PART I

The astronomical planet: Earth's place in the cosmos

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An introductory tour of Earth's cosmic neighborhood

1.1 Ancient attempts to determine the scale of the cosmos

The science of astronomy developed in many different cultures and from many different motivations. Because, even in cities of the preindustrial world, the stars could be seen readily at night, the pageant of the sky was an inspiration for, and embodiment of, the myths and legends of almost all cultures. Some people tracked the fixed stars and moving planets with great precision, some for agricultural purposes (the ancient Egyptians needed to prepare for the annual flooding of the Nile River Valley) and more universally to attempt to predict the future. The regularity of the motions of the heavens was powerfully suggestive of the notion that history itself was cyclical, and hence predictable. The idea of human history linked to celestial events remains with us today as the practice of astrology. In spite of a lack of careful experimental tests, or demonstrated physical mechanisms, this powerfully attractive belief system is pursued widely with varying amounts of seriousness, extending in the early 1980s to the level of the presidency of the United States.

Although ancient understanding of the nature of the cosmos varied widely and was usually a reflection of particular mythologies of a given culture, the classical Greeks distinguished themselves by their (often successful) attempts to use experiment and deduction to learn about the universe. Some Greek philosophers understood the spherical nature of Earth and something of the scale of nearby space. Aristotle, in the fourth century BC, correctly interpreted lunar eclipses as being due to the shadow of Earth projected on the surface of the Moon. By noting that the shadow was rounded, he deduced that Earth must be spherical; in fact, another acceptable shape based on that one observation is a disk (Figure 1.1). Others, such as Plato, had much earlier endorsed a spherical shape on aesthetic grounds.

Eratosthenes, who lived in the third century BC, made a remarkably accurate determination of the size of our planet without having to travel too far. He used the observation that at high noon on summer solstice (June 21 in our calendar, when the Sun reaches its northernmost point in the sky of Earth), the Sun was directly overhead at a site in Syene (now Aswan), Egypt, because no shadow could be seen in the vertical well shaft. Eratosthenes lived in Alexandria, due north of Syene, and there he could observe that the Sun cast a shadow at noon on that same date of June 21 (Figure 1.1).

What did this mean? If Earth were a sphere, then different people standing at different locations on Earth at the same time would see the Sun in different parts of the sky. By measuring as an angular distance in the sky, the change in the position of the Sun from one place to another and knowing the distance between the two stations, one could then by a simple calculation work out the circumference of the whole globe. In his home city, Eratosthenes carefully measured the size of a shadow cast by an obelisk of known height, at the same time on the same day that no noontime shadow occurred at Syene. The angular position of the Sun, from the size of the shadow at Alexandria, gave an angle of 7.2 degrees between the position of the Sun at the two stations, or one-fiftieth of the entire angular extent of the sky (which by definition surrounds our globe and therefore extends over 360 degrees). Therefore, Earth's circumference, he knew, must be 50 times the distance between Syene and Alexandria.

The distance was, however, known only approximately from the number of days it took a camel to travel between the two towns and the distance a typical camel walks in a day. Furthermore, to compare the result with the value we know today, the units of measurement used by the Greeks must be converted to modern ones, which is also an uncertain exercise. In modern units, the Syene–Alexandria distance is 570 miles, or 918 kilometers (km), and hence Eratosthenes' experiment yields an Earth circumference of 46,000 km, just 12% too large. This represents an extraordinary achievement, 2,300 years before human beings could view the round globe of Earth from space.

