we mentioned moves above your head in a circle when it is being forced to do so by a string.

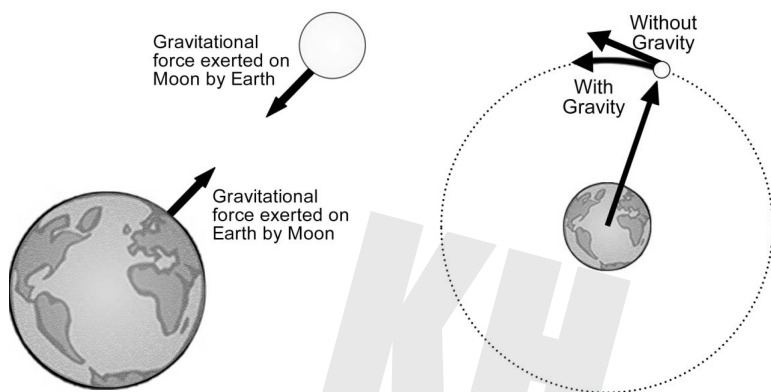


FIGURE 6.1 In Newton's (incomplete) description of gravity, the Earth and Moon attract each other because of the force of gravity between them. If gravity were not present, then the Moon would just fly off into space.

According to Newton:

1. Every object moves in a straight line, with constant speed, unless acted upon by a force.
2. Every object with mass in the universe attracts every other object with mass in the universe.
3. The bigger the masses of the objects, the stronger the attraction between them.
4. The farther the distance between any two objects, the weaker the attraction.

While this theory does an excellent job of predicting how things in nature move, the theory does leave some big questions unanswered: What is doing the “forcing”? Why can't we see what is “pulling” the Moon toward the Earth?

Nevertheless, this model of gravity stood until the twentieth century and is still taught today in high schools and colleges, as it does a worthy job of describing how to build bridges and put a man on the Moon. Then again, it is not good enough to make Global Positioning Systems (GPS) work.

6.2 EINSTEIN AND GENERAL RELATIVITY

While many people learn about Newton and his theory of gravity, most do not realize that our best understanding of gravity actually comes from Einstein.

During the first decade of the 1900s, Einstein began to compose his theory of general relativity and it completely changed the way we view gravity. Instead of gravity being a force that makes things alter their speed or direction as they move through space, general relativity says that what *appears* to be the force of gravity pushing a mass is better described as a mass moving in a “straight line” in what we call “curved space-time.” This is complicated, so we will explain more about this particular kind of “straight line” and what we mean by the bizarre-sounding phrase “curved space-time.”

Einstein’s inspiration for understanding the relationship between space and time came while he was thinking about light. He knew from the experiments of others that light always moves at the speed of light, but wondered what he himself would see if he were moving at different speeds.

Let’s use our crime-show theme to explain Einstein’s thought process.

What would happen if a detective were driving his car at half the speed of light and turned on its headlights (see Figure 6.2)? The light should move away from the car at the speed of light. Since the speed of light is one foot per nanosecond, in two nanoseconds, the light would be two feet ahead of him.

But what would a second detective, standing on the side of the road, see?

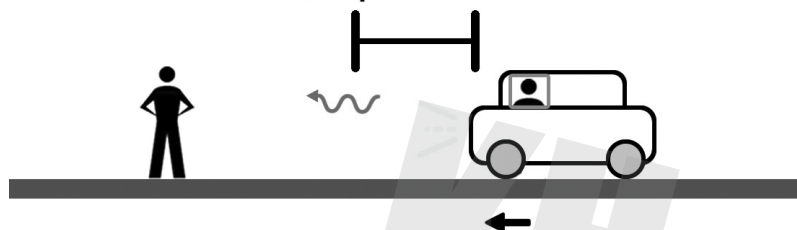
In two nanoseconds, she would see the light move two feet ahead. Because the car moves at half the speed of light, however, it also moves one foot forward during those same two nanoseconds. The second detective would therefore see the photon as only one foot ahead of the car.

