1. Introduction

Astronomy, the study of the stars and other celestial objects, is one of the exact sciences. It deals with the quantitative investigation of the cosmos and the physical laws which govern it: with the motions, the structures, the formation, and the evolution of the various celestial bodies.

Astronomy is among the oldest of the sciences. The earliest human cultures made use of their knowledge of celestial phenomena and collected astronomical data in order to establish a calendar, measure time, and as an aid to navigation. This early astronomy was often closely interwoven with magical, mythological, religious, and philosophical ideas.

The study of the cosmos in the modern sense, however, dates back only to the ancient Greeks: the determination of distances on the Earth and of positions of the celestial bodies in the sky, together with knowledge of geometry, led to the first realistic estimates of the sizes and distances of the objects in outer space. The complex orbits of the Sun, the Moon, and the planets were described in a mathematical, kinematical picture, which allowed the calculation of the positions of the planets in advance. Greek astronomy attained its zenith, and experienced its swan song, in the impressive work of Ptolemy, about 150 a.D. The name of the science, *astronomy*, is quite appropriately derived from the Greek word "$\alpha\sigma\tau\eta\rho$" = star or "$\alpha\sigma\tau\rho o\nu$" = constellation or heavenly body.

At the beginning of the modern period, in the 16th and 17th centuries, the Copernican view of the universe became generally accepted. Celestial mechanics received its foundation in Newton's Theory of Gravitation in the 17th century and was completed mathematically in the period immediately following. Major progress in astronomical research was made in this period, on the one hand through the introduction of new concepts and theoretical approaches, and on the other through observations of new celestial phenomena. The latter were made possible by the development of new instruments. The invention of the telescope at the beginning of the 17th century led to a nearly unimaginable increase in the scope of astronomical knowledge. Later, new eras in astronomical research were opened up by the development of photography, of the spectrograph, the radio telescope, and of space travel, allowing observations to be made over the entire range of the electromagnetic spectrum.

In the 19th and particularly in the 20th centuries, physics assumed the decisive role in the elucidation of astronomical phenomena; astrophysics has steadily increased in importance over "classical astronomy". There is an extremely fruitful interaction between astrophysics/astronomy and physics: on the one hand, astronomy can be considered to be the physics of the cosmos, and there is hardly a discipline in physics which does not find application in modern astronomy; on the other hand, the cosmos with its often extreme states of matter offers the opportunity to study physical processes under conditions which are unattainable in the laboratory. Along with physics, and of course mathematics, applications of chemistry and the Earth and biological sciences are also of importance in astronomy.

Among the sciences, astronomy is unique in that no experiments can be carried out on the distant celestial objects; astronomers must content themselves with *observations*. "Diagnosis from a distance", and in particular the quantitative analysis of radiation from the cosmos over the widest possible spectral range, thus play a central role in astronomical research.

The rapid development of many branches of astronomy has continued up to the present time. With this revised edition of *The New Cosmos*, we have tried to keep pace with the rapid expansion of astronomical knowledge while maintaining our goal of providing a comprehensive – and comprehensible – introductory survey of the *whole* field of astronomy. We have placed emphasis on observations of the manifold objects and phenomena in the cosmos, as well as on the basic ideas which provide the foundation for the various fields within the discipline. We have combined description of the observations as directly as possible with the theoretical approaches to their elucidation. Particular results, as well as information from physics and the other natural sciences which are required for the understanding of astronomical phenomena, are, however, often simply stated without detailed explanations. The complete bibliography, together with a list of important reference works, journals, etc., is intended to help the reader to gain access to the more detailed and specialized literature.

We begin our study of the cosmos, its structure and its laws, "at home" by considering our *Solar System* in Part I, along with *classical astronomy*. This part, like the three following parts, starts with a historical summary which is intended to give the reader an overview of the subject. We first become acquainted with observations of the heavens and with the motions of the Earth, the Sun, and the Moon, and introduce celestial coordinates and sidereal time. The apparent motions of the planets and other objects are then explained in the framework of the Newtonian Theory of Gravitation. Before considering the planets and other objects in the Solar System in detail, we give a summary of the development of space research, which has contributed enormously to knowledge of our planetary system. Part I ends with a discussion of the individual planets, their moons, and other smaller bodies such as asteroids, comets and meteors.

Prior to taking up the topic of the Sun and other stars, it is appropriate to describe the basic principles of astronomical *observation methods*, and we do this in Part II. An impressive arsenal of telescopes and detectors is available to today's astronomer; with them, from the Earth or from space vehicles, he or she can investigate the radiation emitted by celestial bodies over the entire range of the electromagnetic spectrum, from the radio and microwave regions through the infrared, the visible, and the ultraviolet to the realm of highly energetic radiations, the X-rays and gamma rays. The use of computers provides an essential tool for the modern astronomer in these observations.

