Chapter 6. Surveying the Universe

The night sky seen from a very dark site fills us with awe. We view the spectacle of thousands of stars, several visible planets, the Moon with its changing phases, and the irregular band of faint light called the Milky Way. It is immediately apparent that much more exists than the land, water, and air that we can touch on the Earth. From ancient times to the present, humans have made numerous attempts to describe and explain the universe, first with myths and then with models incorporating geometry, mathematics, and physics.

After Kepler and Galileo had shown that the Earth was not the focal point of the universe and Newton had formulated his laws of motion and gravity, many scientists were convinced that the foundation had been laid for an accurate description of the cosmos. Thus began the modern era of cosmology, which is the study of the universe as a whole. It would turn out, though, that some crucially important pieces to the cosmic puzzle were still missing. Nevertheless, it is instructive both to follow the arguments that led to the models and review the evidence that demonstrated that the now-discredited views of the universe were wrong. This is an important exercise because the current theory of the universe, the Big Bang model, appears at first to be too far-fetched to be true! In this and later chapters, we will therefore present the observations and theoretical reasoning that eventually pointed toward the extraordinary idea that the universe began about 14 billion years ago in an initial extremely hot and dense state and has been expanding and cooling ever since.

Newton's Infinite Universe

When Newton devised his Law of Universal Gravitation and then pondered over its application to the universe, he realized that there was a fundamental problem: if all masses attract each other, then the universe should be unstable to gravitational collapse. That is, all bodies (stars, etc.) should fall toward each other, causing the universe to contract to a single point (see Fig. 6-1). Newton thought that this might be avoided if the universe were infinite in size and the stars randomly placed in it, so that there is no center of mass. In this case, any given star would be attracted equally in all directions so that the net force on it would be zero. However, mathematical analysis showed that, if the density of stars were not exactly uniform, each section of the universe would still collapse to a point. Nevertheless, the idea of an infinitely large universe remained prevalent during this era. Newton, who was deeply religious, concluded that one of God's roles was either (1) to create the universe with stars placed in appropriate positions, and with just the right velocities, to provide a net gravitational force of zero and thereby avoid collapse, or (2) to act continuously to prevent collapse.

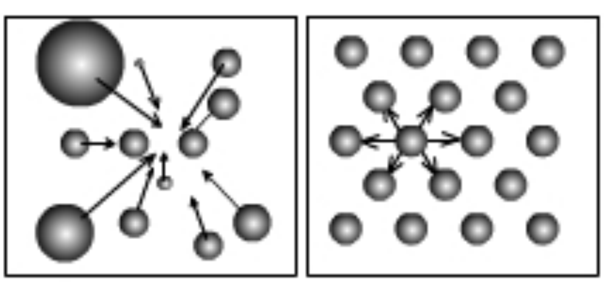

Figure 6-1. *Left:* Gravitational collapse of a finite volume containing many massive objects. Each is attracted to every other object. Arrows show the force of gravity operating on selected objects. Opposing forces cancel, so the net force is toward the center of mass. *Right:* Section of an infinite volume with uniformly placed objects. The net gravitational force on each object is zero (*e.g.*, the one in the right panel with the force arrows pointing outward). However, this is an unstable situation, since a slight change in position of one or more massive objects will lead to collapse of the system.

Newton's universe was also infinite in time, with no beginning and no end. This was the common assumption of the era. It followed the cosmology of Aristotle, who considered the universe to be well-ordered and unchanging.

Clockwork Universe Proposal

Many of the scholars during the Enlightenment viewed Newton's laws of motion as implying that the universe operates according to a set of rules that govern everything in it. As we discussed in Chapter 4, this led to the concept of determinism. An extension to this idea is the "clockwork universe" proposal that the universe has operated mechanically since it was initially set in motion. Once the universe was created with a set of initial conditions plus the laws, nature took care of the rest. An analogy is a clock-maker fabricating a clock, winding it up, and thereafter allowing it to run by itself. Many scholars during the Enlightenment thought this to be a valid and attractive view of the universe.

The cosmology that developed during Newton's era was therefore one of an infinite universe in a steady, unchanging state. But the idea was possible to refute by checking rather obvious data.

The Dark Sky Paradox: the Universe is not Infinite in both Size and Time

We can actually make a simple observation that contradicts the concept of an infinite universe filled with stars that has existed forever. As an analogy, contemplate what you would see in a large, dense jungle. No matter what direction you look in, there is a tree or other plant in the way. No sunlight reaches you directly. Some of the sunlight is blocked by trees near you, some by trees farther away. As a consequence, it is dark. Now imagine that all the plant life becomes luminescent, that is, emits light. Then it would be bright in every direction, just as bright as any given plant. The same is true of an infinite, unchanging universe, which would be just like an endless forest of stars. No matter which way we look, we would see starlight. The model therefore predicts that the night sky should be bright. The fact that it is dark at night is in fact a profound cosmological observation!

This is the dark night sky paradox. Its origin is unclear, but since Kepler presented it in 1610, it pre-dated Newton. The dark night sky is in direct conflict with the notion of an infinitely large and infinitely old universe filled with stars. Even if some substances were to absorb the light, the absorbed energy would heat them up until they were as hot and as glowing as stars.

