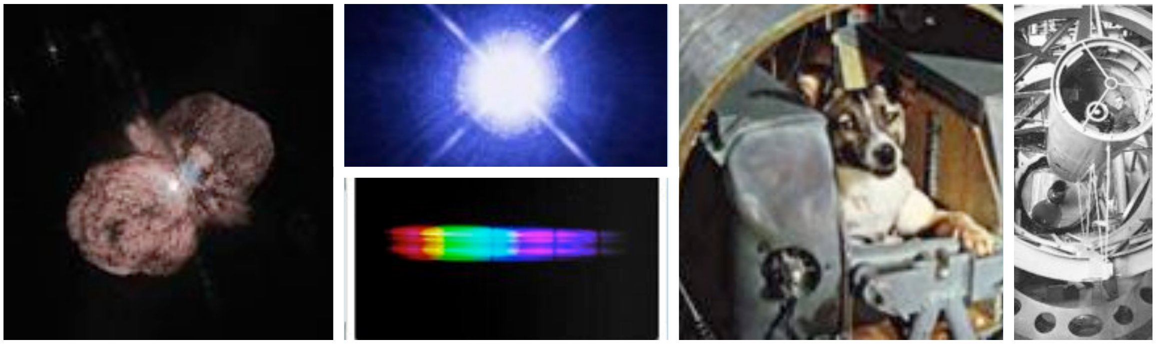
Chapter 3

Five Revolutionary Discoveries

Introduction



Left to right: Eta Carinae, Sirius and its spectrum, Laika (the first dog in space), The Hooker Telescope on Mt. Wilson in California

Only five hundred years ago, people thought the Earth was the center of the Universe and the stars were points of light in the sky. Today we realize the Earth is one small planet beloning to one ordinary star located in a typical galaxy that is one of billions of galaxies in the observable Universe. Five revolutionary discoveries have brought us from the ancient to the modern view of the Earth's place in the cosmos: 1) the Sun is the center of the Solar System, 2) the stars are suns, 3) the Milky Way Galaxy has a finite size, 4) the Universe is filled with galaxies, and 5) the Universe of galaxies is expanding.

1. The Earth is not the center

When you look at the sky at night, it *looks* like the stars surround the Earth. The Moon circles around the Earth once a month. Over the course of the year, the Sun appears to move around the Earth, drifting through the constellations of the zodiac. The planets, too, seem to move around the sky, though in more complicated ways.In all ways, it appeared that the Earth was the center of Creation and everything else moved around the Earth. Two men, more than any others, are responsible for making mankind realize that the Sun, not the Earth, is the center of the Solar System. The first was Nicolaus Copernicus, a Polish astronomer, who developed the first mathematical theory that explained the motions of the planets in terms of a Sun-centered Solar System. The great controversy between the Earth-centered and the Sun-centered theories is called the Copernican Revolution in his honor. The second man was Galileo Galilei, whose discoveries with the telescope provided the first evidence that Copernicus was right.

Prior to Copernicus, astronomers thought that the Earth was the center of the Universe and the Moon, the Sun, and the planets orbited about the Earth. The planets that were known at the time—the planets that can be easily seen without a telescope—were Mercury, Venus, Mars, Jupiter, and Saturn. In the accepted theory, the so-called Ptolemaic System, the Earth was orbited by, in order, the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. The problem with this system was that it was hard to explain the motions of the planets. The planets show two patterns of motion. The innermost planets, Mercury and Venus, always appear more or less close to the Sun in the sky. They never appear at **opposition,** the direction in the sky opposite to the Sun. The outer planets, Mars, Jupiter, and Saturn, on the other hand, do appear at opposition, but when they are at opposition they stop and go backwards for a few weeks. It require a rather complicated combination of motions to explain these patterns in the Earth-centered system.

In the Sun-centered system of Copernicus, these patterns of motion were easily explained. Mercury and Venus never appear at opposition simply because they are closer to the Sun than the Earth is. To be seen at opposition, a planet must be farther away than the Earth. As for the outer planets, the Earth moves in its orbit faster than they do. When an outer planet is at opposition, the Earth passes it by, and the planet seems to go backwards for a while. The ease with which the Sun-centered theory explained something that was so difficult to explain in the Earth-centered theory was a big plus.

