CHAPTER ONE

The Birth of Science

To most people astronomy means stars; stars mean constellations; and constellations mean astrology. In fact, each step of this association contains misconceptions. Modern astronomers deal with more than just stars; they think of stars in terms of more than just constellations; and they use the constellations differently from astrologers. Nevertheless, astronomy and astrology do have the same historical roots, in the geometric patterns formed by the stars in the night sky. Let us begin, therefore, our journey of exploration of the universe with the constellations.

The Constellations as Navigational Aids

In prehistorical times nomadic peoples found that knowing the constellations helped them with directions. The most familiar constellation in the Northern Hemisphere is, of course, the Big Dipper. The Big Dipper is actually part of an astronomical constellation called *Ursa Major*, the Big Bear. Figure 1.1 shows how to use the "pointer stars" of the Big Dipper to find the pole star, Polaris. Polaris indicates the direction north, and it will continue to do so for another thousand years.

It has been speculated that early nomads developed stories to help them remember the various constellations and their relative positions in the sky. These stories pass as entertaining myths today, but in earlier times were

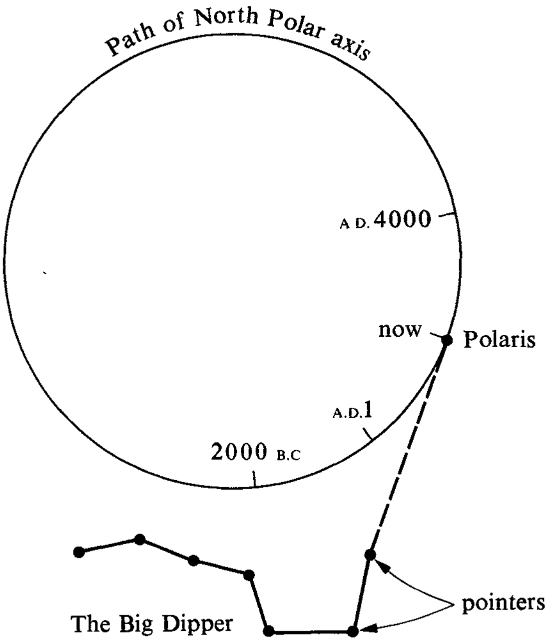


Figure 1.1. The Big Dipper and Polaris. To find the pole star, Polaris, go along the pointers to a distance roughly equal to four times their separation. Polaris lies very nearly in the present direction of the axis of the North Pole of the Earth. However, because of the tidal forces exerted on the Earth by the Sun and the Moon, the spin axis of the Earth makes a slow precession. Every 26,000 years, the polar axis describes a circular path in the sky. Thus, in 2000 B.C. or A.D. 1 the North Pole did not point so nearly at Polaris as now, and neither will it one or two thousand years from now.

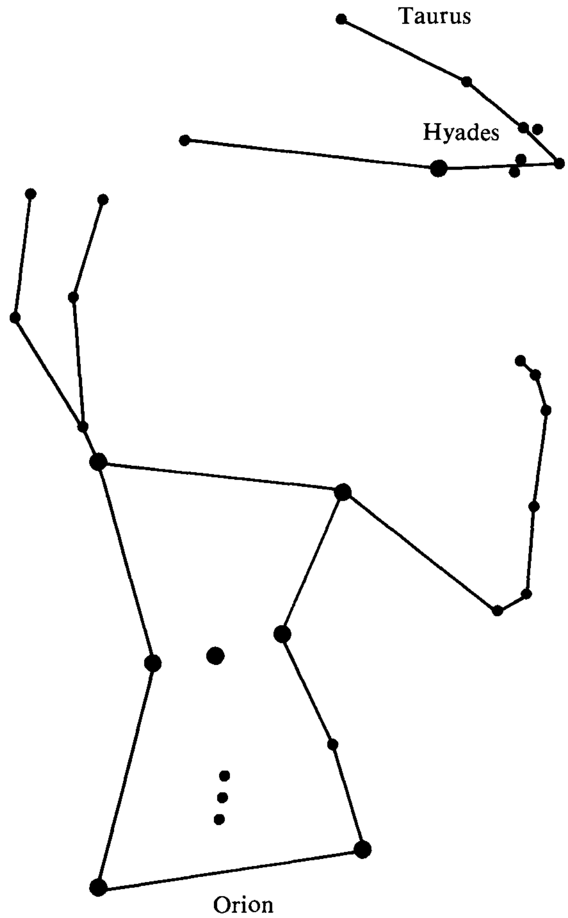


Figure 1.2. Orion, Taurus, and the Hyades star cluster.

probably very important mnemonic devices. Consider, for example, the biblical account of how Samson slew a thousand Philistines with the jawbone of an ass. Later he drinks water out of a hollow place called Lehi. A silly story, you say?

Now, *Lehi* in Hebrew means jawbone, and water in Greek is *hyades*. If we look up in the winter night sky, we find the group of stars known as the Hyades located in the jawbone of Taurus the Bull. Nearby is the mighty warrior Orion (Figure 1.2). Thus, the historian of science Giorgio de Santillana gives the following interpretation for the biblical account: the hero of the original story must be Orion, and that rigmarole about the jawbone of an ass and drinking water out of the hollow of Lehi is simply a mnemonic device for finding the relative positions of the constellations Orion and Taurus and the group of stars called the Hyades.

In other cultures we find the same story but different characters. Thus, the Polynesians—who were excellent navigators—have a story about Maui the Creator using Orion as a net to snare the sunbird. Having caught the sunbird, he proceeds to beat it up with the jawbone of his grandmother!

The Constellations as Timekeeping Aids

When nomads turned to farming, the constellations became equally useful for telling time, especially for keeping track of the seasons. The diurnal rotation of the whole sky forms the unit of time that we know as the day. People noticed that, apart from the daily rotation, the stars appear not to move with respect to one another; consequently, the stars were considered "fixed." Today we understand that the diurnal rotation of the entire sky results simply from the spin of the Earth, and that the relative positions of the stars are fixed simply because of their immense distances from us and from each other. During very long periods of time, say, tens of thousands of years, stars do move detectably with respect to one another, even according to naked-eye observations. Thus, the constellations will not always have their present forms. This fact was not known, of course, to peoples whose recorded history only spanned a few thousand years.