Part III is devoted to *stars*, which we first treat as individual objects. We give an overview of the different types of stars such as those of the main sequence, giants and supergiants, brown dwarfs, white dwarfs and neutron stars, as well as the great variety of variable stars (Cepheids, magnetic stars, novas, supernovas, pulsars, gamma sources ...) and of stellar activity, and become acquainted with their distances, magnitudes, colors, temperatures, luminosities, and masses. In this part, the *Sun* plays a particularly important role: on the one hand, as the nearest star, it offers us the possibility of making incomparably more detailed observations than of any other star; on the other, its properties are those of an "average" star, and their study thus yields important information about the physical state of stars in general. The treatment of the *physics of individual stars* occupies an important place in Part III. Along with the theory of radiation, atomic spectroscopy in particular forms the basis for quantitative investigation of the radiation and the spectra of the Sun and other stars, and for the understanding of the physical-chemical structure of their outer layers, the stellar atmospheres. Understanding of the mechanism of energy release by thermonuclear reactions and by gravitation is of decisive importance for the study of stellar interiors, their structures and evolution.

We then discuss the development of the stars of the main sequence, which includes the phase of intensive stellar hydrogen burning, continuing to their final stages (white dwarf, neutron star or black hole). The formation of stars and their earliest development are treated in the following sections in connection with the interstellar material in our galaxy. At the end of Part III, we deal with strong gravitational fields, which we describe in the framework of Einstein's General Relativity theory; here, we concentrate in particular on black holes, gravitational lenses, and gravitational waves.

In Part IV, we take up *stellar systems* and the macroscopic structure of the universe. Making use of our knowledge of individual stars and their distances from the Earth, we first develop a picture of stellar clusters and stellar associations. We then discuss the interstellar matter which consists of tenuous gas and dust clouds, and treat star formation. Finally, we develop a picture of our own Milky Way galaxy, to which the Sun belongs together with about 100 million other stars. We treat the distribution and the motions of the stars and star clusters and of the interstellar matter. After making the acquaintance of methods for the determination of the enormous distances in intergalactic space, we turn to other galaxies, among which we find a variety of types: spiral and elliptical galaxies, infrared and starburst galaxies, radio galaxies, and the distant quasars. In the centers of many galaxies, we observe an "activity" involving the appearance of extremely large amounts of energy, whose origins are still a mystery.

Galaxies, as a rule, belong to larger systems, called galactic clusters. These are in turn ordered in clusters of galactic clusters, the superclusters, which finally form a "lattice" enclosing large areas of empty intergalactic space and defining the macroscopic structure of the Universe. Like individual stars, the galaxies and galactic clusters evolve with the passage of time. The mutual gravitational influence of the galaxies plays an important role in their development.

At the conclusion of Part IV, we consider the *Universe as a whole*, its content of matter, radiation, and energy, and its structure and evolution throughout the expansion which has taken place over the roughly $2 \cdot 10^9$ years from the "big bang" to the present time.

Finally, after pressing out to the far reaches of the cosmos, we return at the end of Part IV to our Solar System and take up the problems of the *formation and evolution of the Sun and the planets* as well as the existence of planetary systems around other stars. In this section, we give particular attention to the development of the Earth and of life on Earth.

I. Classical Astronomy and the Solar System

Humanity and the Stars: Observing and Thinking
Historical Introduction to Classical Astronomy

Unaffected by the evolution and the activities of mankind, the objects in the heavens have moved along their paths for millenia. The starry skies have thus always been a symbol of the "Other" – of Nature, of deities – the antithesis of the "Self" with its world of inner experience, striving and activity. The history of astronomy is at the same time one of the most exciting chapters in the history of human thought. Again and again, there has been an interplay between the appearance of new *concepts and ways of thinking* on the one hand and the discovery of new *phenomena* on the other, the latter often with the aid of newly-developed *observational instruments*.

We cannot treat here the great achievements of the ancient Middle Eastern peoples, the Sumerians, Babylonians, Assyrians, and the Egyptians; nor do we have the space to describe the astronomy of the the Far Eastern cultures in China, Japan, and India, which was highly developed by the standards of the time.

The concept of the *Universe* and its investigation in the modern sense dates back to the ancient Greeks, who were the first to dare to shake off the fetters of black magic and mythology and, aided by their enormously flexible language, to adopt forms of thinking which allowed them, bit by bit, to "comprehend" the phenomena of the cosmos.

How bold were the ideas of the pre-Socratic Greeks! Thales of Milet, about 600 B.C., had already clearly understood that the Earth is round, and that the Moon is illuminated by the Sun, and he predicted the Solar eclipse of the year 585 B.C. But is it not just as important that he attempted to reduce understanding of the entire universe to a *single* principle, that of "water"?

