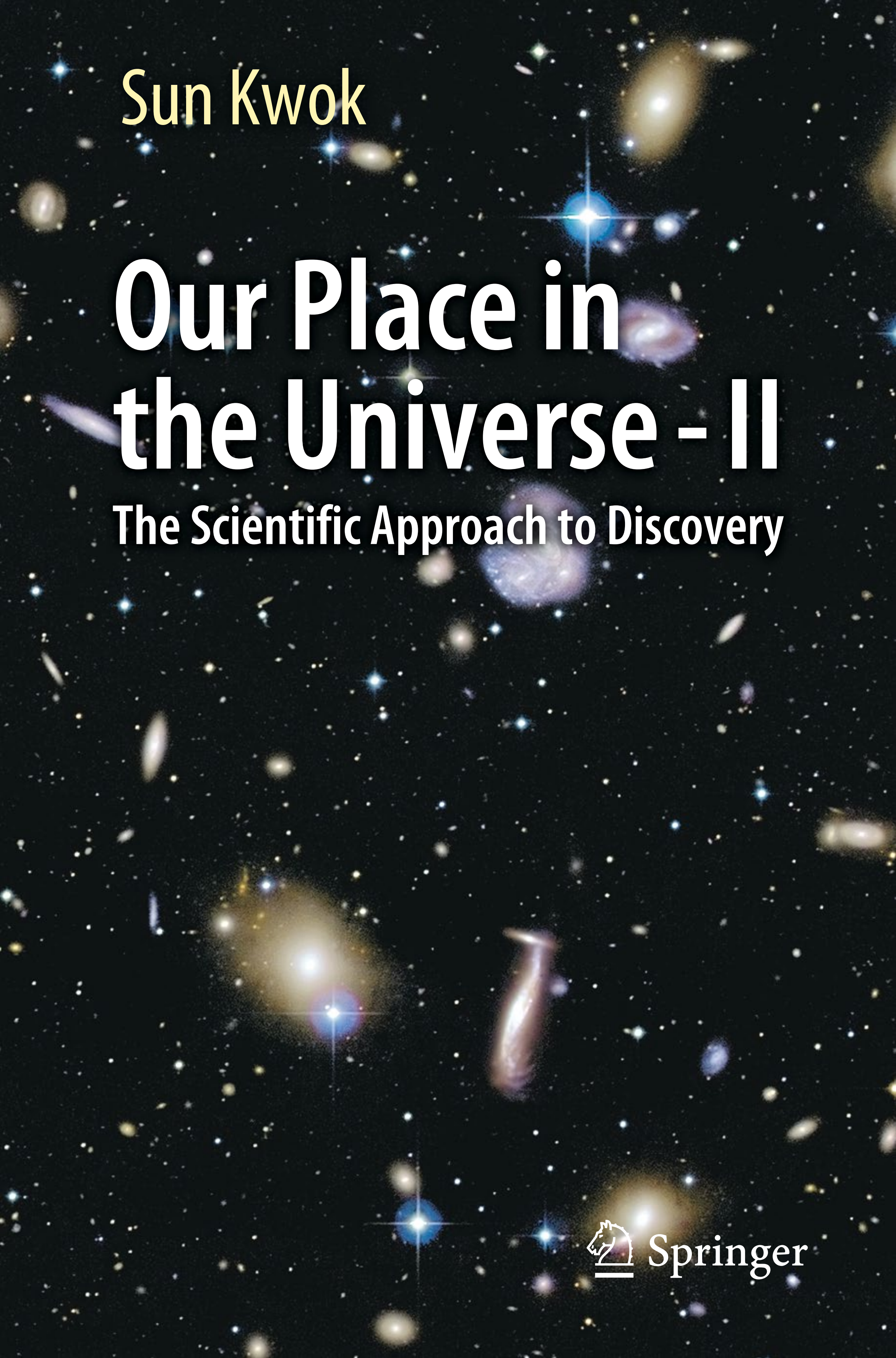

Sun Kwok

Our Place in the Universe - II

The Scientific Approach to Discovery

Springer

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Preface

This is the second volume of the book *Our Place in the Universe*. The first volume *Understanding Fundamental Astronomy from Ancient Discoveries* covers the development of astronomy from ancient times to Newton. The book uses the historical development of astronomy to illustrate the process of rational reasoning and its effect on philosophy, religion, and society. This volume follows this theme and discusses the development of astronomy after Newton, and the parallel evolution of ideas in geology and biology. While the effect of science on technology is well known, the effects of science on how we see ourselves and our world are much less appreciated. The aim of this book is to demonstrate how science motivated intellectual thought and had a major impact on the social development of humans throughout history. Specifically, we use the examples in the development of astronomy to illustrate the process of science, and the effects of evolution in science on our perception of the Universe and on ourselves.

In our educational system, science is often presented to our students as a series of facts. In reality, science is about the process of rational thinking and creativity. What we consider to be the truth is constantly evolving and has certainly changed greatly over the history of humankind. The essence of science is not so much about the current view of our world, but how we changed from one set of views to another. This book is not about the outcome but the process.

As an example, every student knows that the Earth revolves around the Sun. They accept the heliocentric theory as a fact because this was told to them by an authority. However, in my experience, almost no one could cite a single piece of direct evidence for the Earth going around the Sun. As we will see in Chaps. 2 and 3 of this book, direct confirmation of the heliocentric theory is not trivial and only came two hundred years after Copernicus. The fact that this is not emphasized in our teaching of science is indeed worrying. We are asking our students to accept certain facts of science without telling them the tortuous process by which we came to that conclusion. The goal of this book is to show how we know.

Science is often presented as "logical" and the development of science is taught in textbooks as one success after another. The version of scientific development presented is often a sanitized version, where only successes are mentioned. In fact, there have been many (now forgotten) failures and misconceptions that were very popular at the time. When the correct theories came along, they were often resisted, ridiculed, or ignored by the contemporary authorities. If we are unaware of such struggles, we are likely to repeat the same mistakes.

