23

DARK MATTER, DARK ENERGY, AND THE FATE OF THE UNIVERSE

LEARNING GOALS

23.1 UNSEEN INFLUENCES IN THE COSMOS

- What do we mean by dark matter and dark energy?

23.2 EVIDENCE FOR DARK MATTER

- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?

23.3 DARK MATTER AND GALAXY FORMATION

- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?

23.4 DARK ENERGY AND THE FATE OF THE UNIVERSE

- Why is accelerating expansion evidence for dark energy?
- Why is flat geometry evidence for dark energy?
- What is the fate of the universe?

I soon became convinced, however, that all theorizing would be empty brain exercise and therefore a waste of time unless one first ascertained what the population of the universe really consists of, how its various members interact and how they are distributed throughout cosmic space.

—Fritz Zwicky, 1971

Over the past several chapters, we have painted a portrait of the history of the universe that is supported by strong scientific evidence. This evidence indicates that our universe was born about 14 billion years ago in the Big Bang, and that the universe as a whole has been expanding ever since. In regions of the universe that began with slightly enhanced density, gravity was able to take hold and build galaxies, within which some of the hydrogen and helium atoms produced in the Big Bang were assembled into stars. We exist today because galactic recycling has incorporated heavier elements made by early generations of stars into new star systems containing planets like Earth.

Scientists broadly agree with this basic outline of universal history, but at least two major mysteries remain. The first concerns the source of the gravity that forms galaxies and holds them together. The combined mass of all the stars and gas we observe turns out to be insufficient to account for the observed strength of gravity, leading scientists to hypothesize that most of the mass in the universe takes the form of some unseen *dark matter*. The second has emerged from measurements of the universe's expansion rate. Scientists had long expected that gravity would be slowing the expansion rate with time, but observations now indicate the opposite, leading to the idea that a mysterious *dark energy* counteracts the effects of gravity on large scales.

In this chapter, we will explore the evidence for dark matter and dark energy, and the roles they appear to play in shaping our universe. We'll also see why they qualify as two of the greatest mysteries in science, and why the fate of the universe hinges on their properties.

23.1 UNSEEN INFLUENCES IN THE COSMOS

What is the universe made of? Ask an astronomer this seemingly simple question, and you might see a professional scientist blush with embarrassment. Based on all the available evidence today, the answer to this simple question is "We do not know."

It might seem incredible that we still do not know the composition of most of the universe, but you might also wonder why we should be so clueless. After all, astronomers can measure the chemical composition of distant stars and galaxies from their spectra, so we know that stars and gas clouds are made almost entirely of hydrogen and helium, with small amounts of heavier elements mixed in. But notice the key words "chemical composition." When we say these words, we are talking about the composition of material built from atoms of elements such as hydrogen, helium, carbon, and iron.

While it is true that all familiar objects—including people, planets, and stars—are built from atoms, the same may not be true of the universe as a whole. In fact, we now have good reason to think that the universe is *not* composed primarily of atoms. Instead, observations indicate that the universe consists largely of a mysterious form of mass known as *dark matter* and a mysterious form of energy known as *dark energy.*

What do we mean by dark matter and dark energy?

It's easy for scientists to talk about dark matter and dark energy, but what do these terms really mean? They are nothing more than names given to unseen influences in the cosmos. In both cases observational evidence leads us to think that there is something out there, but we do not yet know exactly what the "something" is.

We might naively think that the major source of gravity that holds galaxies together should be the same gas that makes up their stars. However, observations suggest otherwise. By carefully observing gravitational effects on matter that we can see, such as stars or glowing clouds of gas, we've learned that there must be far more matter than meets the eye. Because this matter gives off little or no light, we call it **dark matter**.* In other words, dark matter is simply a name we give to whatever unseen influence is causing the observed gravitational effects. We've already discussed dark matter briefly in Chapters 1 and 19, noting that studies of the Milky Way's rotation suggest that most of our galaxy's mass is distributed throughout its halo while most of the galaxy's light comes from stars and gas clouds in the thin galactic disk (see Figure 1.15).

