9
Dark Matter and Dark Energy

The composition of the heavens was a great mystery until the spectroscopic discoveries of the mid 1800s showed that the chemical elements in stars are the same as those on Earth (as we discussed in Chap. 6). But today we find ourselves grappling once again with a great mystery relating to the composition of the universe. We now have good reason to believe that most of the universe is in fact *not* made of ordinary atomic matter.

Understanding the composition of the universe is of great interest in its own right. In addition, accounting for all the matter in the universe is important for predicting its future evolution. In Chap. 8 we learned that the fate of the universe and its large-scale geometry depend on whether the density parameter, $\Omega = \frac{\rho}{\rho_c}$, is less than, equal to, or greater than one. We have already calculated the critical mass density ρ_c, so now let us turn to the measurement of the average mass density ρ. We shall see that this pursuit led to the discovery of dark matter. We will also discuss the surprising emergence of another major component of the universe called dark energy.

9.1 The Average Mass Density of the Universe and Dark Matter

On large enough scales, galaxies are approximately evenly distributed through space. Thus to calculate the *average mass density*, ρ, of the universe, a reasonable proposition seems to be to add up the masses of a large number of galaxies that span a sufficiently large volume, and then divide by that

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volume. So, how does one determine the mass of each galaxy in our sample volume? One approach is based on galactic luminosity. Astronomers can use the amount and spectrum of light from a galaxy to estimate the number and types of its constituent stars. One can then add up the stellar masses, yielding a mass for the luminous matter in the galaxy. By doing so, one obtains $\Omega_{stars} \approx 0.005$. This is much smaller than unity, but we should not be too quick to conclude that the universe is open—there may still be a considerable quantity of mass hiding in stellar remnants (white dwarfs, neutron stars, and black holes), interstellar gas and dust. We need to find another way to measure the amount of mass in a galaxy that includes these "invisible" contributions.

Conveniently, we can "weigh" galaxies using our knowledge of Newtonian mechanics, just like we were able to "weigh" the Sun in Chap. 2. If a mass, M, is orbited by an object at a radius r with velocity v, then by measuring the radius and velocity, it is possible to calculate the mass inside the orbit using

$$M = \frac{v^2 r}{G} \tag{9.1}$$

Thus the Earth's orbital radius and velocity yield the Sun's mass.[1] Similarly, the orbital radius and velocity of a star around the center of a galaxy, yields the mass of the galaxy (that is contained within the orbit).

When astronomers plot the rotation speeds of planets (or stars) vs the distance from the center of the Solar System (or a galaxy), they obtain a "rotation curve". The rotation curve for the Solar System is found to be precisely in accordance with the theoretical prediction: planets further out have slower orbital velocities (see Fig. 9.1). Rotation curves for many spiral galaxies have also been measured (see Fig. 9.2). However, they defy predictions. As we move from the center, the rotation velocity grows, since the orbit includes more matter. The problem arises when we get to the visible edge of the galaxy. One might expect the rotation curves to start dropping off, as they do for the Solar System. But they do not. In many cases the rotation velocity remains flat, or even increases, to distances well beyond the visible edge. This indicates that there must be a large amount of "dark matter"

[1]In fact, because the planets themselves have so much less mass than the Sun, we can pick any planet, and use its distance and its orbital velocity to calculate the Sun's mass. It doesn't matter whether we use Mercury or Neptune, or any planet in between, we always get the same answer for the Sun's mass.

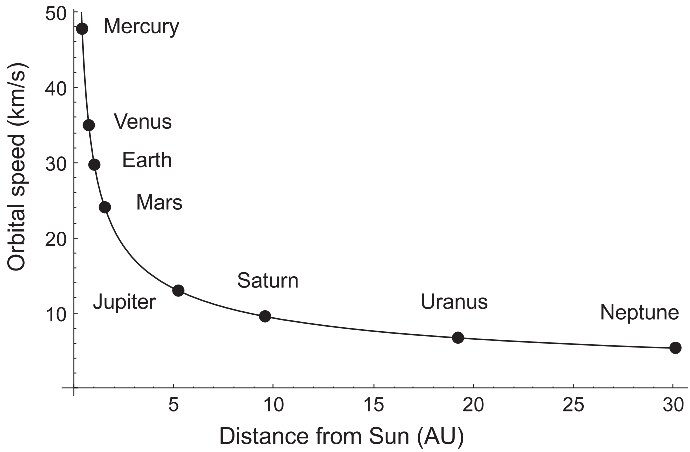

Fig. 9.1 Solar System rotation curve. The orbital velocities drop in inverse proportion to the square root of the distance from the Sun. This is known as a Keplerian fall off, and can be deduced from Eq. (9.1)