During shorter periods of time, say, a year, people did notice that certain objects did not keep the same positions relative to the "fixed" stars. Rather, they wandered to and fro in a narrow band of the sky, named the Zodiac (Figure 1.3). *Planetes* the Greeks called these wanderers; we now say "planets." Foremost among the "planets" was the Sun; and in ancient times, six other wanderers were known: the Moon, Mercury, Venus, Mars, Jupiter, and Saturn. Today, of course, we no longer think of the Sun and the Moon as planets; instead, we think of the Earth as one of the wanderers, and the Moon as its companion. Today, we explain the to-and-fro wanderings about the Zodiac in terms of the planets' orbits (including that of the Earth) about the Sun, which are confined more or less to a single plane, the "ecliptic" (Figure 1.4). However, for describing the "how" of the planetary motions and not the "why," the ancient description is just as good; in fact it is better for the purposes of an observer on Earth who is trying to visualize the celestial events.

The early Greeks were sophisticated geometers who knew the size, shape, and rotation of the Earth. They possessed a reasonable calculation of the size and distance to the Moon. They also proposed a theoretical method which could have yielded, in principle, the distance of the Sun. Unfortunately, their observational measurements were not precise enough for the last task; so the distance they calculated was a serious underestimate. Despite this underestimate, they still deduced

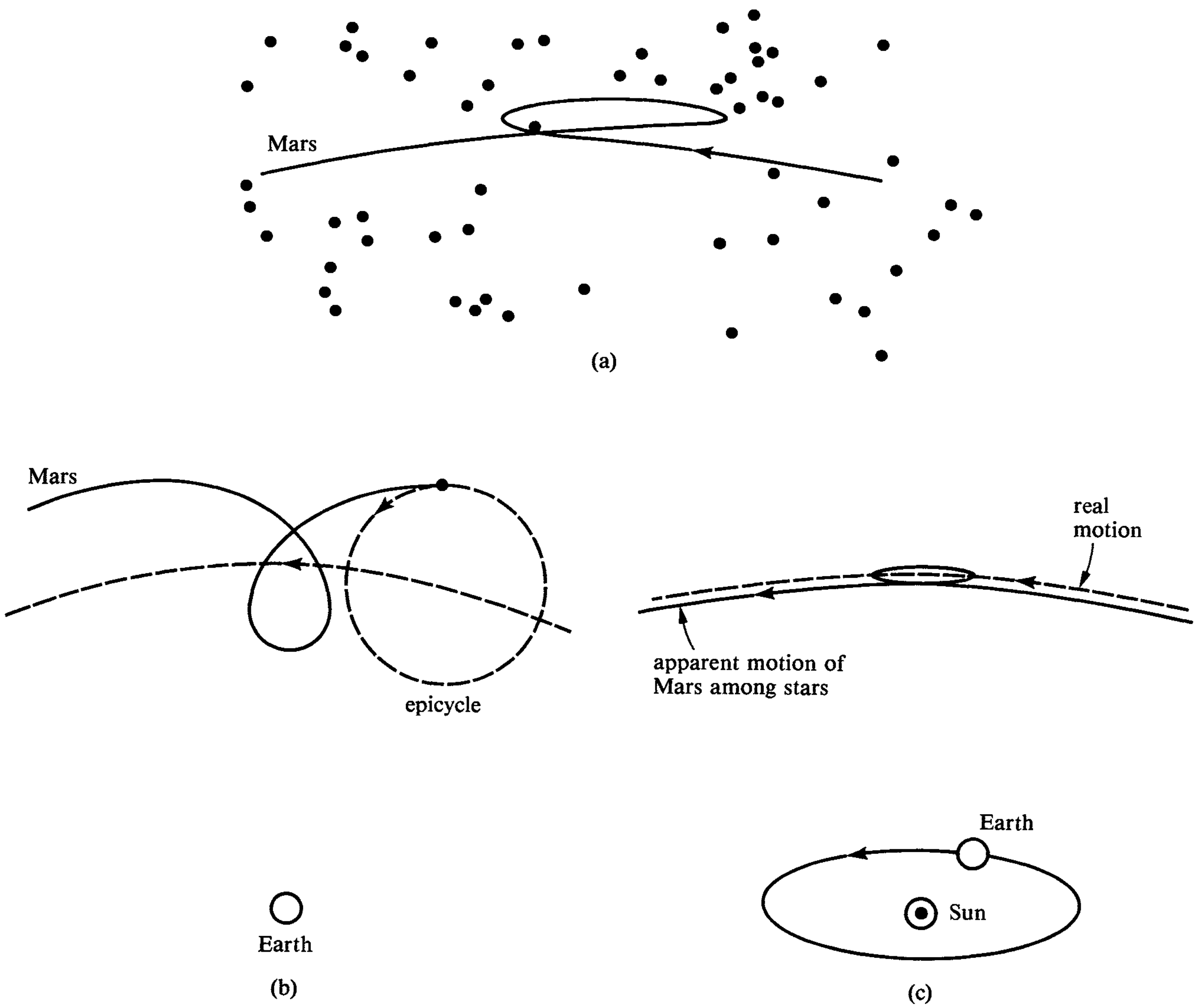


Figure 1.3. The apparent motion of the planet Mars. In an Earth-centered system. Ptolemy required a complicated theory of epicycles to explain these motions. In a Sun-centered system, Copernicus was able to explain the same motions much more simply: namely, at certain points in the motion of the Earth about the Sun, the Earth would seemingly catch up with a planet's projected orbit, and then that planet would appear to go backward.

that the Sun is substantially larger than the Earth. Because of the apparent dominance of the Sun, some of the Greeks speculated correctly that the Earth revolved about the Sun, rather than the other way around. These ideals fell into disfavor when Aristotle argued, on seemingly common-sense grounds, that we could not inhabit a moving and rotating Earth without being more aware of it. For example, Aristotle argued that motion of the Earth should cause foreground stars to be displaced annually with respect to the background (an effect now called **parallax**), whereas no parallax could be detected for any star by the Greeks. We now understand this null result to arise from the very great distances to even the nearest stars (see Problem 3.2).

Problem 1.1. This problem and the next one retrace the early arguments of the Greeks about the sizes of the Earth, Moon, and Sun, and the distances between them.