Not everything about the cosmos that the Greek philosophers deduced or inferred came out right. The most celebrated mistake was that of Ptolemy, who lived 400 years after Eratosthenes and is associated most closely with the cosmological system in which the Sun and the planets (in fact, the whole cosmos) were thought to orbit Earth. However, this was just the penultimate round in a long debate on the topic: Aristarchus of Samos, a generation before Eratosthenes, put the Sun at the center with

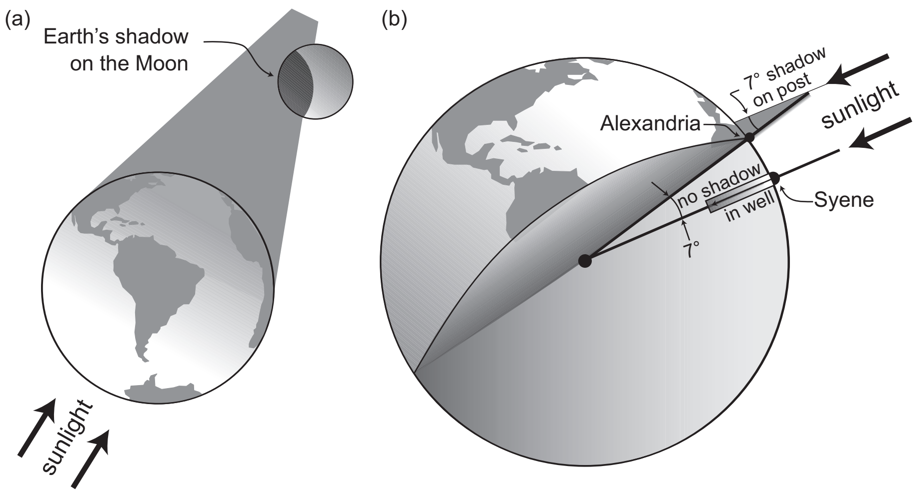

Figure 1.1 Two ancient Greek observations of the cosmos: (a) Aristotle's determination of Earth's sphericity via a lunar eclipse; (b) Eratosthenes' measurement of the size of Earth. Adapted from Snow (1991).

Earth and the other planets orbiting it. This correct model of the solar system was discredited at the time because the Greeks could not see the stars shift in position as Earth moved from one point in its orbit to the opposite side. In fact, the stars do appear to shift position, in the phenomenon called parallax that we describe later, but they are so far away that the shift cannot be detected with the unaided eye. This the Greeks did not know, and the failed experiment led them down the wrong path of an Earth-centered cosmos that would not finally be discarded until the times of Copernicus and Galileo, over 1,500 years later.

We should not fault the classical Greeks for their wrong interpretations, but should admire their startling successes, which were based on observations unaided by the technologies available at present, coupled with the disciplined logic of inductive and deductive reasoning, which was the foundation of the scientific method. Few of us today could repeat the insights of the handful of extraordinary philosophers who anticipated by many centuries some of the outcomes of the Copernican Revolution. In point of fact, we in the industrialized world still have a mindset in essence of an Earth-centered universe: we think little of the sky, increasingly obscured by the lights of cities and hence unfamiliar to us, unless it is to wonder when the Sun will set today, or what the local newspaper horoscope claims our immediate future will hold.

1.2 Brief introduction to the solar system

The solar system consists of eight major planets, several classes of minor planets, some 180 named natural satellites (or *moons*), and innumerable small bodies, all orbiting the Sun. In 2006 Pluto was "demoted" by the International Astronomical Union from the status of planet to a member of a class of "dwarf planets" that include other members in the region beyond the orbit of Neptune, and the largest bodies in the "main asteroid belt" between Mars and Jupiter. Robotic spacecraft have traversed the distance to the farthest planet in the solar system, some 6 billion km. The distance to the nearest star, Proxima Centauri, is 6,000 times greater; hence, we have no hope of seeing spacecraft reach such targets in the foreseeable future. In view of this, the solar system is our cosmic neighborhood, accessible for study by spacecraft and constituting the setting within which Earth has evolved through time.

Here the solar system is summarized in tutorial form to provide a context for what follows. The information presented is the result of at least three millennia of observations and insights, capped by three decades of intense scientific study from the ground and space. Some of this effort is described in the book, but to present a complete history of the exploration of the solar system would require a separate volume.

Figure 1.2 is a map of the solar system. The eight planets fall roughly into three classes according to their size and composition. The four *terrestrial* planets Mercury, Venus, Earth, and Mars range in diameter from 4,800 km (Mercury) to 12,700 km (Earth). They occupy a small, inner region of the solar system, and are composed of a mixture of rocky and metallic materials.