Some may ask: why teach theories that we know to be wrong? The fact is that many of those theories were held up as the truth at the time. Only by tracing the process of discovery can we understand how science works. Students will be able to see current scientific theories in a more critical light and be able to more objectively assess information given to us by the media or authorities today. For scientists, if they are not aware of mistakes made in the past, they may find themselves making similar mistakes in their research now.

This book is based on a course designed for the Common Core Program of the University of Hong Kong (HKU). The HKU Common Core courses are not based on a specific discipline and are designed to help students develop broader perspectives and abilities to critically assess complex issues. I developed this course and taught it from 2010 to 2018. Every year, the class contained about 120 students from all faculties of the university, including architecture, arts, business and economics, dentistry, education, engineering, law, medicine, science, and social sciences. Because of the students' diverse background, no mathematical derivations or calculations were used. The students were, however, expected to understand qualitative concepts, develop geometric visualizations, and perform logical deductions.

At the end of each chapter are some discussion topics that can be used in tutorial sessions or be assigned as essay topics. These questions are designed to motivate students to think beyond the class materials and explore implications of the topics covered. Often these questions have no right or wrong answers and are open-ended to encourage creative thinking.

Jargons are great obstacles to learning. In this book, I try to minimize the use of jargons as much as possible and some technical terms are replaced by simple words with similar meaning. Some concepts have precise definitions, and the use of technical terms is unavoidable. All definitions are presented in the Glossary.

For more technical readers, I have added some optional mathematics and physics in this book, with additional materials presented in the Appendices. Non-mathematical readers can skip these parts. To focus on the evolution of concepts, I have deliberately omitted certain details. Readers who wish a more in-depth understanding of certain topics should consult the respective textbooks.

Every year, students ask me whether they will be handicapped by their lack of previous knowledge of physics and astronomy. In fact, the reverse is true. Students in science are told all the modern notions but usually have often never learned how we arrived at those conclusions. In this book, we try to retrace historical steps to find out how we got to these conclusions.

