Chapter 2
Large Scale Structure

Dark Matters: The Cosmic Web

Cosmologists have now discovered that something else must have formed in the earliest stages of the universe, something that has been hidden from us until very recently: *dark matter*. By about 1960, astronomers had noticed that the stars in some galaxies revolved around the center of the galaxy much faster than expected, as though gravity was much stronger than all the known matter could produce. This seemed to suggest that galaxies had much more mass than all of the stars and dust we could see (because they emit light). Calculations suggested that we were seeing only about 10% of the mass of galaxies and the other 90% was somehow invisible, or dark. Apparently, this dark matter was producing gravity, as all matter does, but not light.

More recent observations have hinted that the entire universe also has a great deal of "missing mass" or dark matter. The latest data suggest that the universe we can see—all of the stars and galaxies and clouds of gas and dust—may comprise only a few percent of the total contents of the universe. Apparently, most of the universe is invisible!

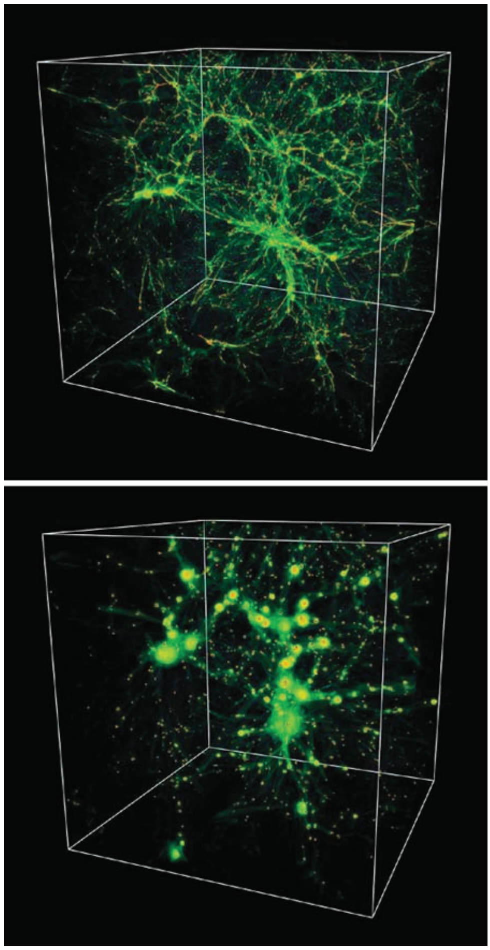
We do not yet know what dark matter actually is, only that it must be there and that it cannot be any form of *baryonic matter* (the familiar kind of matter made of protons and neutrons). This rules out things like burned out stars (called black dwarfs), cold dust clouds, and probably black holes. Some physicists now suspect that dark matter may be mostly comprised of some kind of exotic particle (dubbed the *WIMP*, for weakly interacting massive particle) that interacts only very weakly with normal matter except through gravity; but, as yet, this particle has not been detected (the Large Hadron Collider may eventually solve the mystery of dark matter).

The presence of dark matter is now being mapped out by its effect on things we *can* see—things that produce light. One method uses an effect called *gravitational lensing*, which is the bending of light as it passes through regions of strong gravity. In the last decade, gravitational lensing images of large sectors of the universe have revealed a gigantic skeleton of dark matter on which the visible universe hangs.

Another method of mapping out dark matter uses the distribution of galaxies at very large scales. These maps show that galaxies are not smoothly spread out, but concentrated in enormous sheets and filaments, with huge voids in between. This uneven distribution of galaxies traces out an intricate scaffolding of dark matter that has come to be called the *cosmic web* (see Figure 2-1) (Simcoe 2004).

Figure 2-1

Computer simulations of the cosmic web of dark matter, 2 billion years after the Big Bang (above) and today (below). The earlier box is 30 million light-years across while the later box is four times bigger, because of 12 billion years of cosmic expansion.



Courtesy: Renyue Cen, Princeton University

A third technique that reveals the cosmic web looks at the huge empty spaces between galaxies, which are not really empty but filled with a very thin gas of hydrogen and helium. When astronomers analyze the light that has passed through this *intergalactic medium*, they find that the gas is not spread out uniformly, but concentrated along the filaments of a web with varying density. All of the different methods used for detecting the cosmic web are now coming into agreement, allowing researchers to create maps of the cosmic web of dark matter and the large-scale universe. Although the cosmic web is completely invisible, its existence is now well established. But how did it form?