After the telescope was invented in 1608, Galileo realized that a test of the two theories could be made by observing the phases of the planet Venus. In a telescope, Venus shows phases like the Moon. The Earth-centered theory predicted that Venus would be seen only as a thin crescent. The Sun-centered theory predicted that Venus would show all phases, including the **gibbous** phase, the more-than-half-full phase. Galileo's observation of the gibbous phase of Venus in 1610 was strong evidence in favor of the Copernican Theory. Galileo's argument was an example of the **scientific method,** the scientist's way of deciding among competing theories. There are basically three steps in the scientific method:

1) Observe something in nature

2) Devise an hypothesis or theory to explain the observation.

3) From your theory, make a prediction about another observation you can make.

4) Go back to step 1. If your prediction is confirmed, your theory is supported. If your prediction is *not* confirmed, you will have to modify or abandon your theory.

In this instance, the phenomenon is the motions of the planets in the sky, the theory is the Earth-centered theory or the Sun-centered theory, the other observation is the phases of Venus. The essence of the scientific method is the continual interplay of theory and observation.

Using the evidence he had discovered using the telescope, Galileo became a powerful advocate of the Sun-centered theory. It took a long time, but in time it became universally accepted. Our conception of Earth and Heaven changed fundamentally—there was a revolution in the way people think about the Earth. That's why it's called the Copernican Revolution.

The Copernican Revolution marked the beginning of modern astronomy and a turning point in science. Astronomers realized that the Earth is one of the planets and that the planets are world like our own. Scientists realized that the scientific method was the way to scientific discovery. Mankind had taken the first step in understanding the Earth's true place in the cosmos.

2. The stars are distant suns

The facct that the stars are distant suns was worked out in the 1800s. Three independent discoveries confirmed this idea: the *stellar parallax, spectroscopy,* and *binary stars*.

Stellar Parallax

The idea of the stellar parallax goes back to Copernicus and even earlier. The Copernican Revolution revolved, we might say, about the planets. It didn't much concern the stars. The stars would look much the same whether the Sun goes around the Earth or vice versa. There is one way, however, that the motion of the Earth around the Sun has an effect on the stars: that is the **stellar parallax.**

Suppose first of all that some stars are nearer than other stars. (This is true.) Now imagine that you are looking at a nearby star. As the Earth orbits around the Sun, the nearby star will appear to change position in the sky compared with more distant stars in the background (Fig. n). This shift in position in the sky is called the stellar parallax. It is very small. In fact, it is so small, that it can't be seen without a telescope. The reason the parallax shift is small is that the stars—even the nearest stars—are much, much farther away than the Sun. It turns out that the size of the parallax depends on the distance to the star: *the farther the star, the smaller the parallax.* Very distant stars don't show any measurable parallax at all; that's why they serve as a fixed background.

The parallax of even the nearest stars, like Sirius, is so small that it couldn't be detected with the telescopes available in Galileo's day. People realized that this meant that the stars must be very, very far away. Realizing that the Sun, if placed at such tremendous distances, would look just like a star, they made a bold guess: *the stars are suns that are very far away.* It was a good guess!

It took 200 years before telescope technology advanced to the point where the parallax of stars could be measured. The first convincing measurement of the parallax of a star was made by Friedrich Bessel in the 1830s. He measured the parallax of a double star, 61 Cygni, and calculated that it was *800,000* times farther away than the Sun—about 11 light-years. At that distance, the Sun would look not much brighter than 61 Cygni. Slowly, astronomers measured the distances to other stars. Some, like Sirius, turned out to be closer than 61 Cygni. The closest turned out to be another double star, Alpha Centauri and its tiny companion, Proxima, which are 4 light-years from the Sun. Most stars turned out to be much farther away than 61 Cygni. The stars of the Big Dipper proved to be about 100 light-years away. Many stars were so far away, their parallax could not be measured. That meant they must have been hundreds or thousands of light-years distant. It was clear that the stars were far enough away that they could well be suns.

Stellar Spectra

About the same time, a scientist by the name of Fraunhofer made a quite unexpected discovery that also implied that the stars were suns—the discovery of stellar **spectra.** A *spectrum* (plural *spectra*) is what you get when you pass the light of a star through a prism and separate the colors of light. Fraunhofer did this with the Sun and made an interesting discovery (Fig. n). The Sun's light showed all the colors of the rainbow, but there were narrow gaps, missing colors, that astronomers call *lines* because they look like dark lines drawn on the spectrum. Subsequently, chemists discovered that they could produce these lines in gasses on Earth. They found that each line was due to a different chemical element. For example, the line that Fraunhofer labeled C is due to the element hydrogen (today astronomers call it the **hydrogen alpha** line). During the 1800s, astronomers found that other stars also have spectra with lines. Some spectra were similar to the Sun's spectrum and some were quite different, but the spectra showed that stars are made of the same elements as the Sun—they showed that indeed the stars are merely distant suns.