The little that we know of Pythagoras (in the middle of the 6th century B.C.) and of his school seems surprisingly modern. The spherical shapes of the Earth, the Sun, and the Moon, the Earth's rotation, and the revolution of at least the inner planets, Venus and Mercury, were already known to the Pythagorans.

After the collapse of the Greek states, *Alexandria* became the center of ancient science; there, the quantitative investigation of the heavens made rapid progress with the aid of systematic measurements. The numerical results are less important for us today than the happy realization that the great Greek astronomers made the bold leap of applying the laws of *geo*metry to the cosmos! Aristarchus of Samos, who lived in the first half of the 3rd century B.C., attempted to compare the *distances* of the Earth to the Sun and the Earth to the Moon with the *diameters* of the three bodies by making the assumption that when the Moon is in its first and third quarter, the triangle Sun-Moon-Earth makes a right angle at the Moon. In addition to carrying out these first quantitative estimates of dimensions *in* space, Aristarchus was the first to teach the *heliocentric system* and to recognize its important consequence that the distances to the fixed stars must be incomparably greater than that from the Earth to the Sun. How far he was ahead of his time with these discoveries can be seen from the fact that by the following generation, they had already been forgotten. Soon after Aristarchus' important achievements, Eratosthenes carried out the first measurement of a degree of arc on the Earth's surface, between Alexandria and Syene: he compared the difference in latitude between the two places with their distance along a much-traveled caravan route, and thereby determined the circumference and diameter of the Earth fairly precisely. However, the greatest observer of ancient times was Hipparchus (about 150 B.C.), whose *stellar catalog* was still nearly unsurpassed in accuracy in the 16th century A.D. Even though the means at his disposal naturally did not allow him to make significantly better determinations of the basic dimensions of the Solar System, he was able to make the important discovery of *precession*, i.e. the yearly shift of the equinoxes and thus the difference between the tropical and the sidereal years.

The theory of *planetary motion*, which we shall treat next, was necessarily limited in Greek astronomy to a problem in *geometry* and *kinematics*. Gradual improvements and extensions of observations on the one hand, and new mathematical approaches on the other, formed the basis for the attempts of Philolaus, Eudoxus, Heracleides, Appollonius, and others to describe the observed motions of the planets; their attempts employed the superposition of ever more complicated circular motions. Ancient astronomy and planetary theory attained its final development much later, in the work of Claudius Ptolemy, who wrote his 13-volume Handbook of Astronomy (Mathematics), *Μαθηματιχης Συνταξεως*, in Alexandria about 150 B.C. His "Syntax" later acquired the adjective *μεγιστη*, "greatest", from which the arabic title *Almagest* is derived. The Almagest is based to a large extent on the observations and research of Hipparchus, but Ptolemy also added much new material, particularly in the theory of planetary motion. At this point, we need only sketch the outlines of Ptolemy's geocentric system: the Earth rests at the midpoint of the Universe. The motions of the Sun and the Moon in the sky may be represented fairly simply by circular orbits. The planetary motions are described by Ptolemy using the *theory of epicycles*: each planet moves on a circle, the so-called epicycle, whose nonmaterial center moves around the Earth on a second circle, the deferent. We shall not delve further into the refinements of this system involving additional, in some cases eccentric circular orbits, etc. The intellectual posture of the Almagest clearly shows the influence of Aristotelian philosophy, or rather of *Aristotelianism*. Its modes of thought, originally the tools of vital research, had long since hardened into the dogmas of a rigid school; this was the principal reason for the remarkable historical durability of the Ptolemaic world-system.

We cannot go into detail here about how, following the decline of the academy in Alexandria, first the Nestorian Christians in Syria and later the Arabs in Bhagdad took over and continued the work of Ptolemy.

Translations and commentaries on the Almagest were the basic sources of the first Western textbook on astronomy, the *Tractatus de Sphaera* of Ioannes de Sacrobosco, a native of England who taught at the University of Paris until his death in the year 1256. The *Sphaera* was issued again and again and often commentated; it was still "the" text for teaching astronomy in Galileo's time, three centuries later.

The intellectual basis of the new thinking was provided in part by the conquest of Constantinople by the Turks in 1453: thereafter, numerous scientific works from antiquity were made accessible to the West by Byzantine scholars. For example, some very fragmentary texts concerning the heliocentric system of the ancients clearly made a strong impression on Copernicus. The result was a turning-away from the rigid doctrine of the Aristotelians in favor of the much more lively and flexible thinking of the schools of Pythagoras and Plato. The "Platonic" idea that the process of understanding the Universe consists of a progressive adaptation of our inner world of concepts and ways of thinking to the more and more precisely-studied outer world of phenomena has become the hallmark of modern research from Cusanus through Kepler to Niels Bohr. Finally, with the blossoming of a practical approach to life exemplified by the rise of crafts and trades, the question was no longer "What did Aristotle say?", but rather "How can you do this . . . ?".