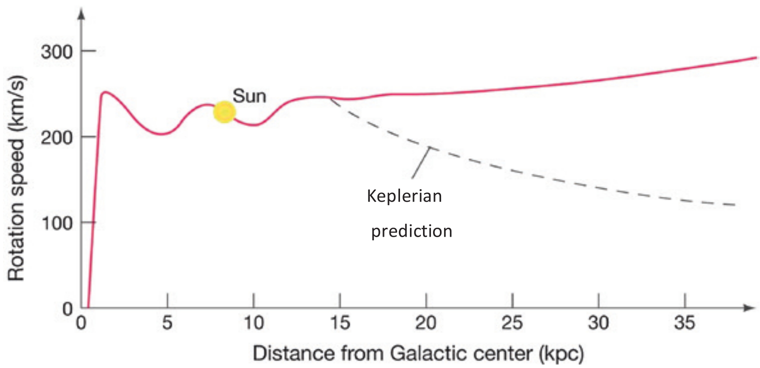

Fig. 9.2 Galaxy rotation curve. This curve can be used to determine the amount of mass lying within any given radius. The dotted curve is predicted if the mass in the galaxy ends at the visible edge of the galaxy, about 14 kpc (or 46,000 light years) from the center. The actual data do not follow the prediction, indicating that unseen mass exists beyond the visible edge. *Credit* Eric Chaisson [from Astronomy Today, Eric Chaisson, Stephen McMillan, Colombus (Ohio)]

beyond the visible distribution of stars. Detailed studies of rotation curves lead to the conclusion that luminous galaxies are embedded in vast dark matter halos, as illustrated in Fig. 9.3.

But how can one measure the rotation speeds for "invisible" objects beyond the visible edge? It turns out that there are vast rotating disks of hydrogen gas that extend way beyond the stars in galactic disks. The gas emits radio waves, and by measuring the Doppler shift of the radiation, the

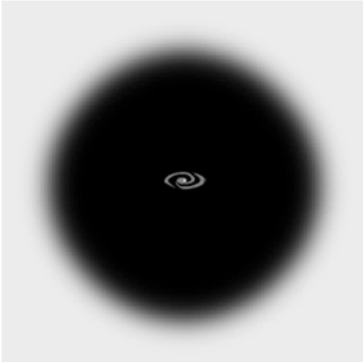

Fig. 9.3 Dark matter halo surrounding the luminous part of a galaxy

rotation curve can be extended. These measurements suggest that the dark matter halos are about 50 times more massive than the stars.

Additional evidence in support of this dramatic conclusion comes from studying *galaxy clusters*.[2] As we discussed in Chap. 4, light from a distant source can be gravitationally deflected by a concentration of mass that lies between the source and the observer. This can result in multiple images of the source, and in amplification and distortion of these images. If a galaxy cluster lies between us and some more distant galaxy, then the angular separation between the images of the distant galaxy on the sky and the amount by which they are distorted allows scientists to estimate how much mass is contained in the intervening cluster. Using such gravitational lensing techniques, clusters of galaxies have been weighed, and the results are consistent with those found from galactic rotation curves.

Fritz Zwicky, the Swiss born astronomer who predicted the existence of dark matter way back in the 1930s, used a different method of weighing clusters. He measured the speeds at which galaxies move in clusters and noticed that the speeds were so high that the galaxies would fly away, unless there was a large amount of unseen matter binding them to the cluster. No one took his idea seriously until four decades later, when Vera Rubin discovered, from the study of galactic rotation curves, that the universe harbors a large amount of dark matter, well in excess of the luminous matter in stars. Today, both Zwicky and Rubin are credited with the discovery of dark matter.

[2]A galaxy cluster is a collection of galaxies that are gravitationally bound to each other.

Another line of evidence for dark matter in galaxy clusters comes from X-ray telescopes that have revealed that clusters have very hot, tenuous atmospheres. These atmospheres are bound to their clusters by gravity, just like the Earth's atmosphere is bound to the Earth. Measurements of their temperature and X-ray radiation intensity yield two important results: (a) the atmosphere itself is several times more massive than the stars in the cluster; and (b) dark matter dominates over normal matter (atmospheric gas plus stellar mass) by a factor of about 5. Like the evidence for dark matter in galaxies, the evidence for dark matter in clusters is very strong (Figs. 9.4 and 9.5).