In addition to lectures, we had weekly tutorials, quizzes, assignments, computer laboratory exercises, a planetarium show, and exams. For the first half of the course, a planetarium show was developed to illustrate the celestial motions observed in different parts of the world and at different times in history. The laboratory exercises were based on computer software, allowing students to have first-hand experience viewing and recording data from simulated observations. The assessments were designed to test whether the students had understood the course materials, could connect material from different parts of the course, had achieved some degree of synthesis, and could apply the acquired knowledge to new situations.

My hope is to help students develop their sense of curiosity and acquire the confidence to ask questions and challenge assumptions. Modern university students should be knowledgeable about our world and aware of how Nature works. From the historical development of science, I hope students will learn to think analytically and quantitatively, keep an open mind, and remain independent from public opinion. They should be able to make rational judgments on the complicated issues facing society today and rise above the ignorance and prejudice that are prevalent in society. These ideas are reflected in my article "Science Education in the 21st Century" published in *Nature Astronomy*, Vol. **2**, p. 530–533 (2018).

For instructors, the two books *Our Place in the Universe: Understanding Fundamental Astronomy from Ancient Discoveries* and *Our Place in the Universe: The Scientific Approach to Discovery* can serve as textbooks for two one-semester general education courses. The first course can be taught independently, but it is advisable that students take the first course before taking the second course.

In the later chapters of this book, I have included some recent research discoveries in astrobiology. I am privileged to have contributed to research in this field during these exciting times. I am also grateful for the opportunity to work with and learn from many contemporary pioneers in this field. I would like to express my sincere appreciation to them, although many of their names are not specifically mentioned in this book.

Over the eight years that I taught the course while serving as Dean of Science, I was ably assisted by lecturers/instructors Tim Wotherspoon, Jason Pun, Anisia Tang, and Sze Leung Cheung. I thank Gray Kochhar-Lindgren, Director of the HKU Common Core Program, for his unyielding support.

Bruce Hrivnak and Anisia Tang provided helpful comments on an earlier draft. I thank Ramon Khanna, my editor at Springer, for encouraging me to publish this book. Clara Wang skillfully drew many of the illustrations in this book.

I first became interested in the subject of the history of science during my second year of undergraduate study at McMaster University, where Prof. Bertram Brockhouse (Nobel Prize in Physics, 1994) introduced me to the subject. His teaching made me realize that physics is more than just mechanical calculations; it is a subject with philosophical and social implications as well.

Vancouver, BC, Canada Sun Kwok

Prologue

天地玄黃, 宇宙洪荒。日月盈昃, 辰宿列張。
寒來暑往, 秋收冬藏。閏餘成歲, 律呂調陽。

千字文 周興嗣

In the beginning, there was the black heaven and the yellow earth. The Universe was vast and without limit. The Sun rises and sets, the Moon goes through phases, and the stars spread over distinct constellations in the sky. The warm and cold seasons come and go, while we harvest in the fall and store our grains for the winter. A year is composed of an uneven number of months, and harmony of music governs the cosmos.

First eight verses from the *Thousand Character Essay* by Zhou Xing Si (470–521 A.D.), translated from Chinese.

Zhou, an official in the Court of the Liang Dynasty, was asked by the Emperor Wu 梁武帝 (reigned 502–549 A.D.) to arrange a set of 1,000 characters into an essay for the education of the young princes. He composed a rhymed essay of 250 four-character verses where each character was used only once. From the sixth century to the early twentieth century, this essay was commonly used as a primary text to teach young children the Chinese characters.

The essay begins with eight verses that express humans' desire to understand the Universe and their appreciation for the celestial objects' orderly movements. As Zhou describes it, people also recognize that observations of the Sun, Moon, and stars have led to the development of calendars and that the structure of the Universe can be understood by theoretical models.