In the 15th century, a completely new spirit in science and in life arose, at first in Italy and soon thereafter in the North as well. The sententious meditations of Cardinal Nicholas Cusanus (1401–1464) have only today begun to be properly appreciated. It is fascinating to see how his ideas about the infinity of the Universe and about quantitative scientific research arose from religious or theological considerations. Near the end of the century (1492), the discovery of America by Christopher Columbus added the classic expression "il mondo e poco" to the new spirit. A few years later, Nicolas Copernicus (1473–1543) founded the *heliocentric system*.

About 1510, Copernicus sent a letter to several noted astronomers of his time; it was rediscovered only in 1877, and was entitled "De Hypothesibus Motuum Caelestium A Se Constitutis Commentariolus". It foreshadowed the major part of the results which were later published in his major work, "De Revolutionibus Orbium Coelestium", which appeared in Nuremberg in 1543, the year of his death.

Copernicus held fast to the idea of the "perfection of circular motion" which had formed the basis for astronomical thought throughout antiquity and the Middle Ages; he never considered the possibility of another form of motion.

It was Johannes Kepler (1571–1630) who, starting from the phythagorian-platonic traditions, was able to break through to a more general point of view. Making use of the observations of Tycho Brahe (1546–1601), which were vastly more precise than any that had preceded them, he discovered his three *Laws of Planetary Motion*. Kepler derived his first two laws from an enormously tedious trigonometric calculation of the motions of Mars reported by Tycho in his "Astronomia Nova" (Prague, 1609). The third law is reported in his "Harmonices Mundi" (1619). We can only briefly mention Kepler's ground-breaking works on optics, his Keplerian telescope, his Rudolphinian Tables (1627), and numerous other achievements.

About the same time, the Italian Galileo Galilei (1564–1642) directed the *telescope* which he had built in 1609 to the heavens and discovered, in rapid succession: the "maria", the craters, and other mountain formations on the Moon; the numerous stars of the Pleides and the Hyads; the four largest moons of Jupiter and their free orbits around the planet; the first indication of the rings of Saturn; and sunspots. His "Galileis Sidereus Nuncius" (1610), in which he describes the discoveries with his telescope, the "Dialogo Delli Due Massimi Sistemi Del Mondo, Tolemaico, e Copernico" (1632), and the "Discorsi e Dimonstrazioni Matematiche Intorno a Due Nuove Scienze" (1638), which was written after his condemnation by the Inquisition and contained the beginnings of theoretical mechanics, are masterworks not only in the scientific sense but also as works of art. The observations with the telescope, Tycho Brahe's observation of the supernova of 1572 and that of 1604 by Kepler and Galileo, and finally the appearance of several comets required what was perhaps the most essential scientific insight of the time: that, in contrast to the opinion of the Aristotelians, there is *no fundamental difference* between cosmic and earthly matter and that *the same natural laws* hold in the realms of *astronomy* and of *terrestial physics* (this had already been recognized by the ancient Greeks in the case of the laws of geometry). This leap of thought, whose difficulty only becomes clear to us when we look back at Copernicus, gave impetus to the enormous upswing of scientific research at the beginning of the 17th century. W. Gilbert's investigations into electricity and magnetism, Otto v. Guericke's experiments with vacuum pumps and electrification machines, and much more, were stimulated by the revolution in the astronomical worldview.

We have no space here to pay tribute to the many observers and theoreticians who developed the new astronomy, among whom such important thinkers as J. Hevelius, C. Huygens, and E. Halley are particularly prominent.

An entirely new era of natural science began with Isaac Newton (1642–1727). His major work, "Philosophiae Naturalis Principia Mathematica" (1687), begins by placing theoretical mechanics on a firm basis using the *calculus of infinitesimals* ("fluxions"), which he developed for the purpose. Its connection with the *Law of Gravitation* explains Kepler's Laws and in one stroke provides the justification for the whole of terrestrial and *celestial mechanics*. In the area of optics, he invented the reflecting telescope and investigated the interference phenomena known as "Newton's Rings". Almost casually, he developed the basic approaches leading to numerous branches of theoretical physics.

Only the "Princeps Mathematicorum", Carl Friedrich Gauss (1777–1855), is of comparable importance; to him, astronomy owes the theory of *orbit calculation*, important contributions to *celestial mechanics* and advanced geodesics as well as the method of Least Squares. Never again has a mathematician shown such a combination of intuition in the choice of new areas of research and of facility in solving particular problems.

Again, this is not the place to pay tribute to the great theoreticians of celestial mechanics, from L. Euler to J.L. Lagrange and P.-S. Laplace to H. Poincaré; however, to finish this historical overview, we describe briefly the discovery of those planets which were not known in ancient times.