The discovery of the spectral lines was milestone. Before that, astronomers didn't study the stars very much. They didn't know how far away they were or what they were made of, so there wasn't much they could say about the stars. It didn't look like they would ever be able to learn what stars are like. The spectral lines opened up a rich avenue of exploration. Eventually they told us not only what stars are made of, but how hot they are, how big they are, and how fast they are going. The study of spectral lines—**spectroscopy**—became the fundamental tool of astronomers. It's not too much of an imagination to say that most astronomers today spend most of their time taking, analyzing, and interpreting spectra.

Binary stars and stellar masses

In addition to the stellar parallax and spectroscopy, a third discover confirmed the sun-like nature of stars. These are the double stars. Double stars, or **binary stars,** as astronomers call them, are pairs of stars that orbit around each other, moving under the influence of their mutual gravitational attraction. Just as planets orbit around the Sun under the force of gravity, stars can orbit about each other. It turns out that they frequently do. The discovery of binary stars was important because if you could measure the parallax of the pair and thereby determine their distance, you could calculate their weight—their **mass.** The idea goes something like this: the more massive the stars are, the stronger the force of gravity between them, and the faster the stars have to orbit around each other to resist the force of gravity. So you just have to time how long it takes the stars to orbit around each other and then you can calculate their masses. (Astronomer's call this principle **Kepler's Third Law.**) This is easier to say than to do, because it can take tens or hundreds of years for the stars to complete one orbit. Nevertheless, it can be done, and the results tell us that stars are roughly the same mass as the Sun. Some may be five or ten times more massive, some may be five or times *less* massive, but on the whole stars are about the same mass as the Sun. This fact again confirms the idea that stars are suns.

3. We live in a Galaxy of finite size, but not in the center.

We know today that stars are concentrated in giant systems of billions of stars called galaxies, separated from each other by vast regions devoid of stars, but this fact wasn't at all obvious at first. Even 100 years ago, many astronomers supposed that stars were sprinkled more or less evenly throughout the Universe—that is to say, they thought there was only one Galaxy.

About 1920 the American astronomer Harlow Shapley showed that our Galaxy, the Milky Way, is large but of finite size. Furthermore, he showed that the Sun is nowhere near the center of the Galaxy. Just as Copernicus and Galileo had shown that the Earth was not the center of the Solar System, now Shapley showed that the Sun was not the center of the Galaxy.

Astronomers had tried to work out the size and shape of the Galaxy by studying stars, but this proved difficult because most stars are so far away their distances can't be measured. There was another problem that astronomers weren't even aware of, and that there is gas and dust *between* the stars that absorbs light and prevents us from seeing more than a few thousand light-years through the disk of the Galaxy. Recall that the Milky Way Galaxy is a spiral galaxy having a thin disk. The disk contains the gas and dust. By gas, we mean hydrogen and helium gas. By dust, we mean microscopic particles made of things like carbon, iron, and ice. It's the dust, actually, that absorbs light. We simply can't see stars on the other side of the Galaxy. In fact, we can't even see the center of the Galaxy. But we didn't know that in 1920.

The way Shapley got around these problems was to study **globular star clusters**. These are large clusters containing hundreds of thousands of stars. They occur above and below the disk of the Galaxy, so they are not much affected by the absorbing dust. They are found all around and even beyond the disk. If we could somehow measure the distances to the globular clusters, we would know how big the disk is. And assuming the clusters are distributed symmetrically in all directions around the center of the Galaxy, we could figure out where the center of the Galaxy is. In fact, it was already known that globular clusters are most common in the direction of the constellation Sagittarius, so Shapley suspected that the center of the Galaxy lay in that direction. But he needed a way to measure the distances to the globular clusters.

Even the nearest globular cluster is so far away that the parallaxes of its stars are too tiny to measure. However, if you could somehow measure the distance to even one star in the cluster, that would be enough, because all the stars in the cluster are essentially at the same distance from the Sun.