Our two detectives get the same answer for the speed of light, but different data for the distance between the light and the car!

This sounds abstract and perhaps unimportant (not to mention it is not clear how we could make a car go that fast), but it has enormous implications. Most people would guess that one detective is right and the other is wrong—although they might disagree on which. Einstein, however, deduced that both perspectives (also like in Figure 5.4) are correct.

To reconcile this apparent contradiction, our detectives must take into account that space and time are more interrelated than most people realize. This becomes

From the perspective of the person on the side of the road, the car moves at half the speed of light and the photon moves at the speed of light. After 2 nanoseconds, the photon is 1 foot ahead of the car.



From the perspective of the driver, the car is stationary and the photon moves at the speed of light. After 2 nanoseconds, the photon is 2 feet ahead of the car.

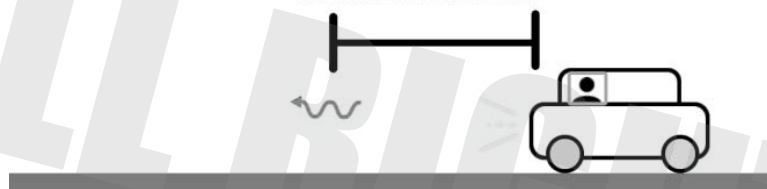


FIGURE 6.2 Two different observers—a person on the side of the road and a car driver—watching a photon move away from a car when its lights are turned on. From the perspective of both people, the speed of light makes the photon travel two feet in two nanoseconds. Since the car moves at half the speed of light, it travels one foot in two nanoseconds. Therefore, from the perspective of the person on the side of the road, the photon is one foot ahead of the car. However, from the perspective of the driver, the car is stationary, but the photon moves two feet ahead of the car in two nanoseconds (since it moved away from the front of the car at the speed of light). Therefore, the driver observes the photon to be two feet in front of the car. The two observers disagree on the result, but relativity explains that both observations are correct.

especially important when speeds are close to that of light. This better understanding is known as **special relativity**. What Einstein figured out is that space (measured with a ruler) is not separate from time (measured with a clock). Rather, both should be thought of as a single combined entity, what we call **space-time**. Space-time has four dimensions: space has three (length, width, and height) and time has one.

If this sounds complicated and bizarre, you are right; it is. You can spend a long time studying Einstein's theory of relativity and there are many good books about

it. However, for our story, it's merely important to understand that space and time are intimately related.