The four *giant* or *Jovian* planets Jupiter, Saturn, Uranus, and Neptune are substantially bigger than Earth, ranging in diameter from 49,000 km (Neptune) to 142,000 km (Jupiter). They are much farther from the Sun than are the inner planets: Jupiter's distance from the Sun is five times that of Earth's and hence is abbreviated as 5 *astronomical units* (AU); Neptune is 30 AU from the Sun. In terms of common units of distance, Earth lies 150 million km from the Sun, and thus Neptune is more than 4 billion km from the solar system's center.

The giant planets are composed of a mixture of rocky and icy material and varying amounts of gases; Jupiter and Saturn are mostly hydrogen and helium gas whereas Uranus and Neptune are predominantly icy and rocky material with lesser amounts of hydrogen and helium gas. (Rocky and icy material is used here to mean atoms of silicon, magnesium, iron, oxygen, carbon, nitrogen, sulfur, and others that tend to form rocky and icy materials under conditions of normal pressure. Because of the

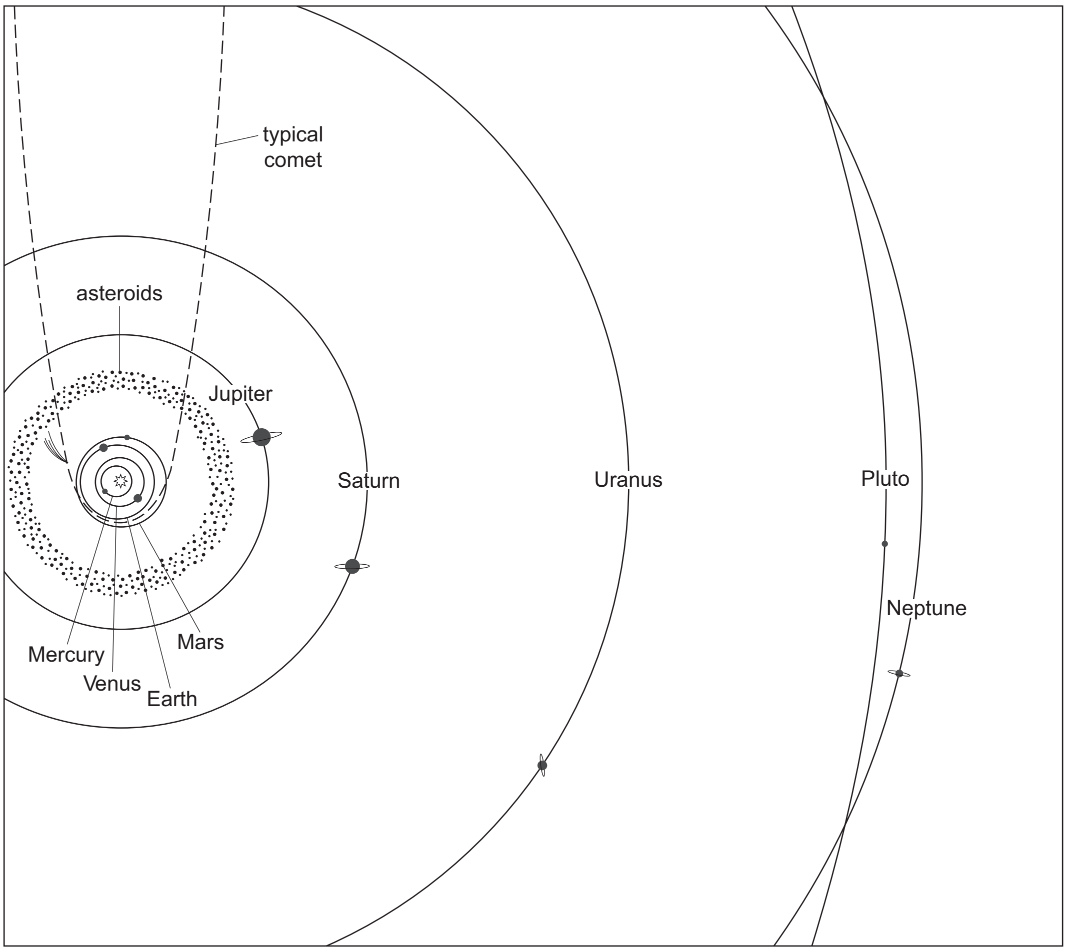

Figure 1.2 Schematic map of our solar system, showing the correct relative sizes of orbits but not of the bodies themselves. Note the small scale of the orbits of terrestrial planets compared to the vast realm of the outer planets. Not shown are the Kuiper Belt beginning just beyond Neptune's orbit and the Oort cloud of comets much further out.

intense pressures deep within these giant planets, much of the icy and rocky material is in atomic form, rather than the molecular form with which we are familiar.)

Six of the planets have moons, as do Pluto and some asteroids. Some moons are small, irregular fragments kilometers across; others – two moons of Jupiter, one of Saturn – are larger than the planet Mercury. The giant planets have multiple satellite systems, some in very regular, circular orbits, which can be considered as miniature solar systems. A class of giant moons, with sizes from that of the Earth's moon upward, include the four Galilean satellites of Jupiter and Saturn's moon Titan. Titan possesses an atmosphere thicker than ours on Earth and sports river channels and lakes and seas filled or once filled with methane and ethane; several other moons have tenuous atmospheres, including our own Moon, which exhibits an extremely rarefied atmosphere of sodium and potassium. All of the planets have atmospheres, though that of Mercury is like our Moon's in being very tenuous.

The four giant planets have ring systems composed of debris from house-sized to dust, which orbits in the equatorial plane of the planet. Saturn's famous ring system is considerably more massive than those of the other major planets. None of the terrestrial planets possesses an organized ring system.