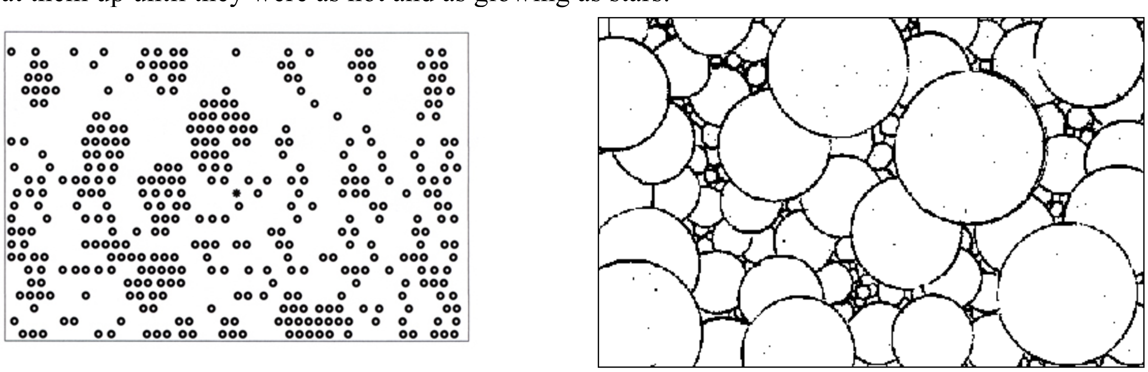

Figure 6-2. If the universe were infinite in size, infinitely old, and unchanging, from every location in the universe, we would see a star in every direction and the night sky would be bright. Here circles represent stars. *Left panel:* Choose a circle near the middle of the diagram and try to draw a straight line that misses all the other circles. It is not possible. It would be impossible from any other circle shown if you were to extend the boundaries to infinity while maintaining a similar density of circles. *Right panel:* A close-up view of a very small patch of sky in such a universe. More distant stars with smaller apparent (angular) sizes fill in the gaps between the nearer stars. The entire sky would appear as bright as a typical star like the Sun.

Actually, since the light does not travel infinitely fast, this argument only works if the universe is both infinite in size and has existed in its current state forever, as was assumed in Newton's cosmology. We now think that the universe is not infinitely old, so starlight has not yet had time to fill all of space. This allows the night sky to be dark.

The Cosmological Principle

Contemplation of the universe invariably involves some philosophical assumptions, for example, that the universe should be governed by physical laws. In the modern era, one underlying assumption, called the Cosmological Principle, is that the universe should appear (on average) the same from any point inside it. That is, any observer anywhere in the universe should see about the same number of very distant objects (e.g., galaxies) in every direction as any other observer at any other location. Of course, each observer will see a different local environment that depends on the density of nearby stars and galaxies, but when we make observations over a large enough volume of space the average appearance should be the same.

In other words, the Cosmological Principle means that *there is no special place in the universe*; all locations are equivalent. Such a universe must be uniform (or homogeneous – the same throughout), on average, and isotropic (the same in all directions). This is often referred to as the "Copernican" Cosmological Principle, since it was Copernicus who began the modern scientific revolution that caused scholars to stop thinking of the Earth as being at a special location, the center of the universe.

The Mystery of the "Spiral Nebulae"

At the same time that cosmological models were being proposed and debated, observational astronomy was progressing. Galileo had used his telescope to show that the Milky Way was actually a band of many individual stars too close on the sky for the eye to resolve. Observations in both the northern and southern hemispheres had shown that the Milky Way extends across the entire sky in a great circle (see Fig. 6-3). In 1755, Imannuel Kant, the great philosopher, guessed correctly that the Milky Way is a flattened disk of stars, with the Sun embedded in the disk.

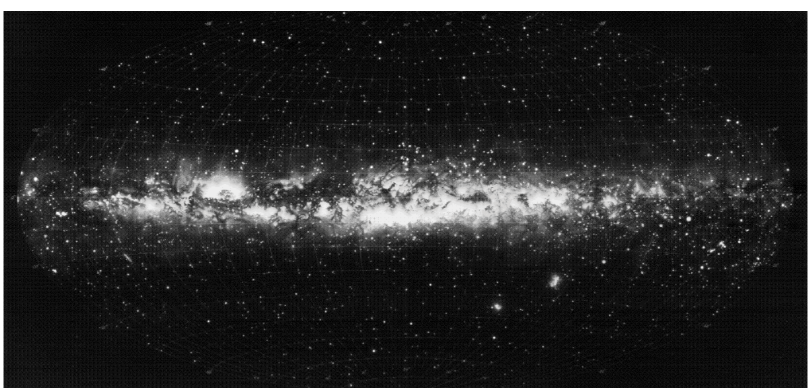

Figure 6-3. The Milky Way in visible light as viewed from the Earth. This is a montage of several photographs. The Milky Way appears as a band that traces out a great circle around the sky. The center is in the constellation Sagittarius, in the direction of the Galactic Center. (Source: Lund Observatory, Sweden)

Astronomers with telescopes, meanwhile, had been studying nebulae (Latin for "clouds"), which are extended sources of light with cloudy appearances. Some of them had elliptical shapes. Kant speculated that these were "island universes," by which he meant distant systems of stars distinct from but equivalent to the Milky Way. Today we call these systems of stars galaxies. In this case, the universe could be vast, perhaps infinite in size as in Newton's cosmology. As telescopes were improved, astronomers found that many of the elliptical nebulae have spiral shapes. This led Pierre-Simon de Laplace to conjecture that these were solar systems forming from the gravitational contraction of a rotating cloud of gas. He was wrong, although many other nebulae with ring-like or irregular shapes are indeed gas clouds.

Thus began a debate that would last for about 1½ centuries over whether the spiral nebulae were similar to the Milky Way or gas clouds inside the Milky Way. The disagreement centered on the size of the Milky Way and the distances to the elliptical and spiral nebulae. The standard method for estimating the size of the Milky Way was to count and measure the distances to stars in every direction. We now examine the basic methods for determining stellar distances.

Distances to Stars

In order to survey the universe, we need to know the sizes and luminosities of stars, galaxies, and the other inhabitants of the cosmos. But what we measure are only the apparent, angular sizes of galaxies and the brightness of the light that we receive from each object. In order to convert these to physical sizes and luminosities, we must determine the distances.