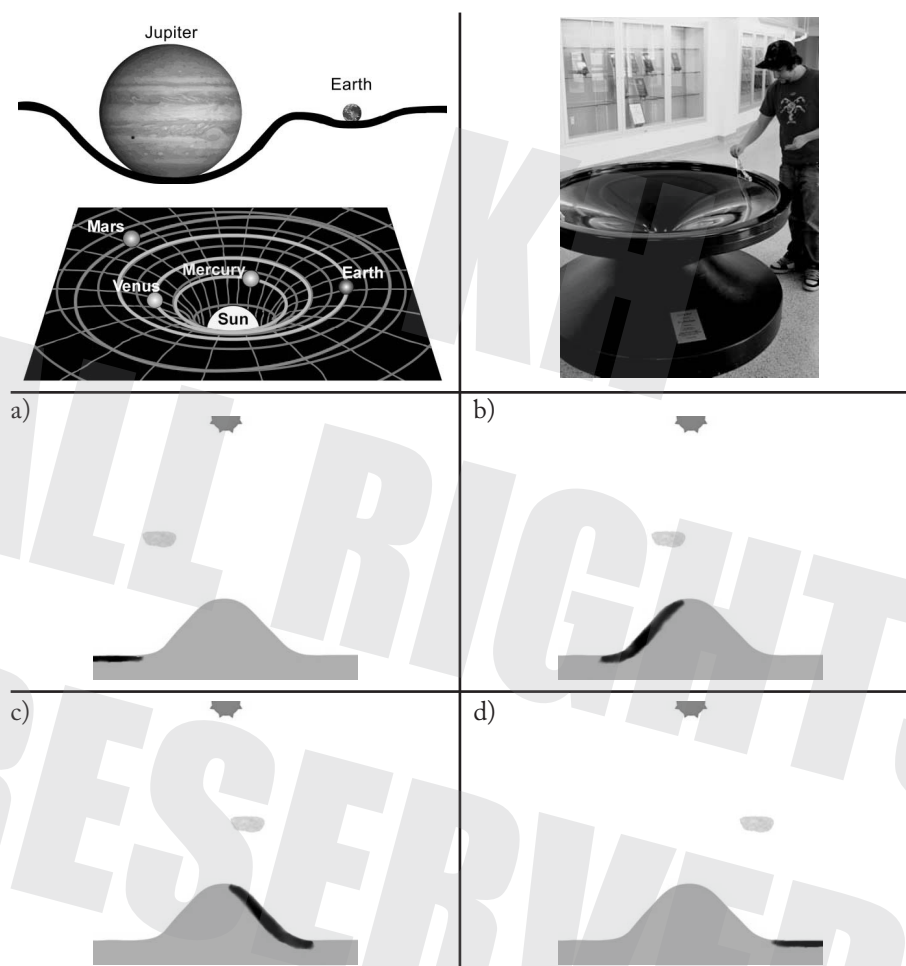


FIGURE 6.3 An artist's conceptions of general relativity. On the top row (top left), heavy masses stretch space-time and cause dents in space-time; an analogy is planets placed on a large, taut rubber sheet. Other masses move in this curved space-time; an analogy is shown in the top right with pennies moving in a gravity well. In the bottom two rows, we show an analogy which illustrates how an object moving in a straight line appears to be moving in a curved path. In these figures, the Sun is shining and a cloud (moving in three dimensions) causes a shadow to be cast on the two-dimensional ground. While the cloud moves in a straight line, the shadow appears to move up and then down the mountain. With these ideas, general relativity describes the inner planets moving in the curved space-time around the Sun, as shown in the top left. (Color versions on Page C-4.)

Einstein realized that this close space-time relationship has many important implications that can seem quite odd. For example, not only can space and time be bigger or smaller for different people as in the case above, but also they can change or curve. With this understanding, he realized it can describe how two objects with mass attract each other, and how this phenomenon can give us a more fundamental understanding of gravity. It is this theory that we refer to as Einstein's general theory of relativity, or "general relativity," for short.

A basic tenet of general relativity is that space-time can be "warped" by things with mass. An analogy to help you visualize curved space-time, but in two dimensions, is shown in Figure 6.3.

In this figure, we see massive things, like planets, causing depressions on a taut rubber sheet. The line represents space-time and the mass of each object makes it sink into the rubber sheet, creating an indentation all around it. The bigger the mass, the bigger the dent it creates in space-time. While it is not a perfect analogy (some scientists find this analogy potentially misleading for the reasons described in Box 6.1), it gives a good visual analogy for what we mean by the phrase "mass curves space-time."

BOX 6.1

Why Scientists Don't Like the Rubber Sheet Analogy

The analogy of a ball on a rubber sheet is good visually, but really makes many scientists cringe—and for good reason. For starters, with a ball and a sheet here on Earth, the dent comes from the pull of gravity on the ball: there is no force making a dent in space-time. It also implies that a second ball "naturally" rolls to the bottom of the dent in space-time because balls naturally roll down hills. While this is also true, the reason it happens is because gravity is pulling the ball as it goes down the hill. That also isn't fair because there is no force pulling the ball down the hill. A third issue is that in our picture, the dent in space-time only describes things in two dimensions, but the dent in space-time is really in three dimensions. That's harder to draw and visualize, especially for someone just starting to learn the basics. What is important is that the geometry of space-time is curved by a mass in space, and that a second mass can speed up (or slow down) as it moves through this curved space-time, depending on the amount of curvature.