The planet *Uranus* was discovered quite unexpectedly in 1781 by W. Herschel. Kepler had already supposed that there should be a celestial body in the gap between Mars and Jupiter (Fig. 2.15); the first planetoid or asteroid, *Ceres*, was discovered in this region on 1.1.1801 by G. Piazzi, but in mid-February, it was "lost" when it passed near the Sun. By October of the same year, the 24-year-old C.F. Gauss had already calculated its orbit and ephemerides, so that F. Zach could find it again. Following this mathematical achievement, Gauss solved the general problem of determining the orbit of a planet or asteroid based on three complete observations. Today, several thousand asteroids are known, most of them between Mars and Jupiter (Sect. 3.3).

From perturbations of the orbit of Uranus, J.C. Adams and J.J. Leverrier concluded that there must be a planet with a still longer orbital period, and calculated its orbit and ephemerides. J.G. Galle then found *Neptune* near the predicted position in 1846.

Perturbations of the orbits of Uranus and Neptune led to the postulate that there was a transneptunian planet. The long search for it, in which P. Lowell (d. 1916) played a decisive role, was finally crowned with success: C. Tombaugh discovered *Pluto* in 1930 at the Lowell Observatory as a “faint star” of 15th magnitude.

Lengthy search programs for a “planet X” beyond the orbit of Pluto have remained unsuccessful; there are *no* indications for the existence of a further large planet. However, in 1992, D. Jewitt and J. Luu succeeded in discovering a *small* object outside Pluto’s orbit, whose size is comparable with that of many of the asteroids. Soon thereafter, a number of “planets” were observed outside the orbits of Neptune and Pluto.

2. Classical Astronomy

Following the historical overview of classical astronomy from ancient times up through the founding of the heliocentric worldview and the discovery of the basic principles of celestial mechanics, we begin in Sect. 2.1 our treatment of astronomy with a description of the motions of the Sun, the Earth, and the Moon in terms of the coordinates on the celestial sphere and of astronomical determinations of time. In Sect. 2.2, we then give a summary of the motions of the other planets, the comets etc. and of the determination of distances within the Solar System. After a brief treatment of the basic principles of mechanics and gravitational theory (Sect. 2.3), we give some applications to celestial mechanics in Sect. 2.4. Finally, in Sect. 2.5, we treat the orbits of artificial satellites and space probes and summarize the most important space research missions within our Solar System.

2.1 Spatial Coordinates and Time; the Motions of the Sun, the Earth, and the Moon

As a beginning of our study of astronomy, in Sect. 2.1.1 we describe apparent motions on the celestial sphere and the coordinate system used to specify the positions of celestial objects. In Sect. 2.1.2, we treat the motions of the Earth, its rotation and its revolution around the Sun, which are reflected as apparent motions on the celestial sphere. Section 2.1.3 is devoted to the astronomical measurement of time. Following these preparatory topics, we gradually become familiar with the objects in our Solar System, beginning this process in Sect. 2.1.4 with our Moon, its motions and its phases. We then treat lunar and solar eclipses in Sect. 2.1.5.

2.1.1 The Celestial Sphere and Astronomical Coordinate Systems

Since antiquity, human imagination has combined the easily-recognized groups of stars into *constellations* (Fig. 2.1). In the northern sky, the Great Bear (or the Big Dipper) is readily seen. We can find the Pole Star (Polaris) by extending the line joining the two brightest stars of the Big Dipper until it is about five times longer. Continuing about the same distance past Polaris (which is the brightest star in the Little Dipper or Small Bear), we see the "W" of Cassiopeia. Using a sky globe or a star map, we can readily find the other constellations. In his "Uranometria Nova" (1603), J. Bayer named the stars in each constellation α, β, γ ..., as a rule in the order of decreasing brightness. Besides these Greek letters, we also use the numbering system of the "Historia Coelestis Britannica" (1725), compiled by the first Astronomer Royal, J. Flamsteed. The Latin names of the constellations are usually abbreviated to 3 letters (see Appendix A.2).

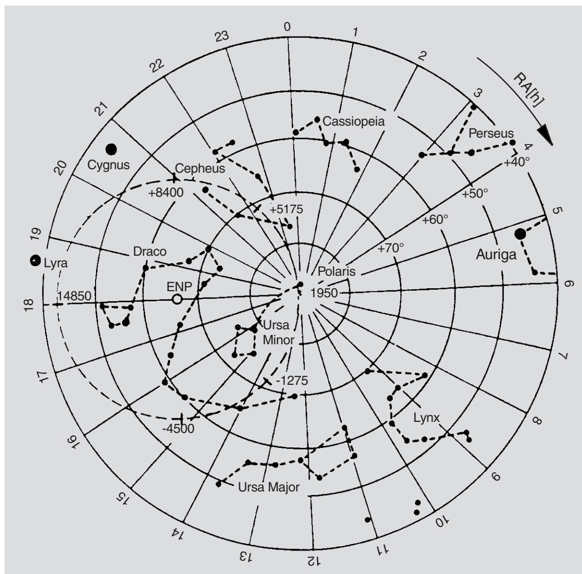

Fig. 2.1. Circumpolar stars from a location having a geographic latitude of $\varphi = +50°$ (about that of Frankfurt or Prague). The coordinate lines indicate the right ascension RA and the declination (+40° to +90°). Precession: the celestial pole circles about the pole of the ecliptic ENP once every 25 700 years. The location of the celestial north pole is indicated for several past and future dates