So what is this dark matter? As we already mentioned, part of it could be in dark stellar remnants—white dwarfs, neutron stars, or black holes. It could also include "failed stars"—low-mass objects not quite large enough to ignite nuclear reactions. But as we shall discuss in Chap. 12, none of these candidates can account for the observed amount of dark matter. We shall see that there are good reasons to believe that dark matter cannot be the usual atomic matter, but should instead consist of some exotic, as yet undiscovered particles. The particles need to be stable (so they can last for the lifetime of

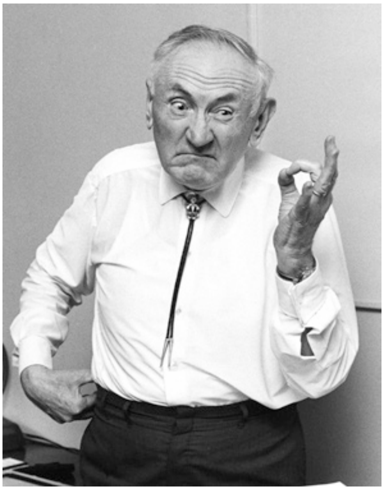

Fig. 9.4 The Swiss born Fritz Zwicky was a Professor of Astronomy at the California Institute of Technology. In addition to his discovery of dark matter, Zwicky also predicted that neutron stars would be produced in supernova explosions, and that gravitational lensing could be used to weigh galaxies and clusters. Despite the legends about Zwicky's confrontational personality (he is rumored to have called some of his colleagues "spherical bastards", because whichever way you look at them, they are still bastards!), accounts of his compassion and generosity include how he and his wife carried out a campaign to stock libraries in war-torn Europe after World War II. Photo by Floyd Clark, courtesy of the Archives, California Institute of Technology

Fig. 9.5 During the 1970s Vera Rubin (1928–2016) found strong evidence that dark matter exists in galaxies, by studying galaxy rotation curves. In 1965 Rubin was the first female to be allowed to use the instruments at Palomar Observatory. Motivated by her own gender based professional challenges, Rubin was a strong advocate for young girls and women to pursue their scientific careers. A mother of four children, (all of whom have Ph.D.'s in the sciences), Rubin was also an observant Jew who saw no conflict between her religious views and her scientific endeavors. *Credit* AIP Emilio Segre Visual Archives, Rubin Collection

the universe) and weakly interacting (otherwise they would easily be detectable). Particle physicists have suggested a number of hypothetical candidates for dark matter particles, but for now we have to accept the fact that we do not know what most of the matter in the universe is made of.

Current measurements of the different contributions to the average density of the universe yield $\Omega_{dm} \approx 0.26$ for dark matter and $\Omega_{at} \approx 0.05$ for the atomic matter (stars and gas). The total density parameter, including both dark and atomic matter contributions, is then $\Omega_{\rm m} = \Omega_{dm} + \Omega_{at} \approx 0.31$. It is less than unity, suggesting that the universe has an open hyperbolic geometry and will expand forever. This, however, is not the end of the story.

9.2 Dark Energy

We now turn to an even more mysterious ingredient of the universe, which was serendipitously discovered by two groups of astronomers in the late 1990s. The two teams, one headed by Saul Perlmutter and the other by Brian Schmidt, set out to study the expansion history of the universe, using supernovae as standard candles. The astronomers compared the redshifts of remote galaxies to their distances, much like Hubble did, but for galaxies much further away. Redshifts were measured directly from the shift of spectral lines; and distances were determined by measuring the apparent brightness of Type 1a supernovae.

The redshift tells us how fast the galaxy was moving at the time when the light was emitted. The present velocity of the galaxy can be found from its distance. The expectation was that galactic velocities at earlier cosmic times were greater than they are today—simply because the expansion of the universe is slowed down by gravity. It therefore came as a huge surprise in 1998 when both teams discovered that galaxies are now moving *faster* than they did before.

The results of the measurements are shown in Fig. 9.6. The purple line corresponds to a universe without gravity, where galaxies are receding at constant speeds. In a decelerating universe the data points should be above this line, while in fact they are predominantly below the line. Thus the expansion of the universe is accelerating! (Figs. 9.6 and 9.7).

The redshift-distance measurements can be used to find the scale factor as a function of cosmic time, directly revealing the expansion history of the universe. The data indicate that the expansion was decelerating in the past, but in more recent times the expansion of the universe started accelerating. The turning point was roughly five billion years ago (around the time our Solar System was formed).