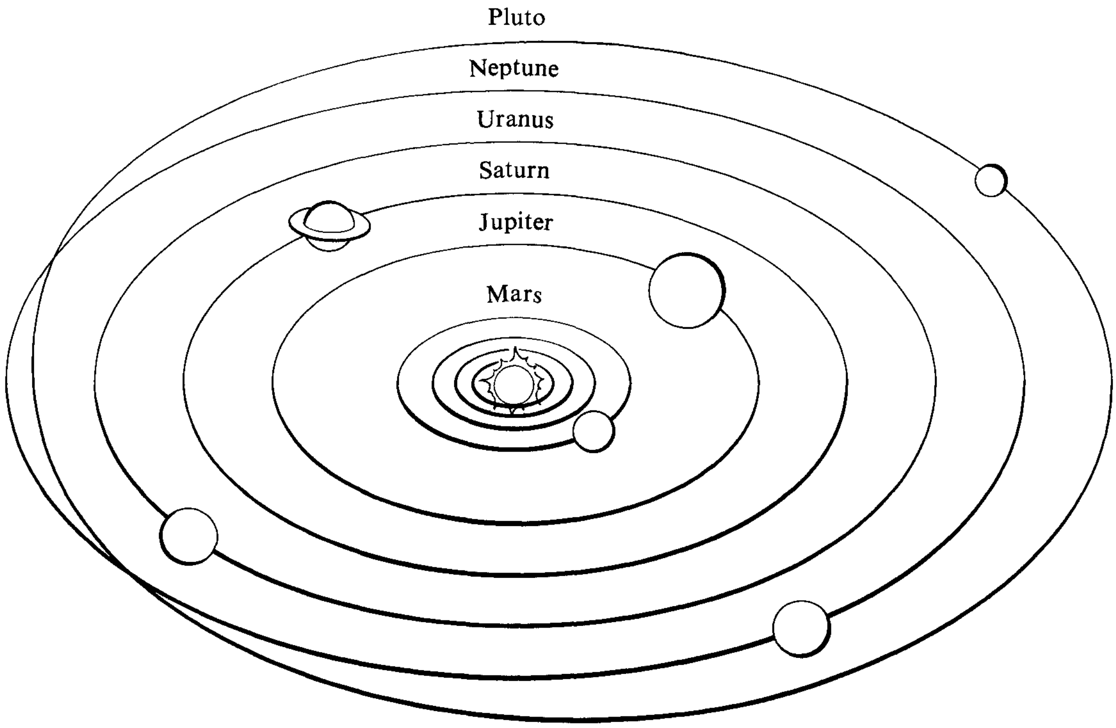
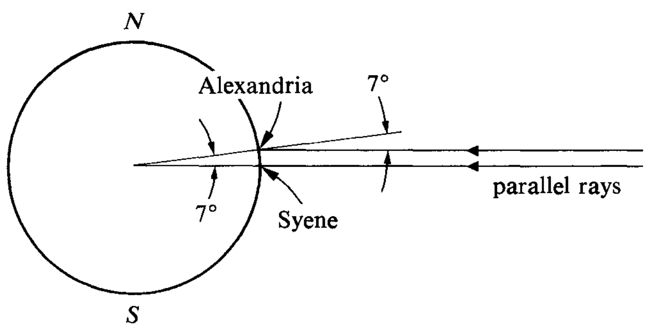


Figure 1.4. The planetary orbits about the central Sun. The plane of the Earth's orbit defines the ecliptic. Except for Mercury and Pluto, all the planetary orbits are nearly circular and lie within several degrees of the plane of the ecliptic. For sake of clarity, the orbits of the three innermost planets, Mercury, Venus, and Earth, are not labeled.

We begin with the size of the Earth. From the shape of the shadow cast by the Earth on the Moon during a lunar eclipse, it can be inferred that the Earth is a sphere. Moreover, the method described in Problem 1.2 shows that the Sun's distance is many times greater than the diameter of the Earth. Erastothenes assumed that the Sun was far enough away that the rays from the Sun are virtually parallel when they strike the Earth (see figure



here). Erastothenes then observed that, at noon on the first day of summer, sunlight struck the bottom of a deep well in Syene, Egypt. In other words, the Sun at that time was directly overhead. At the same time in Alexandria, however, the Sun's rays made an angle of about 7° to the vertical. Erastothenes concluded that Syene and Alexandria must be separated by a fraction $7°/360° \cong 1/50$ of a great circle around the Earth. Assume that this distance of 1/50 of the circumference of the Earth can be paced off to be 800 km. Consult Appendix B for the relation between the radius and circumference of a circle, and calculate the radius of the Earth. Compare your answer with the value given by Appendix A.

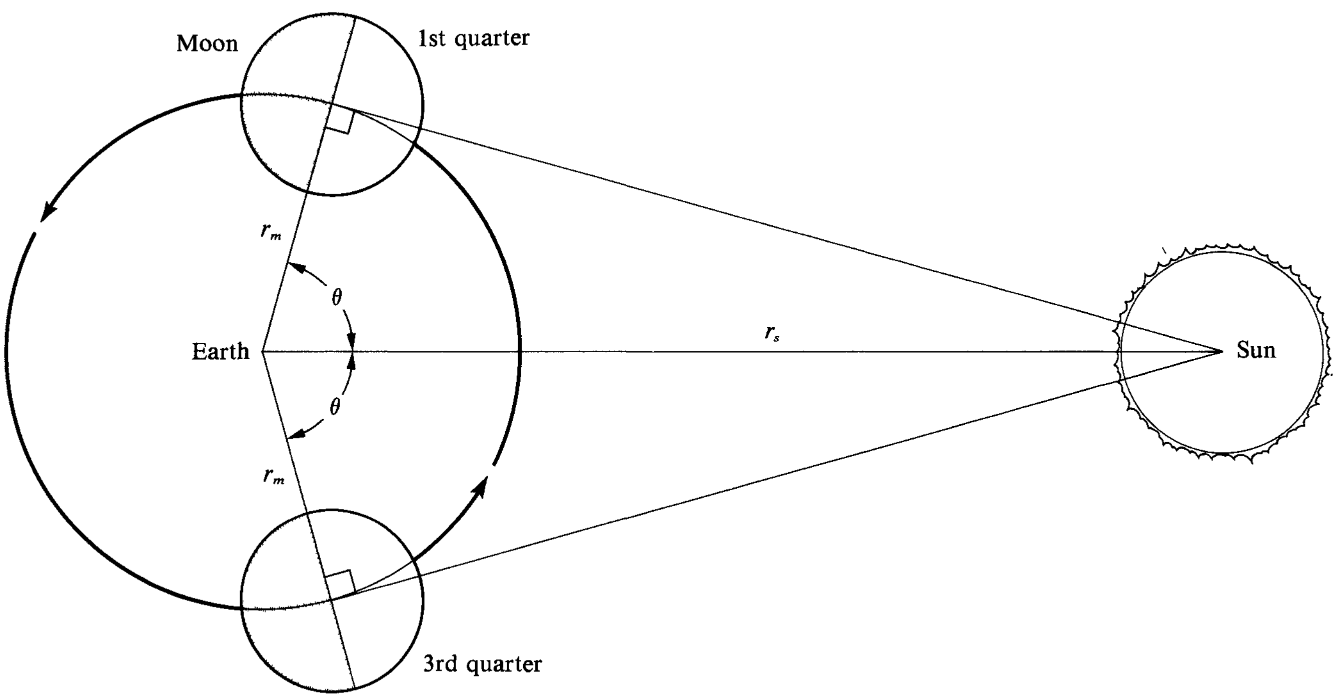
Reconsider now the observation of the shadow cast by the Earth during a lunar eclipse. Assume still that the rays from the Sun make parallel lines, and draw diagrams to show how a comparison of the curvature of the Earth's shadow on the Moon with the curvature of the Moon's edge allows one to infer the relative sizes of the Earth and Moon. This deduction is a slight modification of the method used by Aristarchos to find that the Moon's diameter is about a third of that of the Earth. The modern value is 0.27. With Erastothenes's value for the radius of the Earth, calculate the diameter D_M of the Moon. Given that the Moon subtends an angular diameter at Earth of about half a degree of arc, calculate the distance r_M of the Moon. *Hint*: If θ_M is the angular diameter of the Moon expressed in radians, and if $\theta_M \ll 1$, show that the formula $\theta_M = D_M/r_M$ holds to good approximation.