For a more complete and better description, I point interested readers to Kip Thorn's *Black Holes and Time Warps*.

A second picture in Figure 6.3 shows a student dropping a penny into a curved gravity well like those you find in most science museums. The penny's movement around the well gives you a rough idea of how objects move in curved space-time. As the penny moves toward the deepest part of the dent, it will speed up like a ball as it rolls down a hill.

It gets slightly more complicated before we are done, but we need to understand one more thing about general relativity to see how this all ties together. General relativity agrees with Newton's description that an object moves in a straight line in space unless there is a force acting on it. However, in general relativity, an apple falling toward the ground does not feel a force (since there is no force to feel), but it does move in the equivalent of a "straight line" within the big dent in curved space-time created by the enormous mass of the Earth. Specifically, the speed of the apple, in space, increases because the space-time around the massive Earth is more and more scrunched the closer you get to the center of the Earth.

Moving in a "straight line" in curved, four-dimensional space-time can look the same as moving in a curved path in three-dimensional space. This is more easily understood with an analogy since it is hard to think in four dimensions. One of my favorites is to consider how a plane travels from New York to Paris. We tend to think of the plane as traveling directly from one place to the other, but if you pull out a globe and a piece of string, you'll see that the "straight-line" path is actually curved (scientists call this a geodesic).

Another analogy is shown in the bottom rows of Figure 6.3, where we have the shadow of a cloud moving over a mountain. While the cloud moves in a straight line in regular three-dimensional space, the shadow moves up and down the two-dimensional curve of the mountain.

So in summary, Newton's and Einstein's theories state the following:

- Newton: Unless there is a force, things move in a straight line in three dimensions; gravity provides a force.
- Einstein: Unless there is a force, things move in a "straight line" in space-time, which has four dimensions; gravity is not a force, but appears like one because mass curves space-time and objects move along in curved space-time.

It is not hard to draw an analogy for the Earth's movement around the Sun in this "dent-in-space-time" view. While we do not see it this way with our eyes, the Sun creates curved space-time and the Earth moves in a "straight line" in four dimensions within this curved space-time (again see Figure 6.3). The same is true for

the other planets. In general relativity, the Earth does not move around the Sun because there is a “force” of gravity, but rather it moves in a “straight line” in the curved space-time created by the Sun.

Don't worry too much if you feel like you are not completely grasping this concept. It is very non-intuitive, and no scientist understood it properly before Einstein. What is important is that, in later chapters, we will be able to use the idea of curved space-time to explain the data we have gathered about our universe over the years. Hopefully, as you read these chapters and see how the ideas are used, it will make more sense. For now, we will look at the great experiment that helped show that general relativity was a better description of nature than was Newton's theory.

6.3 THE GREAT EXPERIMENT

Both Newton's and Einstein's theories aptly describe how apples fall toward the Earth and planets go around the Sun. How do we decide if one is right and the other is wrong? Like a good detective or scientist, we need additional evidence. What experiment can we do where general relativity predicts a different outcome than Newton's theory?

To answer this, we will use perhaps the world's most well-known equation: $E=mc^2$. In this equation (which is only true for things that have mass in general relativity), E is energy, m is mass, and c is the speed of light. This equation therefore means that energy and mass are equivalent to each other as long as we take into account the speed of light.

If we consider light—which has no mass—in Newton's theory, then it should not be forced: no mass, no force of gravity. Specifically, if nothing forces or pushes it, light always travels in a straight line.³

General relativity, on the other hand, says that light has energy, which is equivalent to mass, so it should move the same way a mass would move in curved space-time. Therefore general relativity predicts that the path of light traveling through space will bend because of the curvature of space-time—not because of a force on it.

In the late 1910s, experiments were conducted to test which of the two theories correctly predicted what actually happens. We describe a basic version of one such experiment as shown in Figure 6.4.

³ Note that this is a simplified interpretation of Newton's theory. A more thorough reading says that while the light's path will, in reality, bend, it will only do so half as much as general relativity predicts.