We infer the existence of the second unseen influence from careful studies of the expansion of the universe. After Edwin Hubble first discovered the expansion, it was generally assumed that gravity must slow the expansion with time. However, evidence collected during the last two decades indicates that the expansion of the universe is actually accelerating, implying that some mysterious force counteracts the effects of gravity on very large scales. **Dark energy** is the name most commonly given to the source of this mysterious force, but it is not the only name; you may occasionally hear the same unseen influence attributed to *quintessence* or to a *cosmological constant.* Note that while dark matter really is "dark" compared to ordinary matter (because it gives off no light), there's nothing unusually "dark" about dark energy—after all, we don't expect to see light from the mere presence of a force or energy field.

Before we continue, it's important to think about dark matter and dark energy in the context of science. Upon first hearing of these ideas, you might be tempted to think that astronomers have "gone medieval," arguing about unseen influences in the same way scholars in medieval times supposedly argued about the number of angels that could dance on the head of a pin. However, strange as the ideas of dark matter and dark energy may seem, they have emerged from careful scientific study conducted in accordance with the hallmarks of science discussed in Chapter 3 (see Figure 3.24). Dark matter

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*It could just as easily be called *transparent matter,* since light would pass straight through it without interacting.

and dark energy were each proposed to exist because they seemed the simplest ways to explain observed motions in the universe. They've each gained credibility because models of the universe that assume their existence make testable predictions and, at least so far, further observations have borne out some of those predictions. Even if we someday conclude that we were wrong to infer the existence of dark matter or dark energy, we will still need alternative explanations for the observations made to date. One way or the other, what we learn as we explore the mysteries of these unseen influences will forever change our view of the universe.

MA **Detecting Dark Matter in a Spiral Galaxy Tutorial, Lessons 1–3**

23.2 EVIDENCE FOR DARK MATTER

Scientific evidence for dark matter has been building for decades and is now at the point where dark matter seems almost indispensable to explaining the current structure of the universe. For that reason, we will devote most of this chapter to dark matter and its presumed role as the dominant source of gravity in our universe, saving further discussion of dark energy for the final section of the chapter. In this section, we'll begin our discussion of dark matter by examining the evidence for its existence and what the evidence indicates about its nature.

What is the evidence for dark matter in galaxies?

Several distinct lines of evidence point to the existence of dark matter, including observations of our own galaxy, of other galaxies, and of clusters of galaxies. Let's start with individual galaxies and then proceed on to clusters.

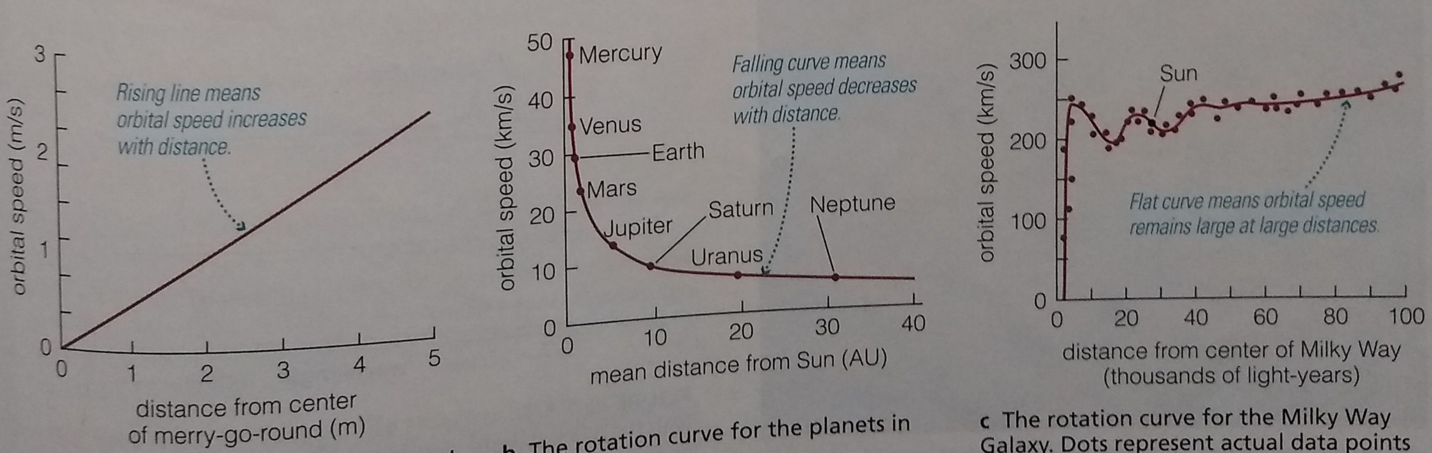
Dark Matter in the Milky Way In Chapter 19, we saw how the Sun's motion around the galaxy reveals the total amount of mass within its orbit. Similarly, we can use the orbital motion of any other star to measure the mass of the Milky Way within that star's orbit. In principle, we could determine the complete distribution of mass in the Milky Way by doing the same thing with the orbits of stars at every different distance from the galactic center.