Problem 1.2. Aristarchos suggested an ingenious method for measuring the relative distances of the Moon and the Sun. Because the angular sizes of the Moon and the Sun do not change appreciably with time, it can be deduced that they maintain nearly constant distances from the Earth. (The orbits are circular.) From the figure here show how to deduce the ratio of the Moon's distance r_M to the Sun's distance r_S as

$$r_M/r_S = \cos\theta,$$

where 2θ is the total angle subtended at the Earth by the Moon's positions between first and third quarters of the Moon's phases. Unfortunately, the angle θ turns out to be too close to 90° to be practical as a way to tell that the value of $\cos\theta$ is not zero (i.e., that the Sun is not infinitely far way compared to the Moon). Modern measurements using radar reflections show that $r_M/r_S = 2.6 \times 10^{-3}$. Thus, the Sun is about 390 times further away than the Moon. On the other hand, solar-eclipse observations demonstrate that the Sun and the Moon have about the same angular sizes. Argue that this implies the Sun is about 390 times larger than the Moon. Given that the Moon is only 0.27 the size of the Earth, show that the Sun is more than a hundred times larger than the Earth. Thus, unless the mean density of the Sun is much less than that of the Earth, the Sun is also likely to be much more massive than the Earth; and it then becomes more plausible to suppose that such a regal body is the true center of the solar system rather than the Earth. If the Earth can revolve about the Sun, then there can be no great philosophical objection to its spinning about its axis to account for the apparent diurnal rotation of the sky.

Given the value of the size D_M and the distance r_M of the Moon calculated in Problem 1.1, compute now the diameter D_S and distance r_S of the Sun. Convert your answer to light-seconds, and discuss how long it typically takes to bounce radar waves back and forth between objects in the solar system (e.g., between Earth and Venus). Discuss how geometry might be used to deduce the radii of the orbits of Venus and Earth about the Sun. This is the best method to obtain r_S.



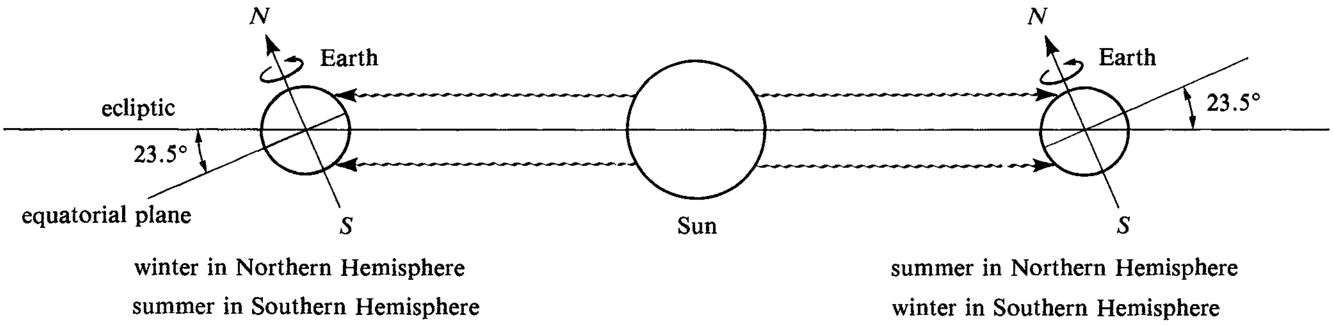


Figure 1.5. The reason for the seasons. Because the equatorial plane of the Earth is inclined by 23.5° with respect to the plane of the ecliptic, the Sun's rays strike the ground more perpendicularly at one point of the Earth's orbit than at the opposite point half a year later. At any one time, however, if it is winter in the Northern Hemisphere, it is summer in the Southern Hemisphere. This geometric result is the same whether we think of the Earth moving around the Sun or the Sun around the Earth. (Note: radii in this drawing are not to scale.)