How do we estimate the distances to objects in our everyday life? Let's say that we see a car moving along a highway on the other side of a large field. We know the size of a typical car, so we can tell how far it is from us by how big it appears, that is, by how much of our field of vision it occupies. This apparent size is actually an angle (our entire field of vision covers about 180°). Astronomers call this the angular size. If it is night-time, we cannot see the car itself, but the light from its headlights is visible. If this appears faint, we reason that the car is far away; if bright, the car must be near. Of course, we need to be sure that it's a normal car. A pair of bicycles could be very close, yet their lights would have the same brightness as the headlights of a distant car.

Similarly, more remote stars are generally fainter than relatively nearby ones. We can quantify this, since the brightness is proportional to the luminosity divided by the square of the distance (see eq. 5-7). This means that a star that is 0.01 times as bright as another similar star is 10 times more distant. (Here we assume that there is no medium absorbing the light. In our analogy, a car whose headlights shine through fog at night would appear to be farther away than is actually the case.)

In order to use this method to determine distances, we must first obtain the luminosities of the different types of stars. This is the same as knowing the wattage of the headlight of the car in our analogy. We can determine the luminosity of any given type of star only if we can measure the brightness and distance of at least one specimen of that type. Brightness is straightforward to measure. But we need another method for obtaining distances to stars so that we can derive the luminosities of the various types of stars. Fortunately, we have a reliable method that is similar to the triangulation used by surveyors to measure the dimensions of a plot of land.

Distance to a Nearby Star Using Parallax

We can determine distances to relatively nearby stars in the Milky Way galaxy by using trigonometry combined with the fact that the Earth revolves around the Sun. Because of our changing perspective as the Earth moves in its orbit, the apparent position of a nearby star appears to shift relative to the more distant stars and galaxies. The shift is called the parallax, to which we give the symbol p. We can measure the parallax of nearby stars using telescopes, as illustrated in Figure 6-4. Observations of the position of a star taken 3 months apart measure a slight shift (the parallax) in that position, measured in angular units. The magnitude of that shift is inversely proportional to the distance.

From basic trigonometry, we know that the tangent of the parallax, tan p, is equal to the Earth's orbital radius of 1 AU divided by the distance d to the star in AU: $\tan p = (1\text{ AU})/d$. (Here we approximate the Earth's orbit as a circle, which is fairly accurate.) If the parallax is measured in radians, it is always small. We can then use the very good approximation that the tangent of a small angle is equal to the value of the angle in radians, or $\tan p \approx p$. We now have $p = (1\text{ AU})/d$ and can solve for the distance: $d = (1\text{ AU})/p$.

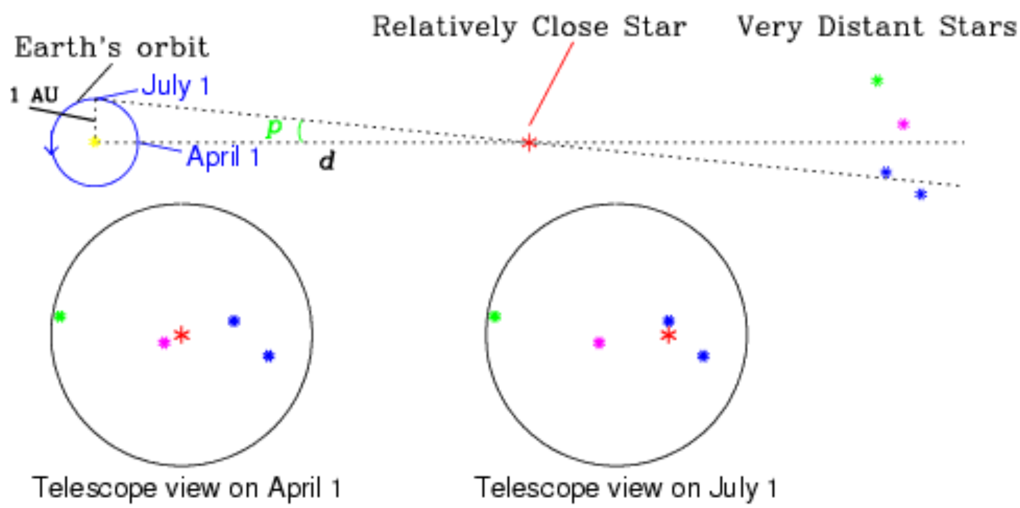

Figure 6-4. Diagram illustrating the parallax of a relatively nearby star. As the Earth orbits the Sun, the star appears to shift in position relative to much more distant stars, whose shifts are too small to notice. Note that this diagram is not drawn to scale – the nearest star to the Sun is more than 250,000 times farther away than the Sun is from the Earth and the shift is not as large as indicated in the telescope views.

However, the parallax of the nearest star (besides the Sun) is about 1/300,000 radians, and its distance is about 300,000 AU. In order not to deal with such large numbers, it is more convenient to measure the parallax in units of arcseconds. (For reference, there are 206,000 arcseconds in a radian, 60 arcseconds in an arcminute and 60 arcminutes in a degree; the angular diameter of the Moon is about 30 arcminutes.) It is also more convenient to use a new unit for distance, the parsec (pc), which is the distance of a hypothetical star that has a parallax of 1 arcsecond:

1 pc = 206,000 AU = 3.1×10^{16} m = 31 trillion km = 3.26 lt-yr.

The last unit of distance, light-years (lt-yr), is familiar to readers of science fiction. One lt-yr is the distance that light travels in one year. Using parsecs for distance and arcseconds for the parallax gives us a simple equation for the distance d to a star in parsecs with a parallax p:

$$d = 1/p \text{ pc}. \tag{6-1}$$

d = distance (in parsecs, pc), p = parallax (in arcseconds).