What could possibly cause the observed accelerated expansion? And what could explain the transition from deceleration to acceleration? It is as though attractive gravity suddenly flipped to become repulsive.

We have already encountered one instance where gravity can be repulsive: remember the vacuum energy density, or the cosmological constant? Let's suppose the vacuum has a nonzero mass density ρ_v. This will produce a repulsive force. If ρ_v is sufficiently large, this force will overcome the attractive gravity of matter. The result will be an accelerated expansion of the universe.

The vacuum density ρ_v remains constant in time, while the density of matter ρ_m changes with the expansion of the universe. The volume of any given region grows like the cube of the scale factor,

$$V(t) \propto a^3(t) \tag{9.2}$$

If M is the mass of matter contained in the region, then the density of matter is

$$\rho_m(t) = \frac{M}{V(t)} \propto \frac{1}{a^3(t)} \tag{9.3}$$

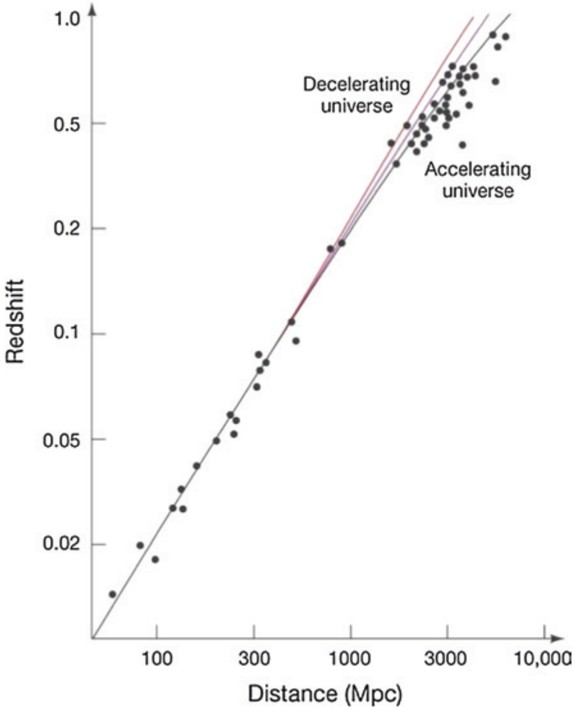

Fig. 9.6 Redshift-distance graph for distant supernovae. The *red* (*upper*) and *black* (*lower*) lines correspond to decelerating and accelerating universes, respectively. The *purple line* (in the *middle*) is for a universe without gravity, where galaxies move at constant speeds. The data indicate that our universe is accelerating. *Credit* Eric Chaisson [from Astronomy Today, Eric Chaisson, Stephen McMillan, Colombus (Ohio)]

Fig. 9.7 Saul Perlmutter of the Lawrence Berkeley Laboratory, Brian Schmidt of Mt. Stromlo Observatory in Australia and Adam Riess of Johns Hopkins University won the 2011 Nobel prize in physics for their role in the discovery of accelerated expansion of the universe. *Credit* (c) Nobel Media AB *photo* Ulla Montan

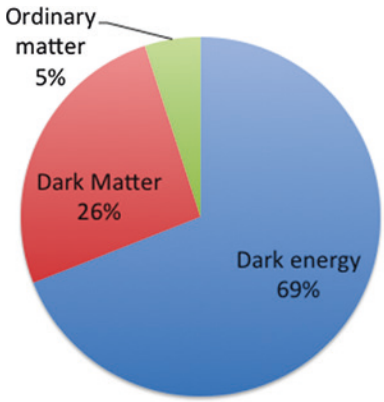

Fig. 9.8 The present composition of the universe

So at early times, when the scale factor is very small, ρ_m must be much greater than ρ_v. Thus the attractive gravity of matter overwhelms the repulsive gravity of the vacuum. But, as the universe expands, the matter density is diluted, and eventually it drops below the vacuum density. At that point the cosmic acceleration begins. [More precisely, acceleration begins when $\rho_v > \rho_m/2$; see Chap. 5, Eq. (5.3)].

If ρ_v is indeed the reason for the accelerated expansion, we need to determine how large it is. The best fit to the data is obtained for $\rho_v \approx 2.2\,\rho_{m0}$, where ρ_{m0} is the present matter density.[3] The corresponding vacuum density parameter is

$$\Omega_{vac} = \rho_v/\rho_c \approx 0.69 \tag{9.4}$$

The vacuum energy, which is often called "dark energy", is thus the dominant component of the universe (see Fig. 9.8). An intriguing consequence of Eq. (9.4) is that the total density parameter is very close to unity: $\Omega_{tot} = \Omega_{vac} + \Omega_m \approx 1$. It seems as though the universe is perched on the borderline between being open and closed—it is flat, or at least very nearly flat.[4]

[3]Note that ρ_{m0} includes both dark and atomic matter.