These verses exemplify the yearning for knowledge of our place in the Universe, which is shared by all ancient cultures. Through tireless observations, our ancestors on different continents observed the behavior of the Sun, Moon, planets, and the stars. They were aware that these patterns were regular, but by no means simple. Although the data collected were similar across cultures, the interpretations of the celestial patterns differed. These interpretations were incorporated into social, religious, and philosophical structures. Throughout history, the evolution of our models of the Universe led to changes in these structures. This book is an attempt to tell the story of the evolution of astronomical development over two millennia and its effect on our society.

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About the Author

Sun Kwok is a professional astronomer and author, specializing in astrochemistry and stellar evolution. He is best known for his theory on the origin of planetary nebulae and the death of Sun-like stars. His recent research covered the topic of the synthesis of complex organic compounds in the late stages of stellar evolution. His recent books include *The Origin and Evolution of Planetary Nebulae* (Cambridge, 2000), *Cosmic Butterflies* (Cambridge, 2001), *Physics and Chemistry of the Interstellar Medium* (University Science Books, 2007), *Organic Matter in the Universe* (Wiley, 2012), *Stardust: The Cosmic Seeds of Life* (Springer, 2013), and *Our Place in the Universe: Understanding Fundamental Astronomy from Ancient Discoveries* (Springer 2017). He has lectured extensively at major universities, research institutes, and public forums all over the world. He has been a guest observer on many space missions, including the *Hubble Space Telescope* and the *Infrared Space Observatory*.

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Chapter 1
From Copernicus to Enlightenment

As soon as humans developed a sense of awareness of their surroundings, they realized that their lives are governed by daily cycles of day and night and annual cycles of seasons. They also made the association that these cycles are related to the Sun. For practical and religious reasons, they became keen observers of the heavens. Our ancestors were in awe not only of the existence of celestial objects – the Sun, the Moon, and the stars – but also of the fact that they all move. Not only do they move, but they also do so in regular patterns. The Sun, the Moon, and the stars rise day after day without fail. After the Sun sets and the Earth is covered in darkness, stars can be seen to rise from the eastern horizon, move across the sky, and set in the opposite horizon. The existence of these repeated patterns was believed to be a sign of divine governance and a source of messages from the gods. Motivated by the desire to decipher the hidden meaning of these patterns, our ancestors observed the movement of celestial objects with great diligence.

They soon learned that these patterns, although regular, were complicated. The Sun rises at different times and rises to different heights each day. The length of daylight varies through the year, with longer days in summer and shorter days in winter. When the Sun is highest in the sky, a stick planted vertically on the ground always casts its shadow in the same direction, which is referred to as "north."[1] The existence of this special direction allowed our ancestors to designate four directions: south being opposite to north, and east and west perpendicular to the line of north and south. Although the Sun rises in the general eastern direction, the exact location of sunrise varies each day. The Sun rises in more northerly directions in the summer and in more southernly directions in the winter. As early as 3000 years ago, ancient civilizations realized that there are four special days in a year: summer solstice when the Sun rises in the northernmost direction, winter solstice when the Sun rises in the

[1] In order to simplify the narrative, our references to seasons and other observed events are for the northern hemisphere. This statement is true for an observer in mid-northern latitudes.

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southernmost direction, and vernal and autumnal equinoxes when the Sun rises in the exact east.

Both the Sun and the stars appear to revolve around the Earth each day, but the period of revolution of the stars is slightly shorter (by about 4 minutes) than that of the Sun. This is manifested by stars rising slightly earlier each night, and new stars appearing on the eastern horizon the following night. This results in different constellations of stars being seen at different times of the year: for example, the constellation of Orion is seen in the winter and the constellation of Sagittarius in the summer.

Like the Sun, the Moon also rises in the east and sets in the west. However, unlike the Sun, the Moon changes its shape daily, going through phases. The Moon is sometimes seen at night and sometimes during the day, but its time of appearance is related to its phases. The full Moon rises in the early evening and is seen only during the night, whereas the new Moon rises in the early morning. Although the new Moon is in the sky throughout the day, it is hard to see as it is close to the Sun.