The nearest star to the Sun has a parallax of 0.77 arcseconds, and so is at a distance of 1.3 pc. At present, our instruments can measure parallax only for stars closer to the Sun than a few hundred parsecs. The *Hipparcos* satellite did this for 118,000 stars. The *Gaia* satellite observatory, currently measuring positions of stars, will eventually be able to measure the parallaxes of millions of stars throughout the Milky Way, allowing astronomers to map the Galaxy to high precision.

Distance to a Star Whose Luminosity is Known

Once the parallax had been determined for a number of relatively nearby stars of different types, astronomers were able to derive the luminosity of each type of star by solving equation (5-7) for luminosity (L). For a star that is too distant for astronomers to measure its parallax by current techniques, we can determine the type of star – and therefore its luminosity L – from its absorption-line spectrum. We can also measure its brightness B readily with a telescope equipped with an electronic detector. We can then derive the star's distance from the equation

$$d = \sqrt{\frac{L}{4\pi B}} \qquad (6\text{-}2)$$

> d = distance (in m; can convert to parsecs by dividing by 3. 1×10^{16} m/pc), L = luminosity (in W, equivalent to J/s), B = brightness (in W/m^2). Here "W" stands for "watts."

Many stars lie in clusters of stars, and the size of the cluster is generally much smaller than its distance. If we determine the distance to one of the stars in a cluster, then we know the distance to every star in the cluster. Some rare stars found in such clusters pulsate – become larger, then smaller – which causes their brightness to change with a very regular period. These stars, called Cepheid variables after a variable star in the constellation Cepheus, do so with a period that is proportional to their luminosity. These are very luminous stars that can be seen in telescopic images of other galaxies if they are within about 20 million parsecs of the Milky Way. This makes them very useful for determining distances to other galaxies.

The Size of the Universe

By 1918, J. C. Kapteyn had mapped out the Milky Way by measuring the distances to many stars and counting the number of stars in various directions. He concluded that the diameter of the Milky Way — which he considered to include all the known universe — was 17,000 pc. Furthermore, he placed the Sun at the center of the universe. However, in the same year Harlow Shapley found that globular clusters of stars — massive, dense, nearly spherical groups of hundreds of thousands of stars (see Ch. 12 & 13) — were scattered around a point far from the Sun in the constellation Sagittarius. He correctly identified this point as the center of the Milky Way.

The current picture of the Milky Way Galaxy is that it has a diameter (as defined by its extent in visible light) of about 30,000 pc and contains (1) a flat disk of thickness 400 pc with spiral "arms," (2) a central "bulge," and (3) a low-density, roughly spherical "halo." The Sun is about 8,300 pc from the center of the disk of stars, more than half-way out. There are roughly 200 billion stars in the Milky Way galaxy. Although we cannot get an "alien's eye view" of the Milky Way from above its disk, since we are located inside the disk, observations indicate that it is similar to the galaxy marked in Figure 6-5.

Katpeyn's star-counting method did not work well because, as was demonstrated in the early 1930's, the disk of the Milky Way galaxy contains dust. This is in the form of fine grains (with sizes similar to particles in cigarette smoke) of solid compounds that scatter – reflect in random directions – light. Shorter wavelengths of light are scattered more than longer wavelengths. This causes stars to appear both fainter and redder, with the effect being stronger for more distant stars. Observing the Milky Way from the Earth is therefore similar to being outside on a foggy day: you can only see objects that are relatively close to you. This gives the appearance that your "world" is smaller than is actually the case. Furthermore, you appear to be at the center of the foggy "world." One way to avoid this effect is to observe the Milky Way with radio telescopes, since radio waves are essentially unaffected by dust. Another is to correct for the effects of dust mathematically when the brightness of a star is measured.

Shapley, however, was on the wrong side of the question regarding the nature of the spiral nebulae. In 1920, he engaged in a debate with Heber Curtis at a meeting of the American Astronomical Society, arguing that the nebulae were inside the Milky Way. Curtis took the point of view that they were distant galaxies similar to the Milky Way. Although Curtis ended up being correct, the weight of evidence at the time seemed to be on Shapley's side.

The issue was decided convincingly four years later by Edwin Hubble. He used the newly constructed 100-inch telescope on Mt. Wilson north of Pasadena, California, to resolve individual stars in the spiral nebula M31, now referred to as the "Andromeda Galaxy" (which you can see with your naked eye on a very clear night). The stars were so dim that they — and the "nebula" — must lie well outside the Milky Way. Thus was born the field of extragalactic astronomy.

The history of our changing knowledge of the nature of the Milky Way and other galaxies is a prime example of how science is self-correcting over long periods of time. Despite nearly all of the experts in the early 1900s being convinced that the Milky Way represented the entire universe, the weight of new evidence eventually falsified this view, leading us to appreciate the utter vastness of the universe.

Distances to Galaxies

Figure 6-5 presents a sampling of galaxies (the largest containing trillions of stars) with a variety of sizes and with elliptical, spiral, and irregular shapes. Most galaxies are in clusters, and many clusters are arranged in groups called superclusters. The Milky Way lies in a small cluster of at least 54 galaxies called the **Local Group**. This contains the large, spiral Andromeda galaxy, the smaller spiral galaxy M33, the two irregular Magellanic Clouds ("satellite" galaxies of the Milky Way), and many small irregular and elliptical galaxies, some of which are so faint that they are difficult to detect.