Beyond Neptune lies a part of the solar system poorly explored but, paradoxically, the easiest to see from neighboring stars because of the extensive amount of debris there. The two largest bodies in this region are Pluto and Eris, each about 2,500 km in diameter, and smaller than four of the solar system's moons (Earth's Moon, Jupiter's Ganymede, Callisto, and Saturn's Titan). But they are the largest of a class of debris left over from the formation of the solar system. When Pluto was discovered in 1930 by the American astronomer Clyde Tombaugh, other bodies of such size beyond Neptune were not known, and hence Pluto was classified as a planet. Today we know that Pluto is a part of the "trans-Neptunian region," or "Kuiper Belt," in which hundreds of other bodies have been individually identified and their orbits mapped. The inner edge of this thick belt of material is defined by the giant planets, whose strong gravitational fields have swept the region from 5 to 30 AU clear of debris and cleaned out lanes within the Kuiper Belt itself. Eris, discovered in 2003, is a bit more massive and larger in size than Pluto. In both size and density (amount of mass per volume in the object), Pluto and Eris are remarkably similar to Triton, the largest moon of Neptune, suggesting this latter to have once been a Kuiper Belt object and further hinting at some sort of natural upper limit to the growth of these bodies.

Well beyond the region of Neptune and the Kuiper Belt lies more icy and rocky material in distant orbits ranging out to perhaps 100,000 AU from the Sun. The presence of such material is inferred from the existence of comets, rock-ice bodies perhaps 1 to 10 km in diameter that come into the inner solar system on highly noncircular, that is, elliptical, orbits. Careful plotting of the paths of comets indicates that most of the orbits originate in an ill-defined shell of material termed the *Oort Cloud*. The comets are the small fraction of Oort Cloud objects that fall inward to the Sun after having been perturbed by close-passing stars. The total number of comet-sized Oort Cloud objects may exceed one trillion.

Remote observation of comets as they pass through the inner solar system suggests that they are accumulations of dust, organic material, water ice, and frozen gases. The Oort Cloud material is thought to have been ejected from the 5- to 30-AU region by the giant planets after their formation and, in addition to comet-sized bodies, both larger and smaller objects may reside in this cloud.