The Inverse Square Law

There *is* another way of determining the distance to a star, but it depends on your knowing the intrinsic brightness of the star. The idea is simple: the fainter the star appears to be, the farther away it must be. Astronomers call refer to this principle by the curious name of the **Inverse Square Law.** (We'll explain how it got that name later on.) The essence of the idea is the comparison between the *intrinsic* brightness of the star—how much light energy it gives off—and the *apparent* brightness of the star—how bright it appears in the sky compared with other stars. One way of describing the intrinsic brightness of the star is to ask what the apparent brightness of the star would be if it were placed at a standard distance from the Earth. Astronomers refer to this as the **absolute** brightness of the star. The standard distance that astronomers use is 33 light-years. A star that is 33 light-years away has an absolute brightness that is the same as its apparent brightness. A star that is closer than 33 LY has an apparent brightness greater than its absolute brightness. A star that is farther than 33 LY away has an apparent brightness that is less its absolute brightness.

So here's the idea. Look for a kind of star in the cluster that is peculiar enough that you can recognize it when you see *and* it's absolute brightness has been previously measured. Such a star is called a **standard candle.** The idea is that there is this factory that only produces one kind of candle—they are all identical, all equally bright, but they are a funny color that no other candle has so you know when you see one, no matter how far away it is. Then you know that if it looks dim, it's far away, and it it looks bright, it's close.

The secret to Shapley's success in measuring the distances to the globular clusters is that he found a standard candle that is common in them, a kind of star called an **RR Lyrae star,** named after a star in the constellation Lyra (the Lyre). RR Lyra stars are **variable stars,** meaning, they get gradually brighter and then dimmer over a cycle that lasts a few hours. That makes them easy to recognize. It turns out, however, that their *average* brightness (that is, their absolute brightness) is always the same. Some RR Lyrae stars, not belonging to globular clusters, are found in the Sun's vicinity. By studying them, their absolute brightness was determined. Then Shapley was able to use them as standard candles.

So what Shapley did is look for RR Lyrae stars in globular clusters and measure their average apparent brightnesses. Then, known the average *absolute* brightness of RR Lyrae stars, he used the Inverse Square Law, he calculated the distances to the RR Lyrae stars and thus to the globular clusters that contained them. Then he plotted the globular clusters in three dimensions. And lo! plotting the clusters on a map, he saw that they centered on a point 25,000 LY from the Sun in the direction of the constellation Sagittarius and that the whole Galaxy is about 100,000 LY across (these are modern measurements, Shapley's were actually larger).

No globular cluster was found farther than about 50,000 LY from the galactic center. Beyond that, Shapley asserted, there was only an endless expanse of nothing. But he was wrong about that.

4. We live in a Universe of galaxies.

You may be wondering, if the Universe is filled with galaxies, how could the astronomers of 1920 think that there was only one Galaxy? Couldn't they see the other galaxies? The answer is yes, they could see the galaxies, but they didn't realize they were galaxies.

They thought they were nebula. A *nebula* is a cloud of gas. (The plural is *nebulae,* pronounced NEB-you-lee.) There are different kinds of nebulae, but they are all basically big clouds of hydrogen gas. A *galaxy* is a very different thing–it is a big collection of billions of stars. In the telescope, however, they look quite pretty much the same: just globs of light. The reason is that galaxies are so far away that you can't see individual stars in them unless you have a really big telescope. The telescopes that existed prior to 1920 weren't big enough, so when astronomers looked at a galaxy, all they saw was the light of many stars smeared together. They looked like clouds of gas.

There was one kind of nebula that was so unlike the others that it made astronomers curious. This was what today we call the spiral galaxies. Back then, they were called spiral *nebulae.* The biggest and best-studied was the Great Nebula in Andromeda, known as M31. Today we call it the Andromeda Galaxy. It is the only other galaxy, apart from the Magellanic Clouds, that can be seen with the unaided eye; it looks like a detached part of the Milky Way in the fall sky. With their striking spiral arms, revealed only in photographs, they formed a distinct class of objects. But what were they? There was a lively controversy in the early 20th century about the nature of the spiral nebulae. Some astronomers thought they were collections of stars far outside our own Galaxy, as indeed they turned out to be. But many, probably most astronomers, thought they were small nebulae *inside* the Milky Way Galaxy; these astronomers speculated that they were new solar systems, places where new stars and planets were being formed. It was an exciting idea! They weren't completely wrong, either: we know today that young solar systems are disk-shaped clouds of gas called *solar nebulae,* but these real young solar systems are hard to see because they are surrounded by dust.