In practice, interstellar dust obscures our view of disk stars more than a few thousand light-years away from us, making it very difficult to measure stellar velocities. However, radio waves penetrate this dust, and clouds of atomic hydrogen gas emit a spectral line at the radio wavelength of 21 centimeters [**Section 19.2**]. Measuring the Doppler shift of this 21-centimeter line tells us a cloud's velocity toward or away from us. With the help of a little geometry, we can then determine the cloud's orbital speed.

We can summarize the results of these measurements with a diagram that plots the orbital speed of objects in the galaxy against their orbital distances. As a simple example of how we construct such a diagram, sometimes called a *rotation curve*, consider how the rotation speed of a merry-go-round depends on the distance from its center. Every object on a merry-go-round goes around the center in the same amount of time (the rotation period of the merry-go-round). But because objects farther from the center move in larger circles, they must move at faster speeds. The speed is proportional to distance from the center, so the graph illustrating the relationship between speed and distance is a steadily rising straight line (FIGURE 23.1a).

In contrast, orbital speeds in our solar system *decrease* with distance from the Sun (FIGURE 23.1b). This drop-off in speed with distance occurs because virtually all the mass of the solar system is concentrated in the Sun. The gravitational force holding a planet in its orbit therefore decreases with distance from the Sun, and a smaller force means a lower orbital speed. Orbital speeds must drop similarly with distance in any other astronomical system that has its mass concentrated at its center.

FIGURE 23.1c shows how orbital speed depends on distance in the Milky Way Galaxy. Each individual dot represents the orbital speed and distance from the galactic center of a particular star or gas cloud, and the curve running through the dots represents a "best fit" to the data. Notice that the



a A rotation curve for a merry-go-round is a rising straight line.

b The rotation curve for the planets in our solar system.

c The rotation curve for the Milky Way Galaxy. Dots represent actual data points for stars or gas clouds.

FIGURE 23.1 **interactive figure** These graphs show how orbital speed depends on distance from the center in three different systems.

orbital speeds remain approximately constant beyond the inner few thousand light-years, so most of the curve is relatively flat. This behavior contrasts sharply with the steeply declining orbital speeds in the solar system, leading us to conclude that most of the Milky Way's mass must *not* be concentrated at its center. Instead, the orbits of progressively more distant gas clouds must encircle more and more mass. The Sun's orbit encompasses about 100 billion solar masses, but a circle twice as large surrounds twice as much mass, and a larger circle surrounds even more mass.