Between the orbits of Mars and Jupiter lie belts of rocky objects known as asteroids. The largest asteroids are several hundred kilometers across; in number and total mass they are minuscule compared to the Oort Cloud and the Kuiper Belt. They are thought to be debris that never formed into a planet because of the proximity of Jupiter, whose gravitational field prevented efficient growth of a large body from smaller ones. Another collection of asteroids crosses the orbit of Earth – the so-called *near-Earth asteroids*, some of which may be old comets that have lost their mantles of ice after many passes by the Sun. Finally, lanes and regions of dust released from comets or asteroids lace the solar system; the precise distribution of this material, some of which can be seen faintly after sunset as the *zodiacal light*, remains somewhat uncertain.

The history of collisions between the numerous bits of small debris and the planets is recorded by the ubiquitous existence of craters throughout the solar system. Even Earth shows the scars, Meteor Crater in Arizona being a famous recent example. As we shall see, impacts may have played key roles in the origin and evolution of life on this planet Earth.

The solar system exhibits several regularities in its structure, which are important in understanding its origin, as we discuss later. All planets orbit the Sun in nearly circular orbits, close to the plane of the Sun's equator. The orbits of Pluto and Eris are more typical of the Kuiper Belt, being *inclined* (tilted relative to the Sun's equator) and *eccentric* (significantly noncircular). All orbits are in the same direction; by convention, they are counterclockwise around the Sun when viewed from above the Sun's *northern hemisphere*. With two exceptions, Venus and Uranus, all planetary spins are in the same, counterclockwise, direction. However, the planetary rotational axes are all tilted relative to their orbital planes by varying degrees.

There is a strong correlation between the properties of the planets and their location in the solar system. The four terrestrial planets, which contain proportionately little water and gases, are closest to the Sun and not very massive compared to the giant planets. From Jupiter outward, solid objects (moons and Pluto) contain significant amounts of water ice and more volatile species. (Here, volatile refers to the tendency for a material to transform from a condensed state to a vapor.) The four giant planets seem to be of two classes, with the more gaseous planets, Jupiter and Saturn, closer to the Sun. These regularities provide clues to the origin of the solar system, but most other planetary systems known to exist around other stars do not exhibit such strict regularities as we discuss in Chapter 10.

Summary

Astronomy arose from the practical and the curious: from the need to keep track of time for planting to the questions of where we came from and whether we are alone in the cosmos. The classical Greeks of 2,500 years ago applied geometry and rigorous thinking to the question of the size of the Earth and distances to the Sun and to the stars. Our cosmic backyard is the solar system, which consists of planets, moons, and numerous smaller bodies all in orbit around a rather commonplace star we call the Sun. Evidence that the planets formed from accumulation of smaller material comes from the record of craters – holes formed in the surfaces of the solid planets and moons by high speed impacts. The planets of our solar system seem to be well ordered, with rocky planets orbiting close to the Sun and gas giants with icy moons further out, a situation that may not necessarily be the norm for planetary systems around other stars.

Questions

1. Consider how you have responded to a controversial scientific or technological issue. Did you try to weigh rationally the pros and cons, or did you respond on the basis of your instincts or emotions? In your own experience, which approach – the rational or the emotional – has produced the most satisfactory result in resolving conflicts?
2. Imagine that the knowledge leading to atomic energy had never been achieved. What are some of the things that might have been different about the period from World War II to today? Can you say whether the world would have been better or worse off?
3. Imagine an intelligent species evolved on a planet habitable like the Earth, but with a perpetually opaque atmosphere so that the stars could not be seen. How might they regard themselves and the nature of their world as a planet in such circumstances? Could they infer the presence of other stars, planets, and moons? Would there be any impetus to develop the ability to travel into space? Likewise, how would a species with the intelligence of humankind but restricted to the deep oceans define its "cosmos"?
4. A smaller and smaller fraction of the human species can see a star-filled sky at night, thanks to the increased amount of nighttime illumination used in cities. At the same time, an increased fraction of humankind has access to detailed images of the cosmos from large telescopes in space and on the ground. How do you think this shift in the nature of astronomical information will alter popular thinking about the cosmos in the next few decades? In the next few centuries?