The controversy came to a head in the Great Debate of 1920. This was a conference held at the National Academy of Sciences in Washington, D.C., where two astronomers, Harlow Shapley and Heber Curtis, debated the nature of the spiral nebulae. Shapley, who had recently measured the size of the Milky Way Galaxy, argued that the spiral nebulae were clouds of gas inside our Galaxy. Curtis advocated the idea that the spiral nebulae were star systems outside the Milky Way Galaxy.

Both speakers had good arguments. One of Shapley's best points concerned the Triangulum Galaxy, M33, the third spiral galaxy in the Local Group. The Dutch astronomer Van Maanen had claimed to have measured motion in the spiral arms of M33. This meant that M33 had to be relatively nearby—no more than a few thousand light-years away—because in order to detect motion in a galaxy a million light-years away, the stars in the galaxy would have to be traveling at speeds greater than the speed of light, which is impossible. We now know that Van Maanen simply made a mistake, but there was no way of knowing that at the time. In defense of Van Maanen, mistakes are common in research. The only way to make new discoveries is to push your equipment to the limits of its abilities, and when you do that, the chances of making a false observation are high.

Curtis countered with his claim to have seen *novae* in the Andromeda Nebula. A nova is a star that suddenly flares up in brightness. becoming a thousand times brighter than it had been before. (The plural of *nova* is *novae*, pronounced NO-vee.) Curtis had studied novae in our Galaxy, but the ones in M31 were very faint. If they were actually is bright as the novae he had seen in our Galaxy, then M31 must be far, far outside the Milky Way Galaxy and must be itself as big as our Galaxy.

The Great Debate didn't settle the question, because the evidence was conflicting. What we needed was an accurate measurement of the distance to the Andromeda Nebula or M33, the nearest of the spiral nebulae. Only then would astronomers know whether the Andromeda Nebula was large distant galaxy or a small, nearby nebula. The only way to measure the distance to M31 was to find a standard candle in it and use the Inverse Square Law. But M31 was too far away to see RR Lyrae stars in it. We needed to find another kind of standard candle.

Just about that time, a suitable standard candle was discovered: the Cepheid variable star. Cepheids are pulsating stars, like RR Lyrae stars, but they are much bigger and brighter, and so can be seen from much greater distances. They also have longer periods, ranging from 5 to 90 days. Unlike RR Lyrae stars, however, than don't all have the same average absolute brightness. However, Henrietta Leavitt, studying Cepheids in the Magellanic Clouds, discovered an interesting fact: the brightest Cepheids have the longest periods. This is the famous **period-luminosity relationship** (fig. n). What this means is that once you have measured the period of variability, you look on the graph and can read off the luminosity.

The largest telescope in the world in 1920 was the Hooker Telescope on Mt. Wilson in California, which had been completed in 1917. It was the first telescope big enough to see stars in the Andromeda Galaxy, although they had to be supergiant stars. Working at Mt. Wilson was Edwin Hubble. Hubble turned the great telescope to the Andromeda Nebula in late in 1923 began to find Cepheid variable stars in it. After determining the periods of oscillations of the Cepheids, he could calculate the distance to M31 and could prove that it was far outside the limits of the Milky Way Galaxy. Clearly, M31 was as system of stars—a galaxy—and by implication, the other spiral nebula were probably star systems as well. Astronomers now knew that the Milky Way was just one of *billions* of galaxies in the observable Universe.

Hubble devoted the rest of his career to studying, measuring, and classifying the galaxies. Oddly enough, he never called them galaxies. To the end of his days he referred to them as *extragalactic nebulae.*

5. The Universe is expanding.

About the same time that Hubble was looking for Cepheids in the Andromeda Galaxy, another American astronomer, Vesto Slipher, made an astonishing discovery about all the other galaxies: *they are all moving away from our Galaxy.* How did he find this out? Once again, it was by looking at those spectral lines we mentioned earlier. It just so happens that when a star is approaching the Earth, its spectral lines are shifted slightly towards the violet end of the spectrum. The opposite is true if the star is moving away from us—the spectral lines are shifted toward the red end of the spectrum. In the second case, we say that the spectrum undergoes a **redshift;** in the first case, we say that there's a **blueshift,** although it might have been more logical to call it a violet shift.