The Sun's and stars' asynchronous movements suggest that in addition to the daily motion of the Sun, the Sun is also simultaneously slowly moving relative to the stars over the period of a year. The daily motion of the Sun is from east to west, but its yearly motion through the stars is from west to east. Like the Sun, the Moon also moves relative to the stars, but much more quickly. Instead of a year, the Moon goes through the stars over a period of 27.3 days. This period is close to, but not exactly the same, as the period of the phases of the Moon, which is 29.5 days.

The Sun and the Moon are not the only objects that move relative to the stars. Our ancestors also knew of five bright celestial objects that move through the stars. For this reason, they are called planets, which originated from the Greek word for wandering stars. The planets Mercury, Venus, Mars, Jupiter, and Saturn all move relative to the stars along the same path of the Sun (called the ecliptic), but with different periods. Like the Sun, they usually travel from west to east relative to the stars. But most strangely, they appear to reverse directions from time to time.

The regular patterns of motions of celestial objects provided humans with the first motivation to understand the working of the heavens. This cultivated the seeds for rational thinking. The first example of abstract thinking is the development of a model of the Universe. The fact that the Sun and the stars appear to revolve around the Earth in circular paths led to the first cosmological model of a flat Earth and a spherical sky. The celestial objects move from horizon to horizon on the surface of a sphere, called the celestial sphere. The axis upon which the stars and the Sun turns is assumed to be the pole that holds up the canopy of the sky (Fig. 1.1).

1.1 A Spherical Earth

Although the Earth appears obviously flat from our everyday experience, there are some disconcerting observations that caused ancient astronomers to have doubts about this perception. If we live on a flat Earth, we would see the same stars no

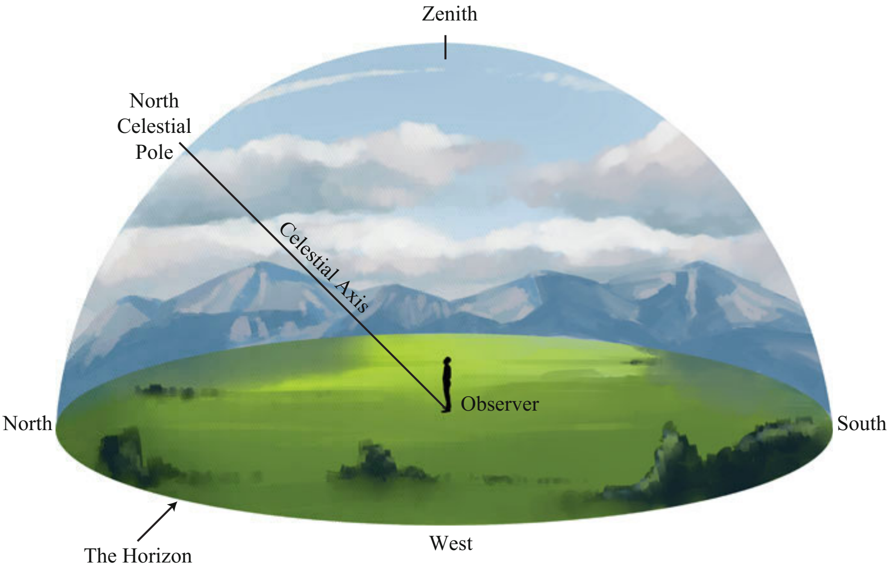

Fig. 1.1 The first cosmological model of a flat Earth and a spherical sky. The celestial axis around which the stars revolve is inclined with respect to the horizon (shown in green). The north celestial pole is the only point on the celestial sphere that does not turn. This figure corresponds to an observer located in the mid-northern latitude

matter where we are. However, some stars can only be seen from certain locations on Earth: Canopus, the second brightest star in the sky, can be seen from Alexandria but not from Athens. Contrary to intuitive expectations, this polar axis around which the stars turn is not planted perpendicularly but is inclined with respect to the horizon. This inclination angle varies from place to place: at Athens, the polar axis is inclined 38° relative to the horizon; in Alexandria, Egypt, it is 31°.