General reading

Boorstein, D. J. 1983. *The Discoverers*. Vintage Books, New York.
Sagan, C. 1996. *The Demon-Haunted World: Science as a Candle in the Dark*. Ballantine Books, New York.

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Snow, T. P. 1991. *The Dynamic Universe: An Introduction to Astronomy*, 4th edn. West Publishing, St. Paul, MN.

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Largest and smallest scales

Introduction

In Chapter 1, we became acquainted with the scale of the solar system – the stage upon which planetary evolution is set. However, the formation of elements out of which planets and life came into being involved the universe of stars and galaxies – a scale much larger than the solar system – and the microscopic world of atoms, which involves size scales much smaller than that of our ordinary experiences. In this chapter we explore how cosmic distances are gauged, and then begin to acquaint ourselves with the basic building blocks of matter.

2.1 Scientific notation

Although the book is written with the nonmathematically inclined reader in mind, the discussion of numbers, both large and small, cannot be avoided if we are to gain a true understanding of Earth and its place in the cosmos. Numbers of interest in science range over enormous magnitudes (Figure 2.1). The number of protons contained in a single star, our Sun, is of order 1,000,000,000,000,000,000,000, 000,000,000,000,000,000,000,000,000, 000,000,000; the size of an individual proton (itself made up of smaller elementary units) is of order 0.0000000000001 cm. (The term *of order* refers to how many powers of 10 a number contains, rather than the specific numerical value it has; hence 200 is of order 100, 40 is of order 10, etc.) These numbers are inconvenient to write down and manipulate in even the simplest mathematical expressions.

Hence *scientific notation* is universally used, where a number is expressed in terms of powers of 10. The number of protons in the Sun is of order 10^{57}; the size of a proton is of order 10^{-13} cm. To express the numerical value, in addition to the order of magnitude, one simply multiplies by the appropriate number. Hence, 5,000 is 5×10^3 and 0.004 is 4×10^{-3}. Any degree of precision can be handled readily; for example, 65,490 is 6.549×10^4 and 0.034256 is 3.4256×10^{-2}. Multiplication and division of such numbers is easy, the exponents in the power of 10 being added or subtracted, respectively, for the two operations.

The one drawback of scientific notation is that it dulls us to the enormous range of numbers that the scale of the universe demands. Somehow, writing 1.67×10^{-27} kilograms (the mass of a hydrogen atom) does not give us the same appreciation for the smallness of this number that writing 0.00000000000000000000000000167 gives. (For US readers, one kilogram is roughly two and a quarter pounds.) In contemplating the history of planet Earth and its place in the cosmos, it is too easy to manipulate such numbers without first considering the philosophical implications of their gigantic or minuscule quality!

2.2 Motions of Earth in the cosmos

We view a universe continually in motion. The most obvious movements, apparent to even the casual observer, are the paths of the Sun across the sky on a daily basis and the rising and setting of the Moon on a subjectively slightly less reliable rhythm. The equivalent nocturnal rhythm of the rising and setting of the constellations also is easily discernible, though much less familiar to increasingly urban populations.

Those who are more careful watchers of the sky will notice two longer rhythms, the march of a changing Moon progressively through the day and night skies on a 28- to 29-day basis, and the annual ritual of the slow climb of the Sun toward a more northerly path in the sky during summer and toward a more southerly path during winter (readers in the southern hemisphere should reverse north and south in the description). At any given location the Moon occasionally wanders into a region of darkness, and reddens in what is called a lunar eclipse. The Sun's light is partially blocked once every few years from a given location, and totally blocked much more rarely at any given place, in a solar eclipse.