[4]Several other independent measurements also indicate that the universe is flat, further adding confidence to the notion that the universe is filled with dark energy. We will address these findings in later chapters.

9.3 The Fate of the Universe—Again

Dark energy also has important implications for the future of the universe. The Friedmann relation between the density parameter and the fate of the universe that we discussed in Chap. 8 only holds when there is no vacuum energy. (We emphasize that the relation between Ω and the *geometry* of the universe is always valid). Once the universe is dominated by vacuum energy (as it is today), it will keep expanding forever, due to repulsive gravity, regardless of the value of Ω. The universe will double in size about every 10 billion years. The velocities of the galaxies will also double on the same time scale.

This kind of expansion is called exponential. As the recession speeds of galaxies exceed the speed of light, they will leave our observable region, never to be seen again. The universe will thus get emptier and emptier, until (in a few trillion years), no stars outside our local galaxy cluster will be visible at all. As for the stars themselves, eventually they will exhaust their nuclear supplies, and their embers will fade into the frigid blackness of space. We should rejoice that we live at the current cosmic epoch, under a bejeweled sky brimming with clues about our cosmic origins.

We need to take a moment to reflect on a very curious feature of our universe. The vacuum energy density was much smaller than that of matter in the early universe, and it will get much greater than the matter density in the future. We happen to live at a very special epoch when these two densities are comparable: $\rho_{vac} \approx 2\rho_{m0}$. Do you think this is simply a coincidence?

Summary
The mass density in luminous stars amounts to a small fraction of the critical density. By studying the rotation curves of galaxies, as well as gravitational lensing and galaxy velocities in clusters of galaxies, we find that, by mass, there is roughly 5 times more dark matter, than all the matter in stars and gas. We don't know what the dark matter is made of, but we now know it is not composed of protons, neutrons and electrons, like ordinary matter.

Even with dark matter included, the total matter density is still less than the critical value. But recent observations of supernova explosions have revealed that apart from dark matter, the universe contains yet another mysterious dark component. Observations indicate that the expansion of the universe is now accelerating with time. The most likely cause of this acceleration is the existence of a space-filling vacuum energy, called "dark energy", which has a repulsive gravitational effect. The discovery of dark energy

changes the fate of the universe—it will continue to expand, regardless of whether it is open or closed.

Questions

1. Astronomers have found that $\Omega_{stars} \approx 0.004$. Briefly explain how they made this measurement.
2. If there is matter in and around galaxies that is not luminous, how can we know it's there?
3. Describe two methods astronomers use to infer that there are large amounts of dark matter in galaxies and clusters of galaxies.
4. Would an electrically charged particle be a good dark matter candidate? Why?
5. Consider a galaxy containing stars that are concentrated within a radius $R_s = 25{,}000$ light years from the galactic center. At this radius, the stars are observed to be rotating at 200 km/s around the galactic center. Find the total mass of matter contained within the radius R_s. Assuming that most of this mass comes from stars with mass comparable to the Solar mass, estimate how many stars are in this galaxy.
   If the same velocity is measured from hydrogen gas at 75,000 light years, how much mass is contained in this larger orbit?
6. Do you find it upsetting that normal atomic matter is just a small percentage of the total matter content in the universe?
7. How do you think Einstein would have reacted to the 1998 discovery that the cosmological constant may not be zero?
8. Today the universe is undergoing accelerated expansion. If we go back in time, was there ever a period when the expansion of the universe slowed down?
9. Roughly when did the universe start to accelerate its expansion—in the last quarter century, several thousand years ago, or a few billion years ago?
10. In the early universe $\rho_v \ll \rho_m$, but today $\rho_v \approx 2\rho_m$. Briefly explain how the vacuum energy density came to dominate the matter density, by considering how ρ_v and ρ_m do or don't change with time.
11. How is dark matter different from dark energy?
12. Show [using Eq. (5.2)] that any "stuff" with a negative pressure that has an absolute value $|P| > \rho/3$ would be gravitationally repulsive.
13. Use Eqs. (5.1) and (5.2) to show that expansion is accelerated when $\rho_v > \rho_m/2$.