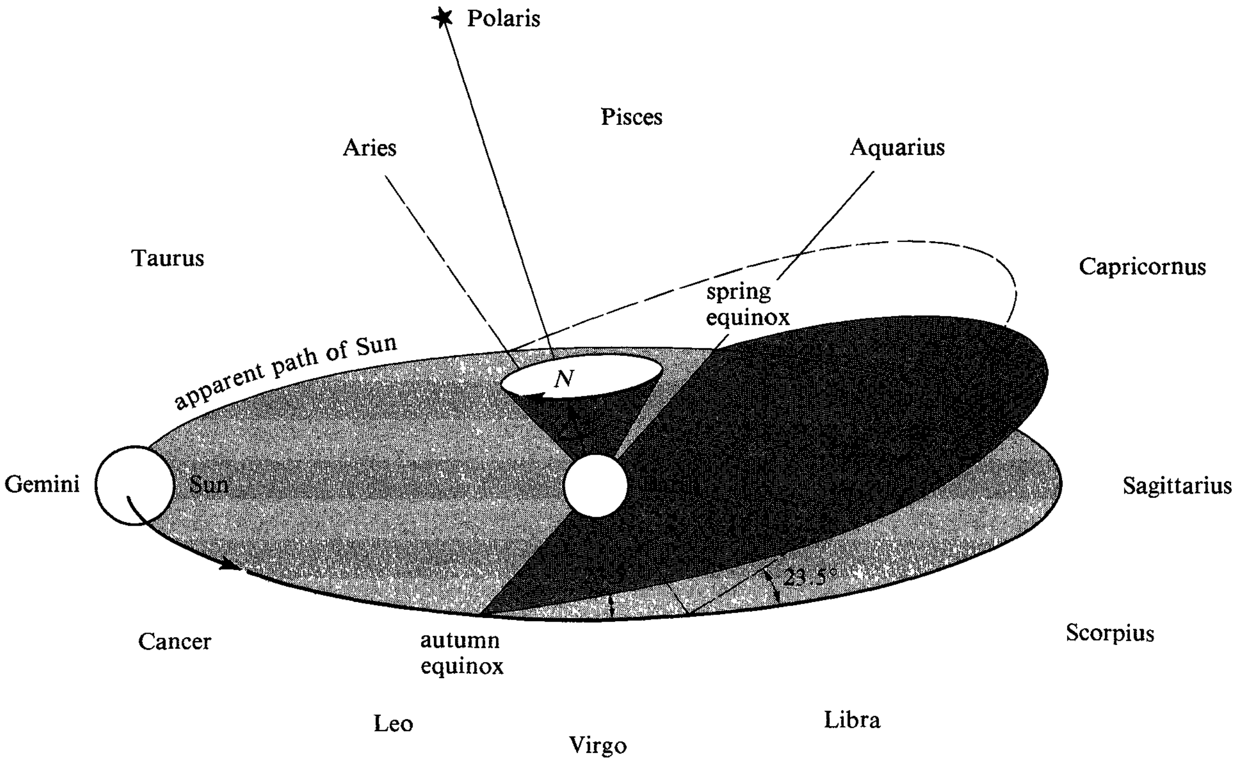


Figure 1.6. The seasons and the signs of the Zodiac. An Earth-bound observer seems to see the Sun move around the Earth once a year in the plane of the ecliptic (lightly shaded oval). At the present epoch, the North Pole of the Earth points toward the star Polaris, and the extension of the equatorial plane of the Earth is shown as the dark semi-oval. The two points of intersection of the Sun's apparent path with the equatorial plane are called the spring and autumn equinoxes. The equatorial plane in 2000 B.C. corresponded to the dashed semi-oval.

The seasons arise because the spin axis of the Earth is tilted with respect to the plane of the ecliptic, which is the apparent path followed by the Sun during the course of one year. Consequently, the Sun's rays at noon fall more vertically during the summer months than during the winter months (Figure 1.5). Spring and fall come when the Sun is at the point of its apparent path where the circle of the ecliptic crosses the circle of the Earth's equator. These intersection points are called the spring and autumn equinoxes (Figure 1.6).

When the Sun is not in the way, stars can be seen in the background all along the ecliptic. There are twelve prominent constellations near the plane of the ecliptic, and these correspond to the twelve signs of the Zodiac. In 2000 B.C., when the Babylonians set up the system of timekeeping, the spring equinox lay in the direction of the constellation of Aries. That is, spring came on March 21, when the Sun entered the "house of Aries," which signaled the beginning of the planting season. However, tidal torques cause a slow precession of the Earth's axis of rotation; so the spring equinox moves backward through the signs of the Zodiac, at about one sign per two thousand years (Figure 1.6). Thus, 2,000 years after the Babylonians had found that the spring equinox lay in Aries, the spring equinox had moved into Pisces. This event coincided approximately with the birth of Christ, and may be why one early symbol of Christianity was the fish. Two thousand years later, the spring equinox is beginning to move into Aquarius (officially in A.D. 2600). This is why our age is sometimes called the coming of the "Age of Aquarius."

The Rise of Astrology

No one knows the exact reasons for the rise of astrology, but it may have been something like the following. To the ancients, it was obvious that the Sun, and to a lesser extent, the Moon, influences events on Earth: witness night and day, the seasons, tides, etc. The Sun and the Moon were like gods. Why not, then the other planets? From very early on, seven wanderers were known: Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn. To honor the planetary gods, the Babylonian priests devised the seven-day week and gave the days the names of the planetary gods. In English, the roots of Sunday, Monday, and Saturday can easily be traced to Sun, Moon, and Saturn. In French, the roots of Mercredi, Vendredi, Mardi, and Jeudi can equally easily be traced to Mercury, Venus, Mars, and Jupiter.

Horoscopes were later based on the hypothesis that the positions of the planets in the Zodiac could influence the course of human events just as the positions of the Sun and the Moon affect the seasons and the tides. Especially important was the position of the Sun at the time of one's birth; thus, if one was born in 2000 B.C. between March 21 and April 19, the Sun was in Aries; between April 20 and May 20, the Sun was in Taurus, etc. Even today, one is given a Zodiac sign on the basis of the Babylonian system. The problem is, of course, that today these signs are 4,000 years out of date! For example, the coming of spring, March 21, no longer occurs when the Sun arrives at Aries but at Aquarius. If astrologers were up to date, they should tell people who are Aries that they are really Aquarius, and people who are Aquarius that they are really Sagittarius, etc.

The Rise of Astronomy

In the beginning there was little difference between astronomy and astrology. Indeed, some famous astronomers of the past earned their keep by casting horoscopes for kings and queens. A major divergence of astronomy and astrology came with the work of Nicholas Copernicus in the sixteenth century. Copernicus discovered that he could explain the seemingly complicated motions of the planets in terms of a stationary Sun about which revolved Mercury, Venus, Earth, Mars, Jupiter, and Saturn. The Moon would still have to go around the Earth, but the looping motions of the other planets (which is what observers actually see) became simple to explain if the Earth itself moved about the Sun. (as Figure 1.3 shows, when the Earth's orbital motion carries it past one of the outer, slower planets, that appears to go backwards!) Copernicus's ideas forced a major change in the prevailing philosophy of a human-centered universe, and the Copernican Revolution is justly considered one of the major turning points of science.

Free thinkers like Galileo and Kepler were quick to adopt the Copernican system, and they provided many of the early pieces of astronomical evidence in support of it. Later Galileo was forced by the Church to recant his espousal of a moving Earth, an episode made familiar by Bertolt Brecht's play on the subject. Popular myth has Galileo secretly defiant, muttering the famous phrase "And yet it moves." In any case, the Copernican viewpoint received its ultimate triumph in the seventeenth century, with the work of Isaac Newton. Newton showed that the laws of planetary motion described by Kepler in a Sun-centered system (see Chapter 18) could be derived mathematically from Newton's formulation of the laws of mechanics and gravitation.