Around 500 B.C., Greek astronomers deduced that the Earth is round from the shape of its shadow during lunar eclipses. Eclipses occur at a precise time, but the hour of occurrence (as measured from the time at noon) as recorded by observers in the east is always later than that recorded by those in the west. The evidence for a spherical Earth was summarized by Claudius Ptolemy (100–175) in his book *Almagest*.

Using a simple stick planted on the ground and measuring the length and angle of its shadow over the course of a day, ancient observers could trace the exact daily paths of the Sun. Over the course of a year, these paths vary from one day to the next. Observers at different locations on Earth also see different apparent paths of the Sun across the sky (Chap. 5, Vol. 1). An observer in Athens never sees the Sun directly overhead but an observer in southern Egypt does. These results are not compatible with the idea of a flat Earth. By measuring the angle of the Sun at Alexandria on the longest day of the year (summer solstice) when the Sun shines vertically onto the city of Syene in southern Egypt, Eratosthenes was able to determine the size of the spherical Earth (Sect. 12.1, Vol. 1). Through the observations of the Sun, the Moon, and the stars, ancient astronomers were able to determine not only that the Earth was round, but also the size of the spherical Earth.

1.2 The First Cosmological Models

After our ancestors realized that the Earth is round and not flat, they were able to make sense of many peculiarities of the motion of celestial objects. The different inclination of the polar axis at different locations is because observers at different latitudes have different horizons (Fig. 1.2). The change in orientation of the horizon accounts for the reason that different stars are visible by observers at different locations. While an observer will see stars rise and set, a star that is too far south of the celestial equator is never visible to an observer in the northern hemisphere because it never rises above his horizon (Fig. 1.2).

All the apparent complexities of the motion of the Sun and the stars can be explained by a two-sphere universe model where a spherical Earth is situated at the center of a celestial sphere upon whose surface the stars lie. In this model, the celestial sphere revolves around the Earth from east to west each day. Because of the rotation of the celestial sphere, stars rise above the horizon in the east and set below the horizon in the west. Some stars can be seen throughout the night but some stars cannot be seen at all (Fig. 1.2).

The Sun also revolves around the Earth, but its motion is slightly slower than that of the stars by four minutes each day. Over the course of a year, the Sun travels across the celestial sphere relative to the stars from west to east along the plane of the ecliptic, which is inclined 23.5° with respect to the equator of the spherical Earth (Fig. 1.3). Because of this inclination angle, the Sun goes through a north-south motion over the course of a year.

The intersection points between the ecliptic and the celestial equator are the vernal and autumnal equinoxes. When the Sun crosses these two points, sunlight shines directly on the equator and the lengths of day and night are equal. On these two days, the Sun rises exactly in the east and sets exactly in the west. The northernmost and southernmost points of the ecliptic are the summer and winter solstices. When the Sun is at these two points, the difference in lengths of day and night is most extreme. Sunrise and sunset will be at their northernmost (on summer solstice) and southernmost (on winter solstice) directions of the year. The two-sphere model, developed by the Greeks over 2000 years ago, can successfully explain the changing seasons and all the known observational facts of the apparent motions of the Sun and the stars.

A practical device called the armillary sphere (Fig. 1.4) based on the two-sphere universe model can be used to predict the time and direction of sunrise/sunset from any place on Earth. It can also determine the length of each day of the year for anywhere on Earth. The two-sphere Universe model was extremely successful.