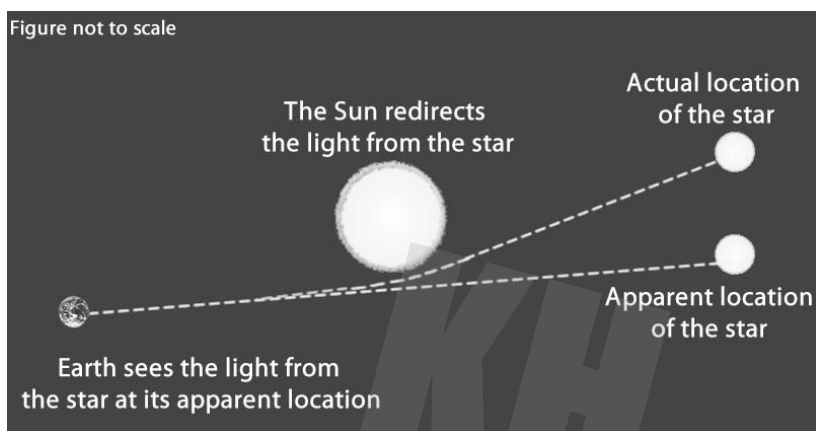


FIGURE 6.4 Light as it travels from a star, past the Sun, and into our eyes here on Earth. In a famous experiment in the late 1910s, scientists looked at light from a star going past the Sun. They did so during an eclipse, to cut out the Sun's glare. The path of the star's light bent and gave the optical illusion of the star being in a different place. This effect is known as gravitational lensing. The difference between the apparent and actual location of the star was exactly consistent with what Einstein predicted and was a stunning confirmation of general relativity.

Astronomers studied the location of the Sun and the stars over time and knew exactly where each should be at a given point during the day. They then focused on a set of stars they knew would be located almost directly “behind” the Sun from their view here on Earth. To be able to see the light from the stars and cut out the glare from the Sun, they did this experiment during a solar eclipse.

Relativity predicted that the light from each star would travel along a path that was “bent” by the Sun's gravity as it passed by the Sun; a star would look as though it were located in a slightly different place than where it should be. You can think of the path of light as passing through a lens, like the one in a pair of glasses, and changing direction. It is important to remember that the amount of this **gravitational lensing** by the Sun would not be much. In fact, the expected deflection from the straight-line path from the star to our eyes is more than thirty times smaller than the eye can discern. However, it was expected to be enough to be measured in very sensitive experiments.

The result was that the apparent position of the stars changed as the light passed from them, through outer space, past the Sun, and to the astronomers on Earth. More importantly, the amount of bending was consistent with the amount

predicted by the curved space-time theory of general relativity, and inconsistent with Newton's predictions. The fact that there were many stars that did this, not just one, was especially convincing.

This was a stunning advancement of science and won Einstein international acclaim. General relativity showed that not only did scientists have a more fundamental understanding about how things are attracted to each other in the universe, but also that this attraction was due to how space and time work together in a single space-time.

There are many instances where Newton and Einstein make slightly different predictions about the details of gravity and motion. After decade of experiments in every case, we have found that Newton's predictions were a little bit off, and Einstein's were more accurate. Modern and more powerful tests using gravitational lensing of light have produced even more conclusive findings.

6.4 DARK MATTER IN GALAXIES

As mentioned in Chapter 2, there is clear evidence for dark matter in the universe and that it fills galaxies. Some of the evidence for this understanding comes from two different methods we are now ready to discuss. One method studies the motion of stars in the galaxy due to gravity, and the other uses galaxies to provide gravitational lensing for objects behind them.

We begin with the first method.

The known laws of gravity do a great job of describing how things with large amounts of mass move around each other. For example, it predicts the speed of the planets around the Sun. It likewise gives an intuitive explanation of why the inner planets (Mercury, Venus, and Earth) travel around the Sun with speeds that are much faster than that of the outer planets (Saturn, Uranus, and Neptune). The agreement between the predictions and the observed speeds of the planets is nearly perfect (see Figure 6.5).