Newton also demonstrated how his theory of gravitation could explain the tides raised on Earth by the Sun or Moon. The basic idea was that the Sun or Moon pulled hardest on the side of the oceans facing toward it. less hard on the center of the Earth, and least on the side

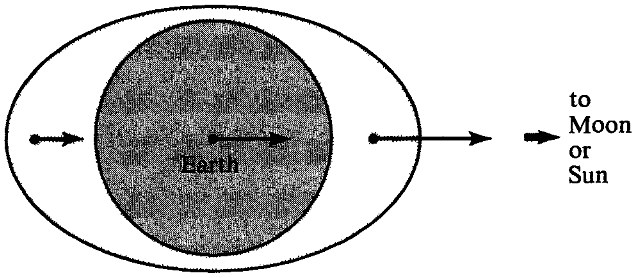


Figure 1.7. The tides. Tides in the oceans arise because the gravity of the Moon or the Sun is greatest on the side facing it and least on the side opposite it. The difference between these two forces is responsible for producing the characteristic two-sided bulge.

of the oceans facing away from it (Figure 1.7). In this way, the oceans would tend to bulge out in *two* directions: on one side because the water is pulled away from the Earth, on the other side because the Earth is pulled away from the water. The difference in force between the two sides of the Earth is called the tidal force. (We shall discuss such forces in other contexts in this book.)

In this manner did astronomy and astrology part ways. With the growing maturity of modern science, astronomy attempted to give *mechanistic* explanations for natural phenomena—seasons, tides, planetary motions—on the basis of laws formulated and tested in laboratories. Astrology continued to attribute *mystical* influences on terrestrial affairs to the planets. Mystical beliefs have a long cultural history, and they die hard. Kepler and Newton were mystics in many ways, and much of the modern world still clings to atavistic concepts.

Modern Astronomy

Today we know that Mercury, Venus, Earth, Mars, Jupiter, and Saturn are only six of the nine planets that go around the Sun; the other three are, of course, Uranus, Neptune, and Pluto. However, as far as we can tell, planets and their satellites are not the major constituents of the universe. Stars are. (Perhaps.) The Sun is a star—the closest one to Earth—and the Sun contains about 99.9 percent of the mass of our solar system. However, the Sun is only one star of myriads that belong to our Galaxy.* Our Galaxy contains more than 10^{11} (one hundred billion) stars! (For a review of the exponent notation, see Box 1.1.) And our Galaxy is only one of myriads in the observable universe. The observable universe contains about 10^{10} (ten billion) galaxies. Thus, in the observable universe there are about 10^{10} galaxies $\times$ 10^{11} stars/galaxy = 10^{21} stars: an astronomical number which has no simple English equivalent.

Since numbers like 10^{21} are enormous, almost beyond intuitive comprehension, we cannot hope to study each individual astronomical object. Even if we could see them with our telescopes—and in fact we cannot see more than a small fraction of them—we would not gain much insight from an object-by-object study. A far more practical and informative goal is to look for patterns of behavior among similar groups of objects. This book is organized in terms of the few theoretical concepts which underlie the structure and evolution of the astronomical objects under study. First, we will emphasize the deep connections between how matter is organized on large scales (**macroscopic** behavior) and on small scales (**microscopic** behavior). Second, we will find that there are two main recurring threads in the organizational fabric of macroscopic objects like stars, galaxies, and the universe. These two threads are the **law of universal gravitation** and the **second law of thermodynamics** (Chapters 3 and 4).

Another implication follows from the enormous number, 10^{21}, of stars in the observable universe. Since our life-sustaining Sun is only one star among an enormous multitude, it seems extremely unlikely that we could be either alone in the universe or the most intelligent species in the universe. This realization motivates the discussion on the chances for extraterrestial life and intelligence that we shall pursue in the last part of this book. Again we shall find the second law of thermodynamics to play an integral role in our discussions.

* When Galaxy is capitalized, it refers to our own galaxy.

BOX 1.1
Exponent Notation

$10^n = \underbrace{1000\cdots000}_{n \text{ zeroes}}.$

$10^{-n} = 1/10^n = \underbrace{.000\cdots0001}_{n-1 \text{ zeroes}}$

multiplication: $10^n \times 10^m = 10^{n+m}$. Also $10^n/10^m = 10^n \times 10^{-m} = 10^{n-m}$.

Important prefixes in exponent notation:
nano = 10^{-9} (one-billionth)
micro = 10^{-6} (one-millionth)
milli = 10^{-3} (one-thousandth)
centi = 10^{-2} (one-hundredth)
kilo = 10^3 (one thousand)
mega = 10^6 (one million)
giga = 10^9 (one billion)

Example: 1 kilometer = 10^3 meter = $10^3 \times 10^2$ centimeter = 10^5 cm.

Rough Scales of the Astronomical Universe

Given that gravitation and the second law of thermodynamics underlie much of natural phenomena, you will appreciate that an honest understanding of modern astronomy requires a healthy dose of physics. The next three chapters of this book provide the physics needed to understand, on a *qualitative* level, the explanations of the important phenomena. The first step, however, toward a unified appreciation of astronomy is to obtain a physical feel for the scale of the phenomena that we shall be dealing with in this book.

The most fundamental measurements that we can make of an object are its size, its mass, and its age (or duration between one event and another). The units of length, mass, and time that we shall adopt are centimeter (abbreviated cm), gram (abbreviated gm or g), and second (abbreviated sec or s); these are called **cgs units** (Box 1.2). Although it is not immediately obvious, it is nevertheless true that all physical quantities can be expressed as various combinations of powers of cm, gm, and sec. A familiar example is the cgs unit of energy: erg = gm cm^2 sec^{-2}. A less-familiar example is the cgs unit of electric charge: esu = gm$^{1/2}$ cm$^{3/2}$ sec^{-1}. At first sight, temperature seems to be an exception. However, in any fundamental discussion, the temperature (degrees Kelvin or K) always enters in the combination "Boltzmann's constant × temperature," which has the units of energy. Some of the more important physical constants in cgs units are given in Appendix A.

Let us now consider the scales of some astronomical objects. Listed in Table 1.1 are the very rough ("**order of magnitude**," i.e., to the nearest power of ten) sizes, masses, and ages of the Sun, the Galaxy, and the observable universe. For comparison, the same quantities are listed for a small child.