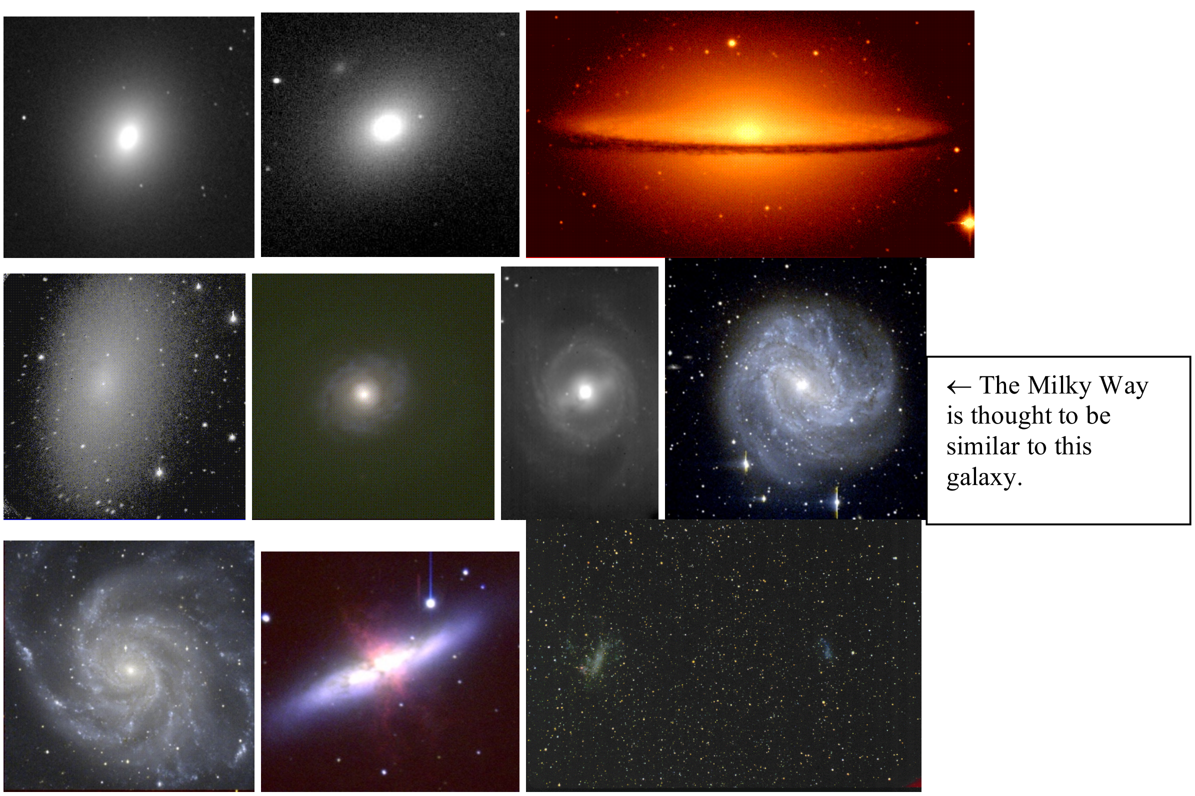

Figure 6-5. Examples of different types of galaxies. (Images courtesy of W. Keel)

Astronomers can determine the distances to relatively nearby galaxies with the luminosity method described earlier. However, at greater distances it is not currently possible to separate individual normal stars on images, even with the high resolution of the Hubble Space Telescope. In order to determine the distances to these more remote galaxies, we must use objects other than normal stars. These objects must have known luminosities or sizes to be useful for this purpose.

Astronomers assign the nickname standard candle to a type of object whose luminosity is well established. One example mentioned earlier is a Cepheid variable, a type of pulsating star with periodic variations in brightness. As Henrietta Leavitt at Harvard College Observatory discovered in 1908, the period of the variations of a Cepheid variable is proportional to its average luminosity. There are actually two types of Cepheid variables. For the more luminous variety, this period-luminosity relation is approximately $P \approx (L/L_{sun})/300$ if we measure the period in days.

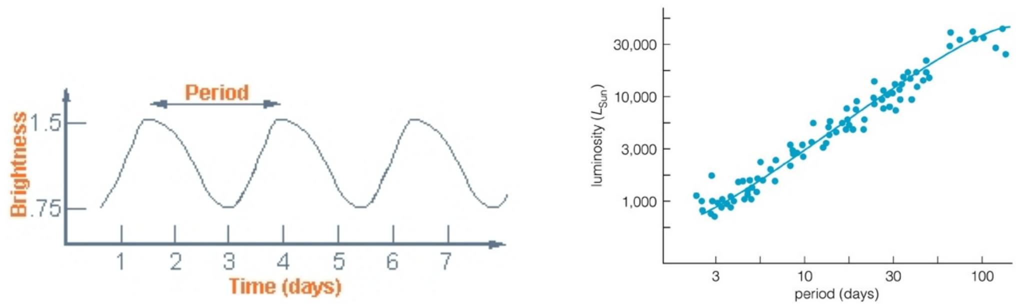

Figure 6-6. *Left:* The period of a Cepheid variable can be measured from a plot of its brightness vs. time. *Right:* The period-luminosity relation, from data for Cepheid variables in clusters of stars in the Milky Way and in the Large Magellanic Cloud, a small nearby galaxy. An approximate fit to the data is expressed mathematically by eq. 6-3. The more luminous Cepheid variables have longer times between the peaks of their cycles of brightness variations. [Sources: *left* - http://www.astro.columbia.edu/~archung/labs/spring2002/images/pulsation.jpg; *right* - http://www.ess.sunysb.edu/fwalter/AST101/images/20-12.jpg]

The luminosity of a Cepheid variable, measured at maximum brightness, is then given by

$$L(\text{Cepheid}) \approx 300\, L_{sun}\, P \qquad (6\text{-}3)$$

L = luminosity (in W), L_{sun} = luminosity of the Sun (3.8×10^{26} watts), P = period of the cycle of brightness changes (in days).

Here, we use the luminosity of the Sun as a convenient standard. In order to get the distance to a galaxy containing a Cepheid variable, astronomers need to measure the Cepheid's brightness as a function of time, determine the period of the variations, use equation (6-3) to get the luminosity, and plug the value into equation (6-2) to determine the distance.