Celestial Sphere. On the celestial sphere (in mathematical terms, the infinitely distant sphere on which the stars seem to be projected), we in addition define the following quantities (Fig. 2.2):

1. the *horizon* with the directions North, West, South, and East,
2. vertically above our position the *zenith*, directly under us the *nadir*,
3. the curve which passes through the zenith, the nadir, the celestial pole, and the north and south points is the *meridian*, and
4. the curve which is perpendicular to the meridian and the horizon, passing through the zenith and the east and west points, is the *principal vertical*.

In the coordinate system defined by these features, we denote the momentary position of a star by giving two angles (Fig. 2.2): (a) the *azimuth* is measured along the horizon in the direction SWNE, starting sometimes from the S- and sometimes from the N-point; (b) the *altitude* is 90° – the angle to the zenith.

The celestial sphere apears to rotate once each day around the *celestial axis* (which passes through the celestial North and South Poles). The *celestial equator* is perpendicular to this axis. The *position* of a star

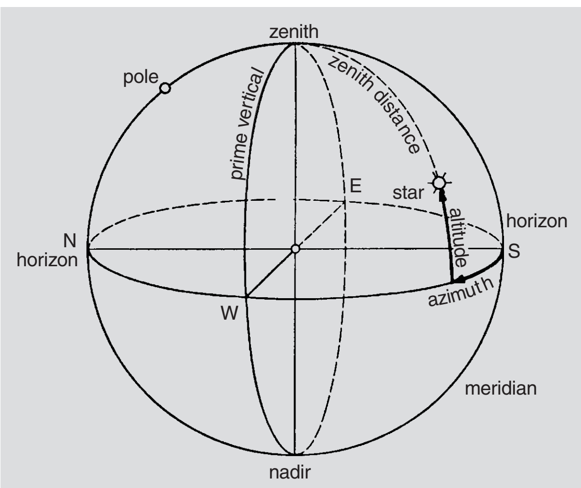

Fig. 2.2. The celestial sphere. The horizon with north, east, south, and west points. The (celestial) meridian passes through the north point, the (celestial) pole, zenith, south point, and the nadir. Coordinates: altitude and azimuth

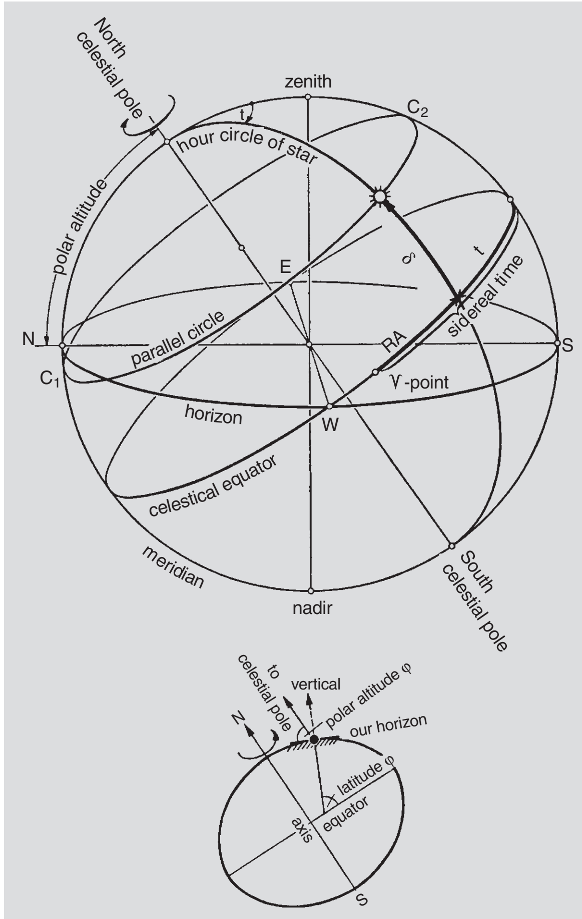

Fig. 2.3. Celestial coordinates: right ascension RA and declination δ. The hour angle $t =$ sidereal time minus the right ascension RA. $C_1 =$ lower culmination, $C_2 =$ upper culmination. *Lower right:* the Earth (polar flattening exaggerated). Polar altitude = geographic latitude

(Fig. 2.3) at a given time on the celestial sphere, imagined to be infinitely distant, is also described by the *declination* δ, which is positive from the equator to the North Pole and negative from the equator to the South Pole, and by the *hour angle* t, which is measured from the meridian in the direction of the diurnal motion, i.e. towards W.