It is believed that dark matter arose during the first second after the Big Bang, along with the protons and electrons of normal matter. For the next 380,000 years it was too hot for the protons and electrons of the normal matter to combine into neutral atoms and release the photons they entrapped. So these protons and electrons and photons remained as a hot smooth plasma that produced an outward gas pressure. This outward pressure counteracted the effects of gravity, so it remained smooth and without structure until it cooled sufficiently. But the much more abundant dark matter followed a different path because it was not subject to an outward gas pressure. The effects of gravity, combined with the small density variations that grew out of the period of cosmic inflation, allowed the dark matter to begin clumping into bubbly filaments and sheets very early in the life of the Universe. This was the birth of the cosmic web, and it grew as the universe expanded, and thickened as gravity pulled more dark matter toward denser filaments.

When the Universe was 380,000 years old, the normal matter had cooled enough to become neutral atoms and the effects of gravity became dominant. By this time the cosmic web of dark matter was well formed and the normal matter quickly began to fall into the web. The large-scale structure of the Universe was now established, but it was nothing more than a veil of hydrogen and helium gas clinging to the cosmic web. The universe was still dark because stars did not yet exist; it was still too hot for them to begin forming.

At the age of about 400 million years, the universe had finally cooled enough for matter to begin falling into small dense clumps of dark matter to become the first stars (Bromm 2009). When the first stars ignited, the radiation that poured out from them ionized surrounding clouds of hydrogen and helium, causing them to glow. The faint glow of this *re-ionization* is the fingerprint of the first stars and has been detected indirectly in the details of the cosmic background radiation. The birth of the first stars was one of the most important events in the life of the Universe because stars perform some of its most crucial functions. Not only do they produce vast quantities of energy, they also manufacture elements and create planetary systems. We will look more closely at the birth, life, and death of stars later in this chapter. After many stars had formed, they began to fall into large regions of dark matter, sometimes called halos. This was the birth of the first galaxies.

Galaxies and Dark Energy

Galaxies are perhaps the most magnificent structures in all of nature, and also some of the oldest and most distant objects in the universe. The further away from us they are, the older they are, because the light from them that we see had to travel billions of years to reach us. That is, the further away a galaxy is, the further back in time we are seeing when we look at it. Observations of the most distant galaxies suggest that the first galaxies formed about 600 million years after the Big Bang, as the result of stars, dust, and gases being pulled into blobs of dark matter. As the matter in an infant galaxy contracts, it also begins to rotate. The more it contracts, the faster it rotates, like a spinning ice skater pulling her arms inward. The effect of this rotation is clear in the shape of large spiral galaxies (Figure 2-2).

Figure 2-2(a)

A galaxy seen "edge-on": The Sombrero Galaxy (M104) is about 30 million light-years away, and is moving away from us at about 640 miles per second! A supermassive black hole resides at the center of this galaxy.

NASA/STSci

Figure 2-2(b)

A galaxy seen "face-on": The Pinwheel Galaxy (M101) is about 27 million light-years away and about 170,000 light-years in diameter. Both the Pinwheel and the Sombrero Galaxy were first seen in 1781.

NASA/STSci

Figure 2-2(c)

Andromeda (M31), our sister galaxy, is very much like our own galaxy, the Milky Way. The smaller bright spots above and below the center are among the many dwarf satellite galaxies in our Local Group. Andromeda is about 2.5 million light-years away and about 100,000 light-years in diameter.

Courtesy: Robert Gendler: http://www.robgendlerastropics.com/

The first galaxies were small and disorganized, but some were drawn toward other infant galaxies by gravity, merging to form larger galaxies. The first few billion years in the life of the universe were dominated by mergers of smaller galaxies into larger ones, and some eventually grew into massive spiral galaxies like our own Milky Way. It is believed that our galaxy is one of the oldest and was probably beginning to form about 13 billion years ago, or about 700 million years after the Big Bang. Galaxies also formed in groups and clusters of groups, guided by the filaments and nodes of the cosmic web of dark matter that permeate the large-scale universe. Around every galaxy is a much larger halo of dark matter that is merely a tiny bulge in a filament of the web.

The Milky Way and its companion Andromeda are large spiral galaxies and are surrounded by at least twenty smaller galaxies, forming what has come to be called the *Local Group*. Recent observations indicate that Andromeda and the Milky Way are moving toward each other and will eventually merge into one super-galaxy. Our Local Group is part of a much larger cluster of galaxy groups, the *Virgo Supercluster*. A map of our neighborhood of the universe that is one billion light years across is shown in Figure 2-3. The presence of the cosmic web is very apparent at this large scale.