A second standard candle is a specific type of exploding star called a Type Ia supernova. When a star explodes, it becomes extremely luminous, often outshining for a few weeks the entire galaxy where it is located. Its brightness first increases, then reaches a peak within 1-2 weeks before fading over the next several months. By observing such events in galaxies whose distances are known from the Cepheid variables and other luminous standard candles, astronomers have established that Type Ia supernovae all have essentially the same luminosity at maximum brightness, about 5 billion times the luminosity of the Sun. (There are minor differences, but these can be accounted for after analyzing the spectra.) This method seems to be quite accurate and, because of the extremely high luminosity, astronomers can see

Type Ia supernovae even if they are in galaxies that lie more than a billion parsecs from the Earth. This is therefore a primary method for measuring distances to very remote galaxies.

A different sort of technique for determining distances is to calculate the velocity of an object by measuring the Doppler shift in its spectrum and to compare this with the motion actually seen in the sky. If the Doppler shift measures a speed v and a series of images show that the object moved an angular distance θ over time t, we know that $v = (\theta d)/t$. If we change to more convenient units, we can then calculate the distance from the equation

$$d = 0.20vt/\theta \text{ pc} \quad (6\text{-}4)$$

d = distance (in pc), v = velocity of motion (in km/s), t = time from first measurement to the last (in s), θ = angular distance on the sky across which the object moves (in arcseconds) during time t.

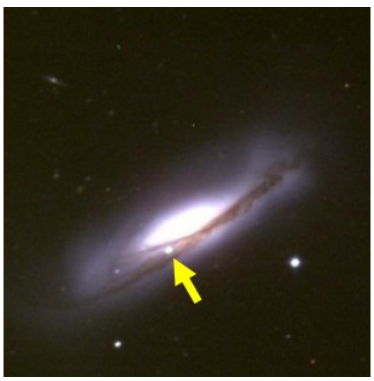
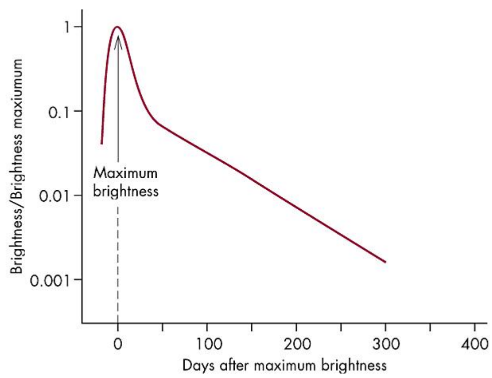

Figure 6-7. *Left:* A Type Ia supernova observed in a galaxy, near maximum brightness. *Right:* Brightness vs. time of a typical Type Ia supernova. At maximum brightness, it is about 5 billion times as luminous as the Sun. [Source: left: www.mpa-garching.mpg.de; right: www.mhhe.com]

Astronomers need to take into account that the Doppler effect is caused by motions toward or away from us, while motion in the sky is perpendicular to our line of sight. Because of this, the method works best for a rotating disk or similar structure found in a galaxy. Although there are only a small number of galaxies for which this type of study has been possible so far, the method is quite accurate and helps to establish the calibration for other methods that depend on knowing the luminosities to rare types of stars.

In general, the farther away an object is, the smaller is its apparent, angular size a on the sky. We can express this as a proportionality:

$$a \propto 1/d \quad (6\text{-}5)$$

a = angular size, d = distance; units are not specified since the relation is a proportionality, not an equation.

For example, the brightest galaxy in a "rich" (many members) cluster of galaxies can be used as a rough "standard ruler" if we assume that these giant galaxies have the same diameter in one such cluster as in another. This provides a check on the other methods for determining distances to galaxies.

Astronomers usually use megaparsecs (millions of parsecs, abbreviated Mpc) as the unit of distance to galaxies. The Andromeda Galaxy, for example, is about 0.9 Mpc from the Milky Way. Distances within a galaxy are measured in kiloparsecs (kpc, thousands of parsecs).

Summary

Astronomers began to observe other galaxies before they even could determine that there is anything outside our Milky Way Galaxy. They debated whether the elliptical and spiral nebulae – cloudy-looking structures they saw through their telescopes – were gas clouds in our Galaxy or complete systems of stars far away from the Milky Way. Centuries of painstaking observations culminated in Edwin Hubble's detection with the new 100-inch telescope on Mount Wilson of individual stars in the Andromeda nebula, stars much too faint to be in our Galaxy. Hubble's finding came within a few years of a debate at which astronomers had decided that the Andromeda nebula was relatively local. This is a prime example of how science is designed to correct its own mistaken conclusions.

In order to probe the universe effectively, we need to know the distances to the cosmic objects we observe. The methods are straightforward, at least in principle: (1) triangulation for relatively nearby stars using parallax, (2) decrease of brightness with distance for "standard candles," objects with known luminosity, (3) actual speed compared with apparent motion on the sky, and (4) physical size compared with angular size on the sky. Method (2) can be applied to extremely distant galaxies through measurements of the brightness of exploding stars called Type Ia supernovae.

The discovery of gravity by Newton started the era of modern cosmology, the study of the universe as a whole. Proposals included the idea of a mechanical, "clockwork" universe that has run itself since it was put in motion. Also popular until 1965 was the concept of an infinite universe that remains constant in time, on average. It seemed a sensible model that avoids edges and a beginning or end. But simple analysis shows that in such a universe the night sky would be about as bright as the Sun in every direction. Clearly, something was wrong with this idea. We will discuss the solution — that the universe had a beginning — in Chapter 10. In order to prepare for this, the next three chapters present the development of our understanding of the physical world that was necessary to describe the universe as a whole.

Glossary

Clockwork universe: Concept that the universe operates mechanistically after initially being set in motion.

The universe: The natural world in which we exist. Originally, it meant everything that exists, but it is possible that there are other universes and collections of universes.

Cosmology: Study of the universe as a whole.