BOX 1.2
The cgs Units

unit of length = centimeter = cm (1 inch = 2.54 cm)
unit of mass = gram = gm or g (1 pound = 454 gm)
unit of time = second = sec or s
(1 year = 3.16×10^7 sec)
unit of force = dyne = gm cm sec^{-2}
(weight of 1 pound on Earth = 4.45×10^5 dyne)
unit of energy = erg = gm cm^2 sec^{-2}
(potential energy of 1 pound at height of 1 foot on Earth = 1.36×10^7 erg)
unit of power or luminosity = erg sec^{-1}
(100 watt = 10^9 erg/sec)

Table 1.1. **Rough scales.**

Object	*Size*	*Mass*	*Age*[a]
child	10^2 cm	10^4 gm	10^8 sec
Sun	10^{11} cm	10^{33} gm	10^{17} sec
Galaxy	10^{23} cm	10^{45} gm	$\gtrsim 10^{17}$ sec
observable universe	10^{28} cm	10^{55} gm	$\gtrsim 10^{17}$ sec

[a] Notice that although the Sun, the Galaxy, and the universe differ appreciably in size and mass, they all have ages comparable in order of magnitude.

The numbers quoted in the last three rows of Table 1.1 are the hard-won efforts of several generations of astronomers and physicists. They result from some truly heroic struggles, and it is a shame that we cannot devote more space in this book to the *history* of astronomy and physics. The principal goal of this book is to develop some appreciation of how numbers like those in Table 1.1 are derived. An important component of such appreciation is understanding the philosophical implications of the results, which can be easy to overlook if we concentrate too much on the specific numerical values.

For example, Table 1.1 gives the age of the universe as somewhat greater than 10^{17} sec. To be more precise, astronomers now believe that the time since creation is between 10 and 20 billion years.* To debate, as experts do, whether the precise age since creation is closer to 10 billion years or to 20 billion years is philosophically and culturally less important than to grasp the following points.

(1) By any human standards, the universe is very old. Nevertheless, the present universe is not infinitely old. There *was* a beginning to time, and that beginning took place on the order of 10^{10} years ago.

(2) By some great stroke of luck, you and I live in an era when it has become possible to measure something as fundamentally interesting as the age of the universe to an accuracy of a factor of two or so. This fortune is well worth some leisurely reflection.

There is another comment we should make about Table 1.1. In quoting a mass and a size, Table 1.1 carefully notes that these estimates apply to the *observable* universe. This distinction between the *universe* and the *observable universe* is important because astronomers have not yet settled the question of whether the universe is *open* or *closed* (Chapter 15). If the universe is open, spacetime (and the number of stars in the universe) is infinite. In other words, although time had a beginning, it has no end, and the amount of space and the number of stars in it are actually infinite. (However, only a finite part of either are observable, even in principle, by us at

* One year = approximately 3×10^7 sec; see Appendix A for more accurate conversion formulae for common astronomical constants.

any finite time after the creation event.) Have you ever contemplated what the truly infinite means? The cosmologist G. F. R. Ellis has, and he makes the following interesting observation. If the number of stars (and planets) is infinite, then all physically possible historical events are realizable somewhere and sometime in the universe. Thus, there may be somewhere and sometime another Earth with a history exactly like our own, except that the South wins the Civil War instead of the North. Elsewhere and othertime, there may even be a reasonable fascimile of Tolkien's Middle Earth! Now, it is highly improbable that such alternative worlds are within our "event horizon"; so we may never be able to communicate with them. Nevertheless, it is fun to speculate on the possibility of such worlds given the truly infinite.

The alternative possibility—that the universe is closed, so that spacetime and the number of stars in it are finite—is almost equally bizarre according to normal conceptions. This possibility leads to the conclusion that the volume of space is finite, yet it does not possess an edge or boundary!

Contents of the Universe

The primary inhabitants of the universe are stars, of which the Sun is only one example. Stars exhibit a great variety of properties. Besides suns of all colors, there are the tremendously distended **red giants** and the mysteriously tiny **white dwarfs.** The Sun itself is quite an average star, neither very massive nor very light, neither very large nor very small. Why, then, does the Sun appear so bright, but the stars so faint? Because the stars are much further away than the Sun. The Sun is "only" eight light-minutes away, but the nearest star, proxima Centauri, is about four light-years distant. A light-year is the distance traveled by light in one year, and equals 9.47×10^{17} cm. To appreciate how enormous a distance is a few light-years, notice that human travel to the Moon, "only" one light-*second* away, represents the supreme technological achievement of civilization on Earth. Will travel to the stars ever be within our grasp?

The rich variety of stars live in our Galaxy mostly singly or in pairs (Figure 1.8). Sometimes, however, hundreds or thousands of stars can be found in loose groups called **open clusters.** The Pleiades is a fairly young open cluster, and the **reflection nebulosity** which surrounds the famous "seven sisters" of this cluster attests to the fact that these stars must only recently have been born out of the surrounding gas and dust. The oldest stars in our Galaxy are found in tighter groups called **globular clusters.** Rich globular clusters may contain more than a million members.

The space between the stars is not completely empty.

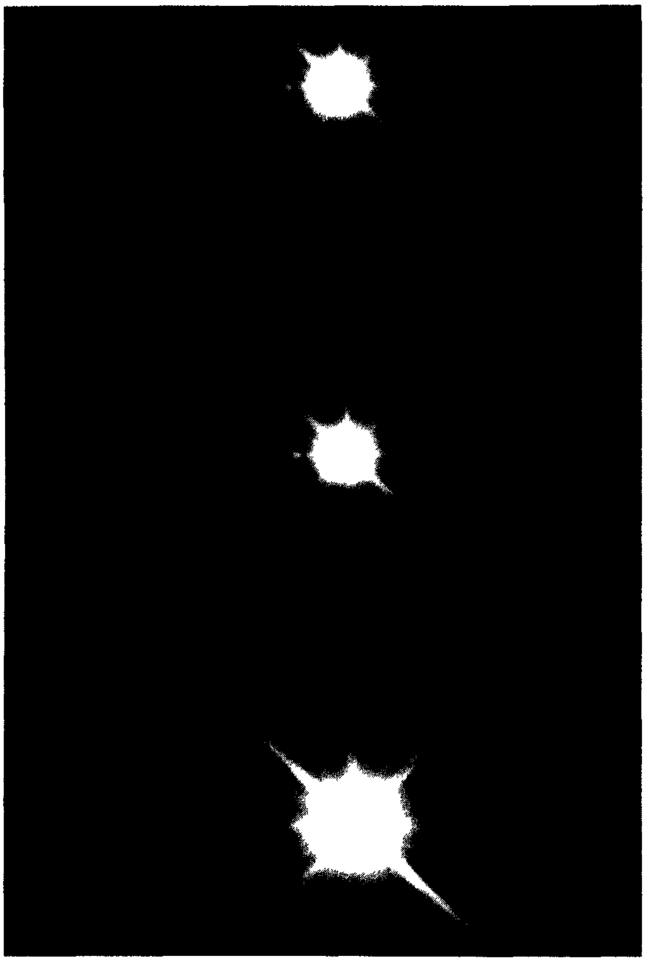


Figure 1.8. These three views of the bright star Sirius show it to be a member of a binary system. The companion of Sirius is a white dwarf. (Lick Observatory photograph.)