In the course of a day, a star therefore traces out a circle on the sphere; its plane is parallel to the plane of the celestial equator. On the meridian, the greatest height reached by a star is its *upper culmination*, and the least height is its *lower* culmination.

Sidereal Time. We also mark the *Aries Point* ♈ on the celestial equator; we shall deal with it in the following section. It marks the point reached by the sun on the vernal equinox (March 21), on which the day and the night are equally long. The hour angle of the Aries point defines the *sidereal time* τ.

Astronomical Coordinates. We are now in a position to determine the coordinates of a celestial object on the sphere independently of the time of day: we call the arc of the equator from the Aries point to the hour-circle of a star the *right ascension* RA of that star. It is quoted in hours, minutes, and seconds. 24 h (hora) correspond to 360°, or

$$1\,\mathrm{h} = 15°, \qquad 1\,\mathrm{min} = 15', \qquad 1\,\mathrm{s} = 15'',$$
$$1° = 4\,\mathrm{min}\,, \qquad 1' = 4\,\mathrm{s}\,.$$

From Fig. 2.3, one can readily read off the relation:

$$\text{Hour angle } t = \text{sidereal time } \tau - \text{right ascension RA}\,. \qquad (2.1)$$

The declination δ, our second stellar coordinate, has already been defined.

If we now wish to train a telescope on a particular star, planet, etc., we look up its right ascension RA and declination δ in a star catalog, read the time from a sidereal clock, and adjust the setting circles of the instrument to the angle hour t calculated from (2.1) and to the declination (+ north, − south). The especially precisely determined positions of the so-called *fundamental stars* (especially for determinations of the time, see Sect. 2.1.3) are to be found, along with those of the Sun, the Moon, the planets, etc. in the astronomical yearbooks or ephemerides; the most important of these is the Astronomical Almanac.

Astronomical Coordinates. The Copernican system attributes the apparent rotation of the celestial sphere to the fact that the Earth rotates about its axis once every 24 h of sidereal time. The horizon is defined by a plane tangent to the Earth at the location of the observer; more precisely, by an infinite water surface at the observer's altitude. The zenith or vertical is the direction of a plumb-bob perpendicular to this plane, i.e. the direction of the local acceleration of gravity (including the centrifugal acceleration caused by the Earth's rotation). The *polar altitude* (the altitude of the celestial pole above the horizon) is given from Fig. 2.3 by the *geographic latitude* φ (the angle between the vertical and the Earth's equatorial plane); it can be readily measured as the average of the altitudes of the Pole Star or a circumpolar star at the upper and lower culminations.

The *geographic longitude* l corresponds to the hour angle. If the hour angle of the same object is measured *simultaneously* at Greenwich (zero meridian, $l_G = 0°$) and, for example, in New York, the difference gives the geographic longitude of New York, l_G. The determination of the latitude requires only a simple angle measurement, while that of a longitude necessitates a precise time measurement at two places. In earlier times, the "time markers" were taken from the motions of the Moon or of one of the moons of Jupiter. The introduction of the "seaworthy" chronometer by John Harrison (ca. 1760–65) brought a great improvement, as did the later transmission of time signals by telegraph and still later by radio.

A few further facts: at a location having (northern) latitude φ, a star of declination δ reaches an altitude of $h_{\max} = 90° - |\varphi - \delta|$ at its upper culmination and $h_{\min} = -90° + |\varphi + \delta|$ at its lower culmination. Stars with $\delta > 90° - \varphi$ always remain above the horizon (circumpolar stars); those with $\delta < (90° - \varphi)$ never rise above the horizon.

Refraction. In measuring stellar altitudes h, we must take the refraction of light in the Earth's atmosphere into account. The apparent shift of a star (the apparent minus the true altitude) is termed the *refraction*. For average atmospheric tmperature and pressure, the refraction Δh of a star at altitude h is summarized in the following table:

h =	0°	5°	10°	20°	40°	60°	90°
Δh =	34′50″	9′45″	5′16″	2′37″	1′09″	33″	0″ .

The refraction decreases slightly for increasing temperature and for decreasing atmospheric pressure, for example in a low-pressure zone or in the mountains.

2.1.2 The Motions of the Earth. Seasons and the Zodiac

We now consider the *orbital motion* or *revolution* of the Earth around the Sun in the Copernican sense, and then the daily *rotation* of the Earth about its own axis, as well as the motions of the axis itself. We first place ourselves in the position of an observer in space. In Sect. 2.4, we shall derive Newton's theory of the motions of the Earth and the planets starting from his principles of mechanics and law of gravitation.