Steady-state model: Theory in which the universe is infinite in size and (on average) does not change with time.

Gravitational collapse: Process by which the attraction of the mass of different regions causes them all to fall toward the center of the mass distribution.

Dark night sky paradox (often referred to as "Olber's paradox"): Problem with models in which the universe is infinite in space and has always existed: the night sky should be bright from distant starlight.

Cosmological Principle (sometimes called the "Copernican" Cosmological Principle): Assumption that the universe has the same appearance, on average, as observed from any place inside it.

Uniform (or homogeneous): The same throughout. When applied to the universe, this term refers to the average properties.

Isotropic: The same in every direction. When applied to the universe, this term refers to the average properties.

Galaxy: A distinct system of many stars and clusters of stars.

Milky Way: Our own galaxy, seen with the unaided eye from the Earth as a creamy band of light that extends from horizon to horizon (see Fig. 6-3).

Local Group of galaxies: A loose cluster of at least 30 galaxies including our own Milky Way and the Andromeda galaxy.

Nebula (Latin word meaning "cloud"): A cloud of gas and/or dust in space.

Andromeda galaxy: A large spiral galaxy in our Local Group of galaxies that was the first galaxy confirmed to lie outside the Milky Way. It was called the Andromeda nebula until Edwin Hubble detected very faint stars in it.

Angular size: The apparent size of a celestial object as it appears on the sky. For example, the angular diameter of the Moon is about 0.5 degrees, or 30 arcminutes.

Parallax (symbol: p): Apparent shift in position of a star caused by our changing perspective as the Earth orbits the Sun. This is the primary method for measuring distances to relatively nearby stars. Measured as an angle in arcseconds. See Figure 6-4 and eq. 6-1.

Parsec (abbreviation: pc; 1 kpc = 1000 pc; 1 Mpc = 1 million pc): Distance unit used for stars and galaxies. 1 parsec is the distance of a star with a parallax of 1 arcsecond. [1 parsec = 3.26 light-years = 3.1×10^{16} m, 1 kpc = 3.1×10^{19} m, 1 Mpc = 3.1×10^{22} m]

Light-year (abbreviation: lt-yr): The distance traveled by light in one year. There are 3.26 light years in 1 parsec.

Brightness (symbol: B): The energy in observed light from an object per unit area and per unit time within a certain range of wavelengths. (Astronomers prefer the term "flux" or "flux density" when referring to this quantity.) Units are watts per square meters (W/m^2).

Luminosity (symbol: L): The total amount of energy radiated by an object in the form of electromagnetic waves. Units are watts (W).

Standard candle: A luminous object whose luminosity is known so that it can be used to determine the distance to the star system in which it is located, following eq. 6-2.

Cepheid variable star: A luminous type of star that is physically pulsating so that its brightness increases and decreases regularly with a well-defined period.

Period-luminosity relation for Cepheid variables: An observed law that the more luminous a Cepheid variable star is, the longer is the period of its brightness variations. See eq. 6-3.

Type Ia supernova: A class of exploding stars with the important characteristic that the luminosity at maximum brightness is the same from one to the other, except for minor differences that can be determined from the spectrum. Very useful as a standard candle to measure distances to galaxies, since Type Ia supernovae are extremely luminous.

Questions for Discussion

A. Is the Cosmological Principle just an assumption or is there a firm basis for it?

B. Why is it not possible for the dark night sky paradox to be resolved by postulating that dust blocks out the light from distant galaxies? [*Hint:* What would happen to such dust after an infinite amount of time of absorbing light energy? Could it stay dark?]

C. What lessons can be learned about the power and — over short periods of time — flaws of the scientific method from the changing view of the universe during the early 1900s?

D. What are the attractive features of the clockwork universe idea? Can you understand why it was popular among scientists after Newton's laws were formulated?

E. Did Newton have a logical reason to believe that God constantly interacts with the universe? What are the intellectual dangers of using a particular concept of God to explain aspects of the universe that are not understood?

F. Why is it so difficult to determine cosmic distances accurately? Compare the methods used to determine distances to stars to those used to determine distances to objects on the Earth.

Examples of How to Determine Distances to Cosmic Objects

1. A star has a parallax of 0.2 arcseconds. Calculate its distance in parsecs (pc).

Answer: Use formula 6-1: $d = 1/p$ pc, where the parallax p is measured in arcseconds. The answer is simple, since we are given $p = 0.2$ arcseconds:

$d = (1/0.2)$ pc = 5 pc.

2. The distance to galaxy A is known to be 10 Mpc. The angular diameter (apparent size as seen from the Earth) of galaxy A is 50 arcseconds. A second galaxy, B, is of an identical type as galaxy A, but has an angular diameter of only 2.5 arcseconds. What is the distance to galaxy B?

Answer: Let a represent the angular diameter. Expression 6-5 gives $a \propto 1/d$. We form an algebraic ratio when comparing the values for galaxy A to those of galaxy B:

$$\frac{a_{\mathrm{A}}}{a_{\mathrm{B}}} = \frac{1/d_{\mathrm{A}}}{1/d_{\mathrm{B}}} = \frac{d_{\mathrm{B}}}{d_{\mathrm{A}}}$$

We can then solve for d_{B}:

$d_{\mathrm{B}} = (a_{\mathrm{A}}/a_{\mathrm{B}})(d_{\mathrm{A}}) = (50/2.5)(10\text{ Mpc}) = (20)(10\text{ Mpc}) = \underline{200\text{ Mpc}}$.

3. Star A and star B are of the same type, so they have identical luminosities. Star A is 100 times brighter than star B. From parallax measurements, we know that the distance to Star A is 50 pc. What is the distance to star B?