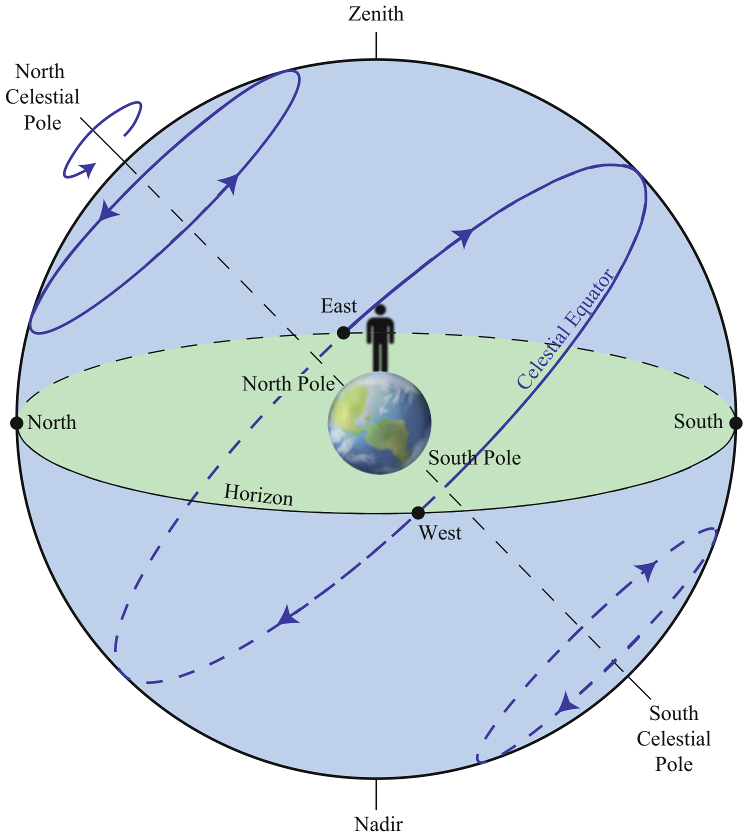

Fig. 1.2 Changing horizon on a spherical Earth. The sphere of stars revolves around an axis, whose angle of inclination with respect to the horizon (the green plane) is dependent on the location of the observer on the spherical Earth. This diagram illustrates the example of an observer at approximately 45° latitude north. The blue circles are examples of trails of three stars at different declinations over one sidereal day. Parts of the trails that are below the horizon (shown as dashed lines) cannot be seen by the observer

1.3 Uneven Movements of the Sun and the Planets

While the two-sphere Universe model represented a tremendous success in explaining the movement of celestial objects, unfortunately, there are other complications. Although the seasons return in regular annual intervals, the lengths of each season are unequal. This anomaly was known as early as 330 B.C. by Callippus (370–330 B.C.), and the lengths of the seasons were measured by Hipparchus (185–120 B.C.) to be 94½, 92½, 88⅛, and 90⅛ days for spring, summer, autumn, and winter, respectively (in the northern hemisphere). Although the planets generally revolve around the Earth from west to east, as does the Sun, they appear to reverse direction (retrograde motion) from time to time. The sphere of fixed stars is not