In the 1970s, scientist Vera Rubin compared the observed speeds of stars around the center of a galaxy to the predictions of gravity. Since the amount of light from a star is related to its mass, the amount of atomic mass in the center of a galaxy is readily predicted. Other methods allow us to measure the amount of atoms in the disk and far outside the disk.

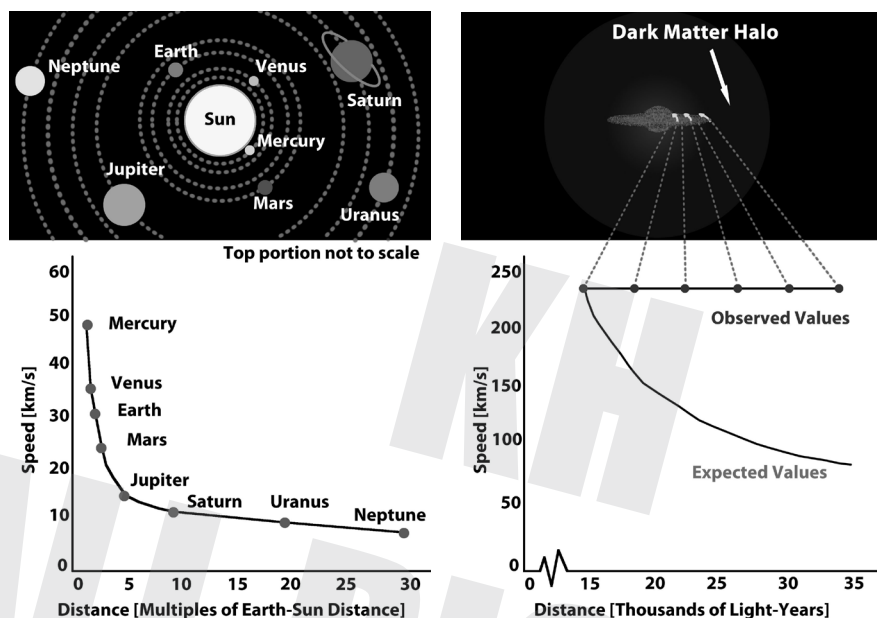


FIGURE 6.5 These two figures show graphs that tell us the speed of a planet or star (vertical axis) and how far away it is from the center of the Sun or galaxy (horizontal axis). For example, from the graph on the left, we see that Neptune is about thirty times farther away from the Sun than is the Earth and it moves about five times slower. We also note the predicted (solid line) and observed speed of the planets (dots) around the Sun. There is remarkable agreement. The figure on the right shows a simplified version of a galaxy. If the galaxy were made of stars alone, then we would see the stars in its outer realm possessing a speed denoted by the solid line indicating “expected values.” However, the real data looks more like the observed data plotted by dots on the horizontal line. Our best understanding is that this means that there is a large amount of dark matter and that it is located in a halo surrounding the galaxy.

The left hand side of Figure 6.5 shows a comparison of the observed speeds of the planets to their predicted speeds based on the mass of the Sun. The right hand side shows the expected speed of the stars in the outer part of the galaxy, assuming all the mass of the galaxy is in its stars. In both cases, orbiting objects far from the center are expected to move much more slowly than objects closer to the center.

The data for the stars in a galaxy, however, do not match that prediction at all. Instead of moving like the planets in our Solar System—with stars far away from the center moving at slower speeds—Rubin found that the stars far out on the disk actually move at virtually the same speed as the stars closer in.

While this could be construed as evidence against general relativity,⁴ we now understand that the stars are feeling the gravity of a far larger amount of mass (matter) that we cannot see directly. This dark matter—felt, but not seen—is what makes the stars in the outer part of the galaxy rotate quickly around its center. This is where dark matter gets its name.