To summarize, orbital speeds in the Milky Way imply that most of our galaxy's mass lies well beyond the orbit of our Sun. A more detailed analysis suggests that most of this mass is distributed throughout the spherical halo that surrounds the disk of our galaxy, extending to distances well beyond those at which we observe globular clusters and other halo stars. Moreover, the total amount of this mass is more than *10 times* the total mass of all the stars in the disk. Because we have detected very little radiation coming from this enormous amount of mass, it qualifies as dark matter. If we are interpreting the evidence correctly, the luminous part of the Milky Way's disk must be rather like the tip of an iceberg, marking only the center of a much larger clump of mass (**FIGURE 23.2**).

THINK ABOUT IT

Suppose we made a graph of orbital speeds and distances for the moons orbiting Jupiter. Which graph in Figure 23.2 would it most resemble? Why?

Dark Matter in Other Spiral Galaxies Other galaxies also seem to contain vast quantities of dark matter. We can determine the amount of dark matter in a galaxy by comparing the galaxy's mass to its luminosity. (More formally, astronomers calculate the galaxy's *mass-to-light ratio;* see Mathematical Insight 23.1.) The procedure is fairly simple in principle. First, we use the galaxy's luminosity to estimate the amount of mass that the galaxy contains in the form of stars. Next, we determine the galaxy's total mass by applying the law of gravity to observations of the orbital velocities of stars and gas clouds. If this total mass is larger than the mass that we can attribute to stars, then we infer that the excess mass must be dark matter.

We can measure a galaxy's luminosity as long as we can determine its distance with one of the techniques discussed in Chapter 20. We simply point a telescope at the galaxy in question, measure its apparent brightness, and calculate its luminosity from its distance and the inverse square law for light [**Section 15.1**]. Measuring the galaxy's total mass requires measuring orbital speeds of stars or gas clouds as far from the galaxy's center as possible. Atomic hydrogen gas clouds can be found in a spiral galaxy at greater distances from the center than stars, so most of our data come from radio observations of the 21-centimeter line from these clouds. We use Doppler shifts of the 21-centimeter line to determine how fast a cloud is moving toward us or away from us (**FIGURE 23.3**).

Once we've measured orbital speeds and distances, we can make a graph similar to Figure 23.1c for any spiral galaxy. **FIGURE 23.4** shows a few examples illustrating that, like the Milky Way, most other spiral galaxies also have orbital speeds that remain high even at great distances from their centers. Again as in the Milky Way, this behavior implies that a great deal of matter lies far out in the halos of these other spiral galaxies. More detailed analysis tells us that most spiral

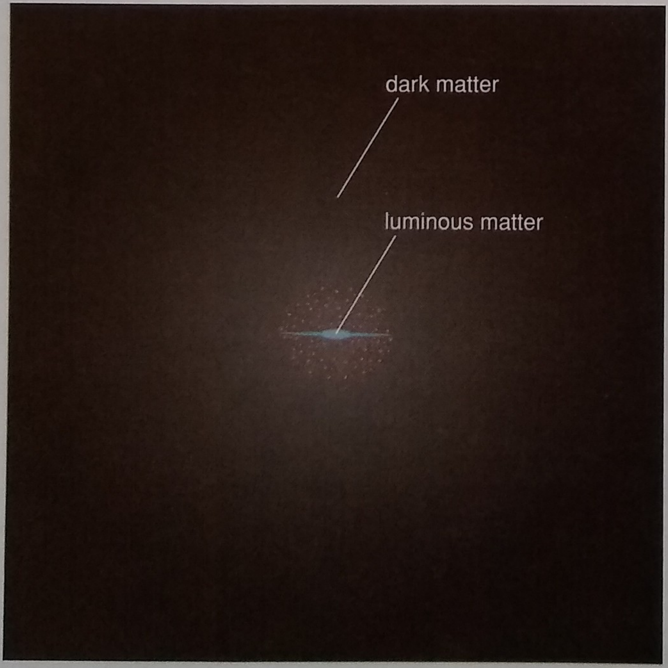


FIGURE 23.2 The dark matter associated with the Milky Way occupies a much larger volume than the galaxy's luminous matter. The radius of this dark-matter halo may be 10 times as large as the the galaxy's halo of stars.