The diffuse matter between the stars is called the **interstellar medium,** but by terrestrial standards it is virtually a perfect vacuum. Clouds of **gas** and **dust,** as well as energetic **cosmic-ray particles** gyrating wildly in **magnetic fields,** reside in the space between stars. Giant fluorescent gas clouds (called **HII regions**) lit up by nearby hot young stars, like the Orion nebula found in the "sword" of Orion, constitute some of the most beautiful objects in astronomy. Other objects like the Crab nebula shine with an eerie light (**synchrotron radiation**) and are now known to be the **remnants** expelled by stars which died in titantic **supernova** explosions. The cores left behind in such cataclysms, **neutron stars** and **black holes,** represent some of the most intriguing denizens of the astronomical kingdom. Other stars die less violently, ejecting the outer shell as a **planetary nebula** which exposes the hot central core destined apparently to become a white dwarf.

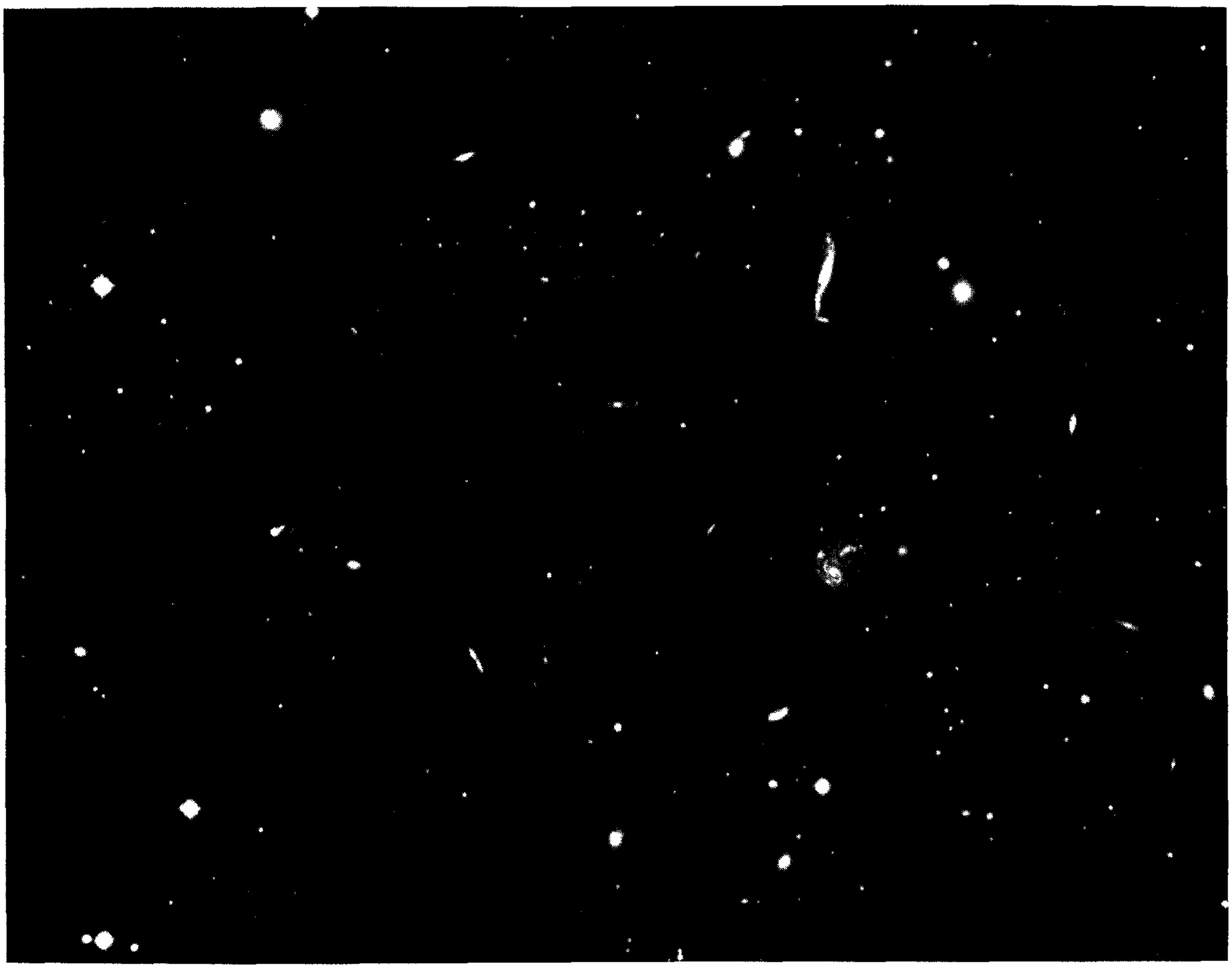


Figure 1.9. A cluster of galaxies in Hercules. (Palomar Observatory, California Institute of Technology.)

Stars and the material between them are almost always found in gigantic stellar systems called **galaxies.** Our own galaxy, the Milky Way System, happens to be one of the two largest systems in the **Local Group** of two dozen or so galaxies. The other is the Andromeda galaxy; it stretches more than *one hundred thousand light-years* from one end to the other, and it is located about *two million* light-years distant from us. If the kingdom of the stars is vast, the realm of the galaxies is truly gigantic.

Apart from small groups like our own Local Group, galaxies are also found in great **clusters,** containing thousands of members (*Figure 1.9*). Most cluster galaxies are roundish **ellipticals** rather than the more common **spirals** found in the general field. Rich clusters have been found at distances exceeding *three billion* light-years from us. Obviously, the observable universe is a tremendously large place! And modern cosmology tells us that it is expanding. Clearly, the universe contains many interesting objects, not the least of which are the Earth and its inhabitants. Of all the objects intensively studied in the solar system, the Earth is the only one known to harbor life. How did we get here? How do we fit into the unfolding drama of the universe? These issues and others are the natural legacy of Copernicus's first inquiries, and they form the subject matter of this book. To survey the entire universe and to develop the important themes fully, our pace must necessarily be fast. Let us start!