This phenomenon is called the **Doppler Effect.** It is a phenomemon of all waves, not just light waves. Sound waves, for example, also are subject to the Doppler Effect. In the case of sound, the Doppler Effect manifests itself as a change in the pitch, or frequency, of the sound. Sound from the siren of an ambulance that is approaching you is raised in pitch, while the pitch is lowered when the ambulance passes you back and starts going away from you. Doppler radar, which uses radio waves, uses the Doppler Effect to tell how fast a car, plane, or stormcloud is moving toward or away from the radar device.

Getting back to astronomy, astronomers in the 1800s used the Doppler Effect to determine measure how fast stars are moving toward or away from the Sun. What they found was that the typical speeds of stars were 10 to 100 km/sec. When Slipher took the spectra of whole galaxies, he expected to get similar numbers, because he believed that the spiral nebulae were gas clouds inside the Milky Way Galaxy. He realized something was wrong when the galaxies turned out to have speeds of hundreds or thousands of kilometers per second. But the really baffling thing was that all galaxies but one showed *redshifts,* meaning that they are all moving away from us. The major exception was the Andromeda Galaxy, which is approaching us, along with some of the other galaxies of the Local Group. All of the galaxies outside of the Local Group are moving *away* from the Milky Way Galaxy. It was as though the Milky Way was infected with a deadly disease and the other galaxies were trying to get away from us as quickly as possible.

Now back to Hubble. After measuring the distance to the Andromeda Galaxy, Hubble used the 100-inch telescope to extend Slipher's measurements of the spectra of galaxies. The big telescope could take spectra of many more galaxies than Slipher could, and more distant galaxies. Hubble also found that all the galaxies outside the Local Group showed redshifts. In addition, Hubble noticed an interesting pattern: faint galaxies had especially high speeds of recession—speeds of *tens of thousands* of kilometers per second! By 1929, Hubble announced the discovery that is known today as **Hubble's Law:**

> *The farther the galaxy, the greater its speed of recession.*

This thing took everybody by surprise. What did it mean? The simplest explanation, perhaps, was that all the galaxies formed in our neighborhood,but something set them moving away from us. It would naturally follow that the galaxies that are moving the fastest will by now be the farthest away from us. But nobody believed this, because nobody believed that our Local Group was the one galaxy cluster that hadn't moved from the place where the galaxies formed—the center of the Universe. It would be like going back to the time when we thought the Earth was the center of the Universe. No, astronomers were quite convinced that we were *not* in the center of the Universe, a notion expressed by the **Copernican Principle:**

> *The Earth is in a typical place in the Universe.*

The idea is that the Earth orbits a typical star in a typical galaxy in a typical place in the Universe. It would be astonishing if our Galaxy, out of the billions of galaxies in the visible Universe, were the one galaxy that was in the center. In fact, astronomers prefer to believe that *no* galaxy is in the center. Now how can that be?

The simplest way to construct a Universe with no center is to make it infinite in extent. We're not entirely sure that the Universe is infinite, but it's a good bet, and for now we'll assume that is the case. That is to say, no matter which direction you go, you can keep going forever. There is no edge or end to the Universe. Since there is no edge, there is no way of pinpointing a center.

Now if there is no center, how is it that the other galaxies seem to be moving away from the Local Group? Doesn't that make the Local Group special? Here's the idea: it looks the same everywhere in the Universe. It doesn't matter what galaxy cluster you live in, all the other galaxies are moving away from you. You see, the galaxies aren't really moving at all; *it's the space between them that is growing.*

Space itself is expanding. The galaxies are simply being carried passively by the expansion of space. This idea sounds strange. How can space expand? We're going to ask you to imagine that empty space is flexible, as though it were made of rubber. It can stretch, it can bend, it can even tear. Einstein had already predicted this property of space. Now astronomers were seeing evidence for it.

A good way to visualize the expansion of space is to picture a loaf of raisin bread. A very big loaf of raisin bread, probably infinitely big. In this analogy, the raisins represent the galaxies (or better, the galaxy clusters). The dough represents the fabric of space. As the dough expands, the raisins are pushed apart. If you are one of the raisins, you will notice that the other raisins are all moving away from you. Moreover, the nearby raisins are moving away slowly, while distant raisins are moving away rapidly. This is Hubble's Law.

By 1930, astronomers realized that the Universe is expanding, that space itself is expanding. The immediate implication is that the expansion started at some time in the past—the time we now call the Big Bang. We turn to the Big Bang in the next chapter.