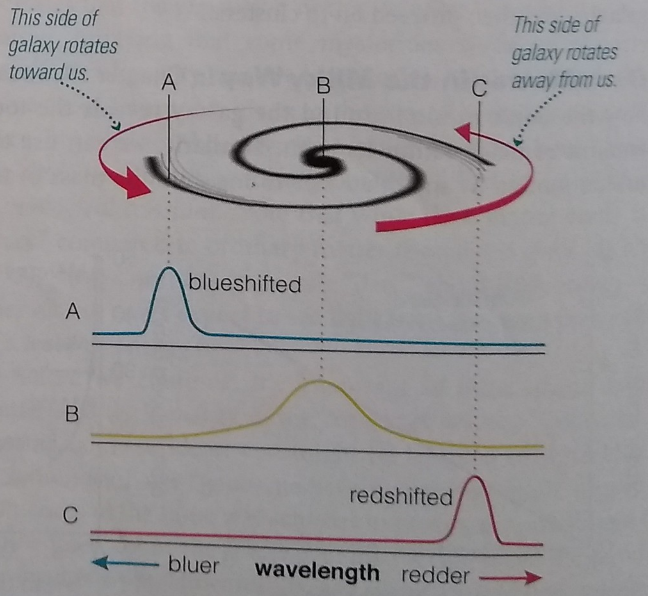


FIGURE 23.3 Measuring the orbital speeds of gas in a spiral galaxy with the 21-centimeter line of atomic hydrogen. Blueshifted lines on the left side of the disk show how fast that side is moving toward us. Redshifted lines on the right side show how fast that side is moving away from us. (This diagram assumes that we first subtract a galaxy's average redshift, so that we can see the shifts that remain due to rotation.)

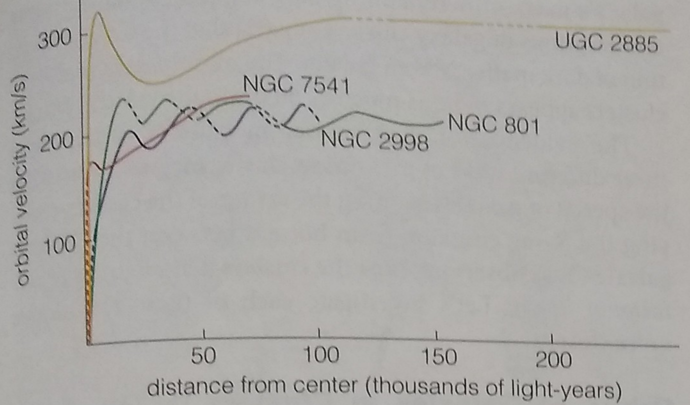


FIGURE 23.4 Graphs of orbital speed versus distance for four spiral galaxies. In each galaxy, the orbital speeds remain nearly constant over a wide range of distances from the center, indicating that dark matter is common in spiral galaxies.

galaxies have at least 10 times as much mass in dark matter as they do in stars. In other words, the composition of typical spiral galaxies is 90% or more dark matter and 10% or less visible matter.

Dark Matter in Elliptical Galaxies We must use a different technique to determine masses of elliptical galaxies, because they do not have large well-organized disks in which we can easily measure how the orbital speeds of stars depend on distance. However, the orbital speeds of their stars still depend on the amount of mass within their orbits, which allows us to measure mass from the width of an elliptical galaxy's spectral lines. If we look at the galaxy as a whole, its spectral lines come from the combination of all its stars. Because each star has its own orbital speed around the center of the galaxy, each produces its own Doppler shift that contributes the overall appearance of the galaxy's spectral lines. Some stars are moving toward the center and others away, so their combined effect is to change any spectral line from a nice narrow line at a particular wavelength to a *broadened* line spanning a range of wavelengths. The greater the broadening of the spectral line, the faster the stars must be moving (**FIGURE 23.5**).