We can work backward to determine not only how much extra mass is needed to make the stars move this way, but also how this mass would need to be spread around the galaxy to reconcile the data with the predictions. Figure 6.6 shows what the orbits of stars around the center of the galaxy would look like with and without dark matter. Detailed calculations show that we often need about five times as much dark matter as atomic matter in a galaxy, and that dark matter engulfs the galaxy like a giant ball.

We can also use gravitational lensing to “observe” dark matter in a galaxy (and in-between galaxies). As in the optical illusion we saw in Figure 6.4—where the Sun changed the apparent location of a star as the star’s light passed by it—we can look at light that gets lensed along its way through the dark matter in a galaxy.

Basically, since there is a large amount of dark matter in a galaxy, its mass bends space-time a great deal, and the curved space-time can significantly bend the path of light. Since the amount of mass is smoothly distributed around a galaxy, any light coming through the dark matter is lensed back toward the middle of the galaxy.

Let us consider light from a distant galaxy; in particular, what happens to light as it passes through dark matter in a nearer galaxy. This is shown in Figure 6.7 and we will refer to them here as the near-galaxy and the far-galaxy. In this case, we can see light from the far-galaxy as it passes by and through the near-galaxy. If the far-galaxy is exactly behind the near-galaxy, then we will not see the far-galaxy directly, but we can see the lensed light from all sides of the far-galaxy in a giant circle, known as an **Einstein ring**, around the near-galaxy. Many of these have been observed in nature.

By using these types of measurements we can determine the quantity and distribution of dark matter in the near-galaxy. These results can be directly compared to measurements of star orbiting speeds in the near-galaxy.

Remarkably, despite how different the speed-of-stars measurement and the lensing-measurement techniques are, they produce similar results for both the amount

⁴ Many people have tried new versions of gravity, but no one has come up with a theory that explains the other data as well as does general relativity.