Answer: We need to use eq. 6-2 for the distance. Since we do not know the luminosity, we need to form an algebraic ratio from that equation:

$$\frac{d_\mathrm{B}}{d_\mathrm{A}} = \frac{\sqrt{\frac{L_\mathrm{B}}{4\pi B_\mathrm{B}}}}{\sqrt{\frac{L_\mathrm{A}}{4\pi B_\mathrm{A}}}} = \sqrt{\frac{L_\mathrm{B}}{4\pi B_\mathrm{B}}} \times \sqrt{\frac{4\pi B_\mathrm{A}}{L_\mathrm{A}}} = \sqrt{\frac{4\pi B_\mathrm{A} L_\mathrm{B}}{4\pi B_\mathrm{B} L_\mathrm{A}}} = \sqrt{\frac{B_\mathrm{A}}{B_\mathrm{B}}}\,.$$

The simplification is possible because $L_\mathrm{A} = L_\mathrm{B}$ and the 4π terms cancel. We can now solve for d_B:

$$d_\mathrm{B} = d_\mathrm{A}\sqrt{\frac{B_\mathrm{A}}{B_\mathrm{B}}} = (50\text{ pc})\sqrt{100} = (50\text{ pc})(10) = \underline{500\text{ pc}}.$$

4. Star E, a Cepheid variable star observed in a cluster of stars in the Milky Way lying at a distance of 5 kpc from the Earth, has a brightness that changes in cycles with a period of 5 days. Star F, a Cepheid variable in another galaxy, has a period of 50 days and a brightness that is 1.0×10^{-6} times that of star E. What is the distance in Mpc to the galaxy containing star F?

Answer: We will again use formula 6-2 to determine the distance. We can form an algebraic ratio, as in sample problem 3. We will need first to use expression 6-3 to determine the luminosity of each star in terms of L_sun:
$L_\mathrm{E} \approx 300\ L_\mathrm{sun}\ P(\text{in days}) \approx 300\ L_\mathrm{sun}\ (5) \approx 1500\ L_\mathrm{sun}$
$L_\mathrm{F} \approx 300\ L_\mathrm{sun}\ P(\text{in days}) \approx 300\ L_\mathrm{sun}\ (50) \approx 15{,}000\ L_\mathrm{sun}$
$L_\mathrm{F}/ L_\mathrm{E} = (15{,}000\ L_\mathrm{sun})/(1500\ L_\mathrm{sun}) = 10$

We form the algebraic ratio from formula 6-2:

$$\frac{d_\mathrm{F}}{d_\mathrm{E}} = \frac{\sqrt{\frac{L_\mathrm{F}}{4\pi B_\mathrm{F}}}}{\sqrt{\frac{L_\mathrm{E}}{4\pi B_\mathrm{E}}}} = \sqrt{\left(\frac{L_\mathrm{F}}{L_E}\right)\left(\frac{B_\mathrm{E}}{B_\mathrm{F}}\right)} = \sqrt{(10)\left(\frac{1}{1.0\times10^{-6}}\right)} = \sqrt{1.0\times10^{7}} = 3200\,.$$

Multiply both sides by d_E to get

$d_\mathrm{F} = 3200 d_\mathrm{E} \approx 3200\ (5\text{ kpc}) = 16{,}000\text{ kpc}$

Convert to Mpc: 1 Mpc = 1000 kpc, so 1 kpc = (1/1000) Mpc = 0.001 Mpc

$d_\mathrm{F} \approx 16{,}000\text{ kpc}\ (0.001\text{ Mpc/kpc}) = \underline{16\text{ Mpc}}$.

Homework Questions

1. Astronomers observe two stars, A and B.
a. Star A has a parallax of 0.04 arcseconds. Calculate the distance to star A.
b. Star B has a spectrum that is identical to that of star A, indicating that the two are the same type of star with the same luminosity. However, the brightness of star B as observed from the Earth is only 0.0001 times that of star A. Calculate the distance to star B.

2. Astronomers observe two stars, C and D.
a. Star C has a parallax of 0.05 arcseconds. Calculate the distance to star C.
b. Star D is of a type that has a luminosity that is 900 times that of star C. However, the brightness of star D as observed from the Earth is only equal to that of star C. Calculate the distance to star D.

3. A certain type of star in the Milky Way has a brightness equal to 1.0 “brightness units” (BU) at a distance of 10 kpc. Calculate the brightness in BU of an identical star in another galaxy at a distance of 20 Mpc. Note that 1 Mpc = 1000 kpc.

4. If the Sun were at a distance of 1 pc from the Earth, it would have a brightness of 3.3×10^{-8} W/m^2. What is the distance in Mpc to a galaxy in which a Cepheid variable star is observed that has a period of brightness variations of 10 days and a brightness of 2.0×10^{-21} W/m^2?

5. Star J, a Cepheid variable star observed in a cluster of stars in the Milky Way lying at a distance of 10 kpc (= 0.005 Mpc) from the Earth, has a brightness that changes in cycles with a period of 3 days. Star K, a Cepheid variable in another galaxy, has a period of 60 days and a brightness that is 1.0×10^{-6} times that of star J. What is the distance in Mpc to the galaxy containing star K?

6. A large elliptical galaxy at the center of a cluster of galaxies at a distance of 40 Mpc has an angular diameter (apparent size as seen from the Earth) of 30 arcseconds. Calculate the distance of a similar galaxy with an angular diameter of 5 arcseconds in another cluster.

7. A very luminous type of star is observed in galaxy X, and another star of identical type is observed in galaxy Y. The distance to galaxy X has already been determined to be 8 Mpc. The star in galaxy X is 10,000 times brighter than the star in galaxy Y. Calculate the distance to galaxy Y.

8. Imagine that a certain type of star exists only in a cloud so that the light from such stars passes through some dust on its way to us. This decreases the brightness we observe from the Earth. If this type of star were used to get distances to other galaxies, would we underestimate or overestimate those distances? Explain how you arrive at your response to this question.