When we compare spectral lines representing regions of elliptical galaxies out to different distances, we find that the speeds of the stars remain fairly constant even quite far from the galaxy's center. Just as in spirals, we conclude that most of

MATHEMATICAL INSIGHT 23.1

Mass-to-Light Ratio

An object's mass-to-light ratio (M/L) is its total mass in units of *solar masses* divided by its total *visible* luminosity in units of *solar luminosities*. For example, the mass-to-light ratio of the Sun is

$$\frac{M}{L}\text{ for Sun} = \frac{1M_{\text{Sun}}}{1L_{\text{Sun}}} = 1\,\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

We read this answer with its units as "1 solar mass per solar luminosity." The following examples clarify the idea of the mass-to-light ratio and explain what it can tell us about the existence of dark matter.

EXAMPLE 1: What is the mass-to-light ratio of a $1M_{\text{Sun}}$ red giant with a luminosity of $100L_{\text{Sun}}$?

SOLUTION:

Step 1 Understand: Finding a mass-to-light ratio simply requires knowing an object's total mass in solar masses and its total luminosity in solar luminosities. We have been given both.

Step 2 Solve: We divide to find the mass-to-light ratio:

$$\frac{M}{L} = \frac{1M_{\text{Sun}}}{100L_{\text{Sun}}} = 0.01\,\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The red giant has a mass-to-light ratio of 0.01 solar mass per solar luminosity. Note that the ratio is *less* than 1 because a red giant puts out *more* light per unit mass than the Sun. More generally, stars *more luminous* than the Sun have mass-to-light ratios *less* than 1 and stars *less luminous* than the Sun have mass-to-light ratios *greater* than 1.

EXAMPLE 2: The Milky Way Galaxy contains about 90 billion (9×10^{10}) solar masses of material within the Sun's orbit, and the total luminosity of stars within that same region is about 15 billion (1.5×10^{10}) solar luminosities. What is the mass-to-light ratio of the matter in our galaxy within the Sun's orbit?

SOLUTION:

Step 1 Understand: Again, we simply divide the mass of this region by its luminosity, both in solar units.

Step 2 Solve: The mass-to-light ratio within the Sun's orbit is

$$\frac{M}{L} = \frac{9 \times 10^{10} M_{\text{Sun}}}{1.5 \times 10^{10} L_{\text{Sun}}} = 6\,\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The mass-to-light ratio of the matter within the Sun's orbit is about 6 solar masses per solar luminosity. This is *greater* than the Sun's ratio of 1 solar mass per solar luminosity, telling us that most matter in this region is *dimmer* per unit mass than our Sun. This is not surprising, because most stars are smaller and dimmer than our Sun.

EXAMPLE 3: Observations of orbital speeds in a spiral galaxy indicate that its total mass is $5 \times 10^{11} M_{\text{Sun}}$; its luminosity is $1.5 \times 10^{10} L_{\text{Sun}}$. What is its mass-to-light ratio?

SOLUTION:

Step 1 Understand: This problem is essentially the same as the others, but with different implications.

Step 2 Solve: We divide the galaxy's mass by its luminosity:

$$\frac{M}{L} = \frac{5 \times 10^{11} M_{\text{Sun}}}{1.5 \times 10^{10} L_{\text{Sun}}} = 33\,\frac{M_{\text{Sun}}}{L_{\text{Sun}}}$$

Step 3 Explain: The galaxy has a mass-to-light ratio of 33 solar masses per solar luminosity, which is more than five times the mass-to-light ratio for the matter in the Milky Way Galaxy within the Sun's orbit. We conclude that, on average, the mass in this galaxy is *much less* luminous than the mass found in the inner regions of the Milky Way, suggesting that the galaxy must contain a lot of mass that emits little or no light.