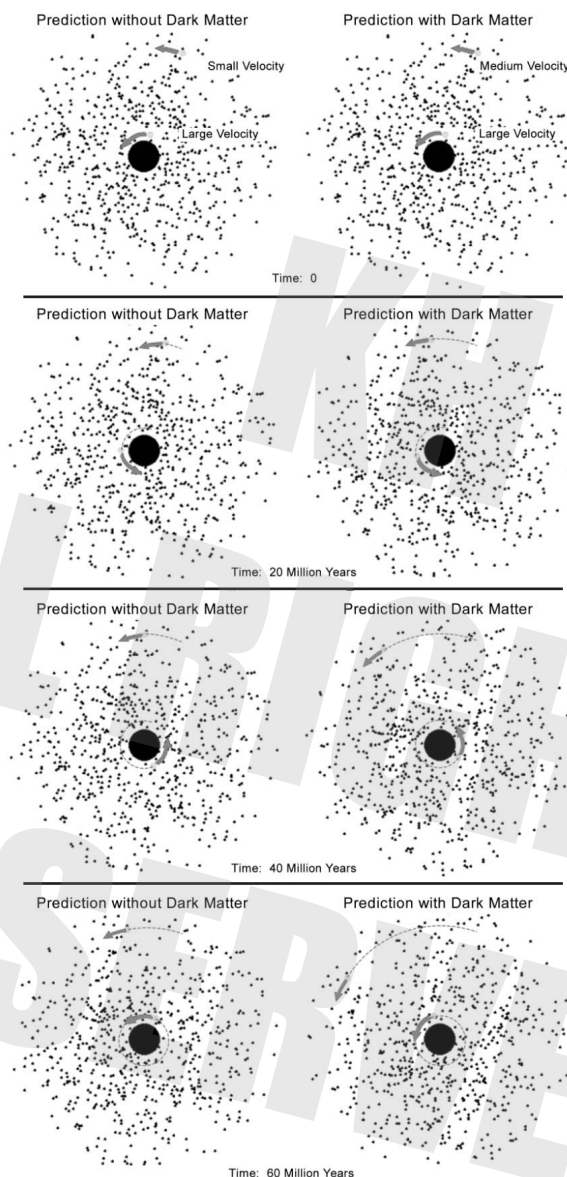
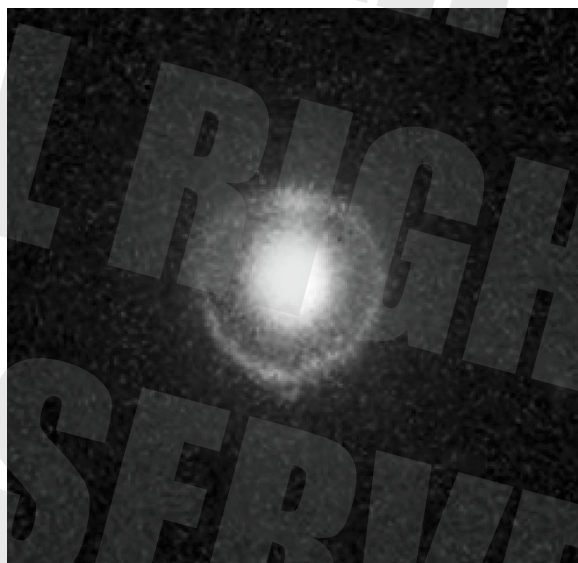
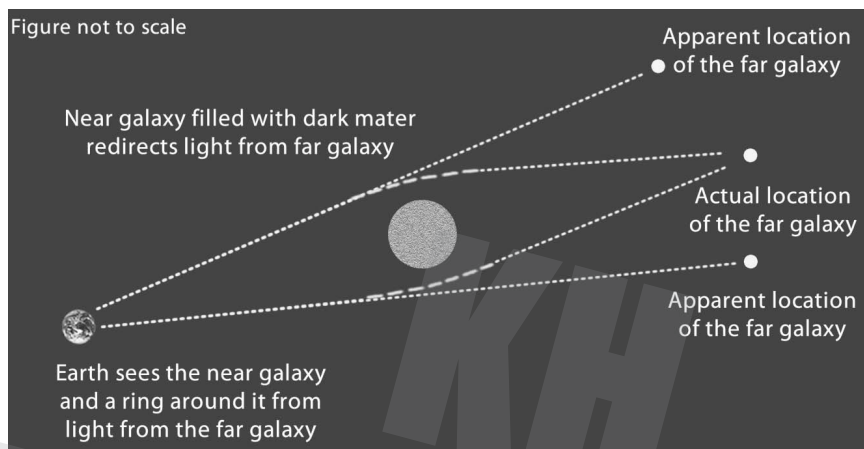


FIGURE 6.6 Two simulations of how fast stars rotate around the center of a galaxy. Notice how the stars near the center are moving quickly. The left side column shows how fast stars should move if there were no dark matter. The right column shows how fast they would move if there were a halo of dark matter in the galaxy. The stars on the outer part of the galaxies are expected to move very differently. The actual data looks much more like the right column than the left.



NASA, ESA, A. Bolton (Harvard-Smithsonian CfA) and the SLACS Team

FIGURE 6.7 One way that light from a distant galaxy would look to us here on Earth when there is another galaxy directly in the way. In the special case that one galaxy is directly in front of another, there can be so much mass in the near galaxy that its gravity lenses the light from the galaxy behind it and creates what is known as an Einstein ring.

An example with real data is shown in the bottom. (Color version on page C-5.)

of dark matter and how it is distributed. In addition to providing strong evidence for both general relativity and dark matter; they give us confidence that the experiments tell a consistent story. We will come back to dark matter in galaxies in Chapter 15.

Ultimately, general relativity brilliantly describes the space in which we live. It is a central part of the story of how we think the universe has changed over time, from its earliest beginnings until today. We will see this more vividly in Chapter 11 when we discuss how space changes shape during the expansion of the universe.

Now that we have discussed gravity and general relativity, we will tackle quantum mechanics and find out what this theory teaches us about the universe's smaller things.

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