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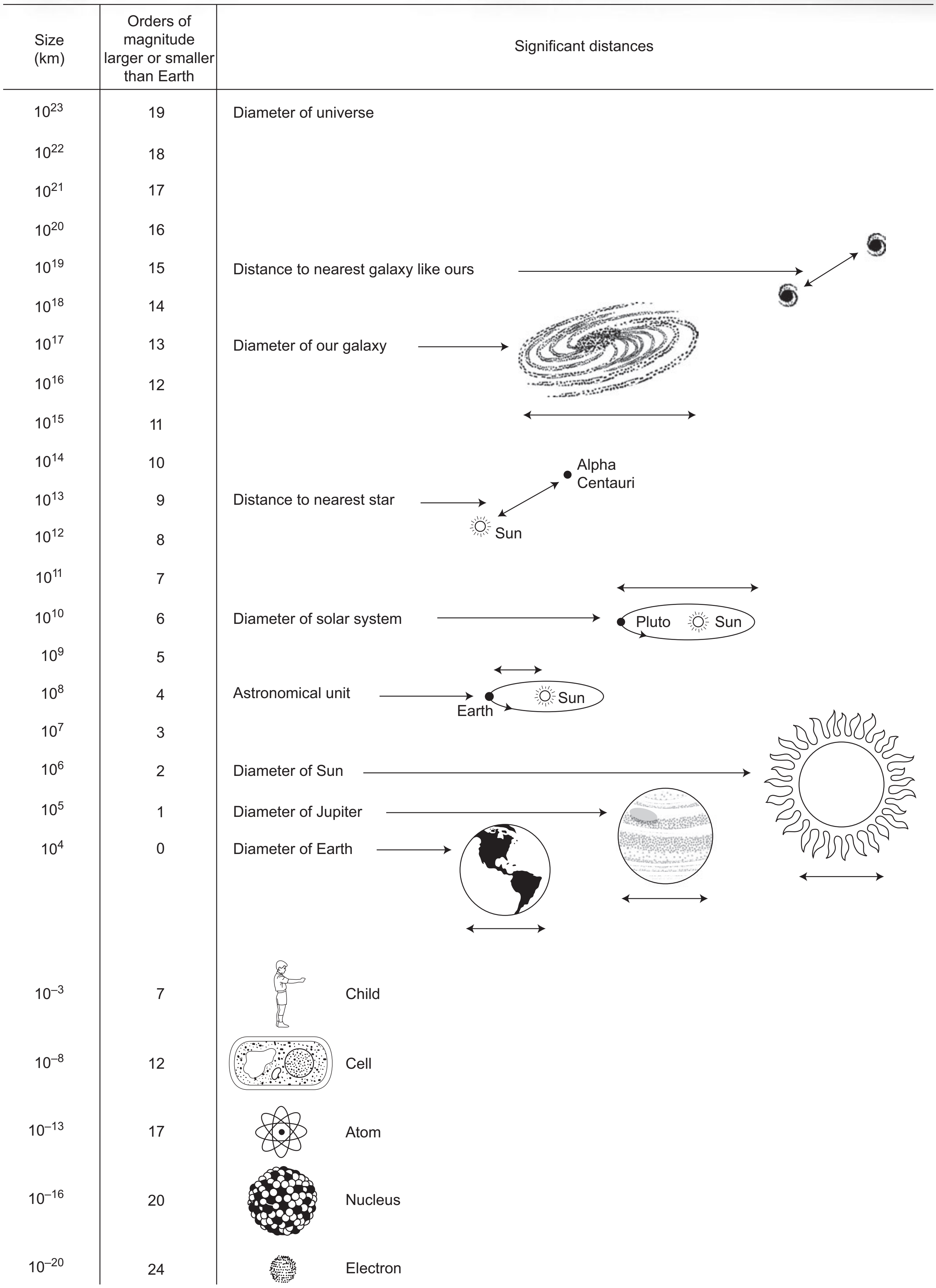

Figure 2.1 Sizes of various objects over the enormous range that the natural world encompasses. From Robbins and Jeffreys (1988) by permission of John Wiley and Sons.