Ecliptic and Seasons. The apparent annual motion of the Sun in the sky was attributed by Copernicus to the revolution of the Earth around the Sun on a (nearly) circular orbit. The plane of the Earth's orbit intersects the celestial sphere as a great circle called the *ecliptic* (Fig. 2.4). This makes an angle of $23°27'$ with the celestial equator, the *obliquity of the ecliptic*. This means that the Earth's axis retains its direction in space relative to the fixed stars during its annual revolution around the Sun; it forms an angle of $90° - 23°27' = 66°33'$ with the Earth's orbital plane.

A brief summary will suffice to explain the *seasons* (Figs. 2.4, 5), starting with the Northern Hemisphere.

In the Northern Hemisphere, the Sun reaches its maximum altitude (midday altitude) at a geographical latitude φ on the 21st of June (the first day of Summer or Summer solstice), $h = 90° - |23°27' - \varphi|$. On the 22nd of December (Winter solstice), it has its lowest midday altitude, $h = 90° - \varphi - 23°27'$. It can reach the zenith at latitudes up to $\varphi = +23°27'$, the Tropic of Cancer. North of the Arctic Circle, $\varphi \geq 90° - 23°27' = 66°33'$, the Sun remains below the horizon around the Winter solstice; near the Summer solstice, the "midnight Sun" acts as a circumpolar star.

In the Southern Hemisphere, Summer corresponds to Winter in the Northern Hemisphere, the Tropic of Capricorn to the Tropic of Cancer, etc.

The *zodiac* is the term for a band in the sky on each side of the ecliptic. Since ancient times, it has been divided into 12 equal "signs of the zodiac" (Fig. 2.5).

It is often expedient for calculating the motions of the Earth and the planets to use a coordinate system oriented on the ecliptic and its poles. The (ecliptical) longitude is measured along the ecliptic starting from the Aries or ♈ point, like the right ascension in the direction of the annual motion of the Sun. The (ecliptical)

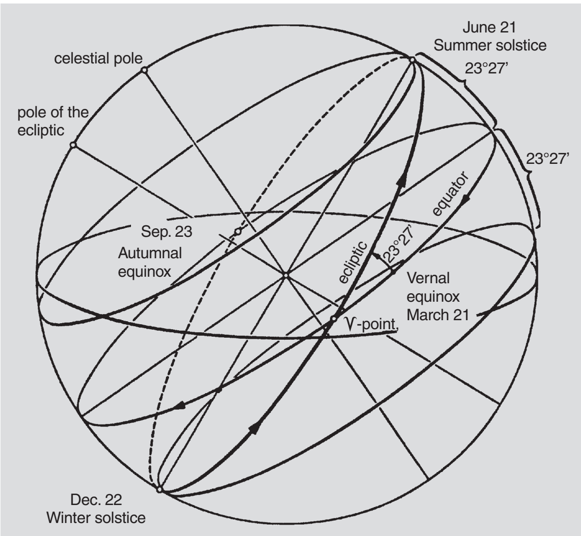

Fig. 2.4. Annual (apparent) motion of the Sun among the stars. The Ecliptic. The seasons

Start date	Name	Coordinates of the Sun		The Sun enters the constellation
		Right ascension RA [h]	Declination δ	
March 21 Spring	Vernal equinox[a]	0	0°	Aries ♈
June 21 Summer	Summer solstice	6	$+23°27'$	Cancer ♋
Sept. 23 Autumn	Autumnal equinox[a]	12	0°	Libra ♎
Dec. 22 Winter	Winter solstice	18	$-23°27'$	Capricorn ♑

[a] On these days, the day and night arcs of the Sun are equal and each correspond to 12 hours.

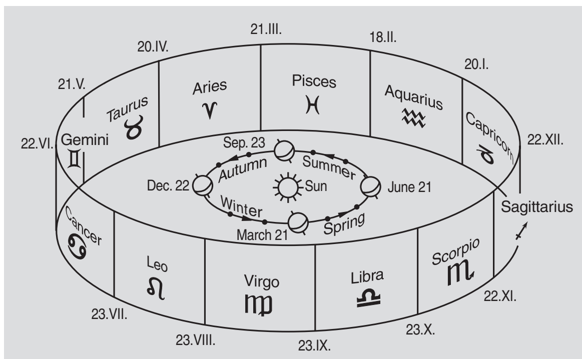

Fig. 2.5. The orbit of the Earth around the Sun. The seasons. The zodiac and the signs of the zodiac. The Earth is at perihelion (closest approach to the Sun) on the 2nd of January, and at aphelion (furthest distance from the Sun) on the 2nd of July