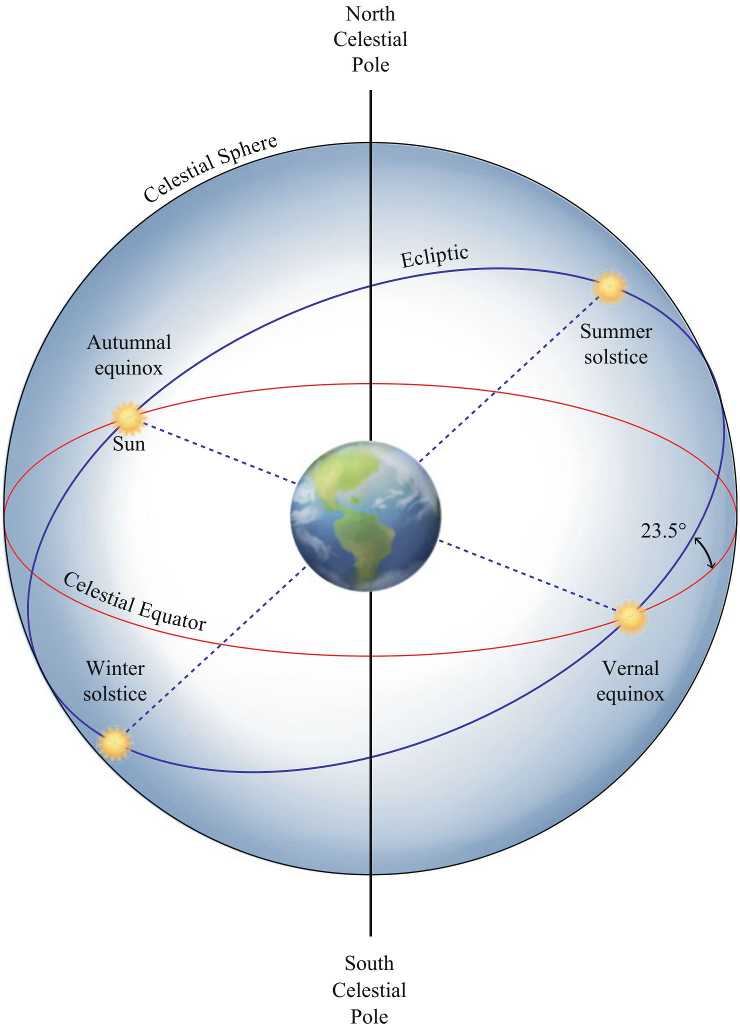

Fig. 1.3 The two-sphere Universe model. The model consists of an inner sphere (the Earth) and an outer sphere (the celestial sphere) and can successfully explain the apparent motion of the Sun at all locations on Earth. The daily (east to west) motion of the Sun is explained by the rotation of the celestial sphere around the north-south axis of the Earth. Perpendicular to this axis is the celestial equator (in red), which is an extension of the Earth's equator to the celestial sphere. The annual (north-south) motion of the Sun is explained by its movement along the ecliptic (in blue), which is inclined with respect to the celestial equator by 23.5°

oriented permanently with respect to the ecliptic, the annual path of the Sun. The intersection point between the celestial equator and the ecliptic shifts about 1° every 100 years. This phenomenon is known as the precession of the equinox.

Fig. 1.4 A model of an armillary sphere. The spherical Earth is at the center. Depending on the latitude of the observer, the north-south axis of the Earth is inclined with respect to the horizon (the thick outside plate). Five rings perpendicular to the north-south axis are the Arctic Circle, Tropic of Cancer, the Equator, Tropic of Capricorn, and Antarctic Circle. The ecliptic (a thick band) is inclined 23.5° with respect to the equator (Chap. 7, Vol. 1). Image created by the Technology-Enriched Learning Initiative of the University of Hong Kong

In order to explain these anomalies, Ptolemy in the first century A.D. introduced additional elements into the two-sphere universe model. Epicycles (cycles upon cycles) were introduced to explain the retrograde motions of the planets. A planet moves at uniform speed around an epicycle whose center revolves along a large circle called the deferent. When the planet is inside of the deferent, it is in retrograde motion (Fig. 1.5).

The concepts of eccentric and equant were also needed to explain the unequal lengths of the seasons, the uneven motion of the planets, and the precession of the equinox. The center of the deferent is separated from the position of the Earth by the eccentric. The center of the epicycle revolves uniformly relative to the equant, not the center of the deferent. All three mathematical constructs are necessary to successfully explain planetary motions.

Ptolemy's model of the Universe consists of a stationary Earth at the center, with a celestial sphere of stars revolving around it. Between the Earth and the celestial sphere are the Sun, the Moon, and the planets all revolving around the Earth near the plane of the ecliptic. The order of celestial bodies from near to far is the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn (Fig. 1.6). To Ptolemy, the epicycles are not just mathematical entities but carry real physical meaning. The orbits and epicycles of the Sun, the Moon, and the planets fill the interior of the celestial sphere without any empty space.

By noting that the horizon of an observer always bisects the whole celestial sphere into two halves no matter where the observer is located on the spherical Earth, Ptolemy concluded that the Earth must be very much smaller than the celestial sphere. In the model of a two-sphere Universe, the Earth is just a point in comparison to the size of the celestial sphere.

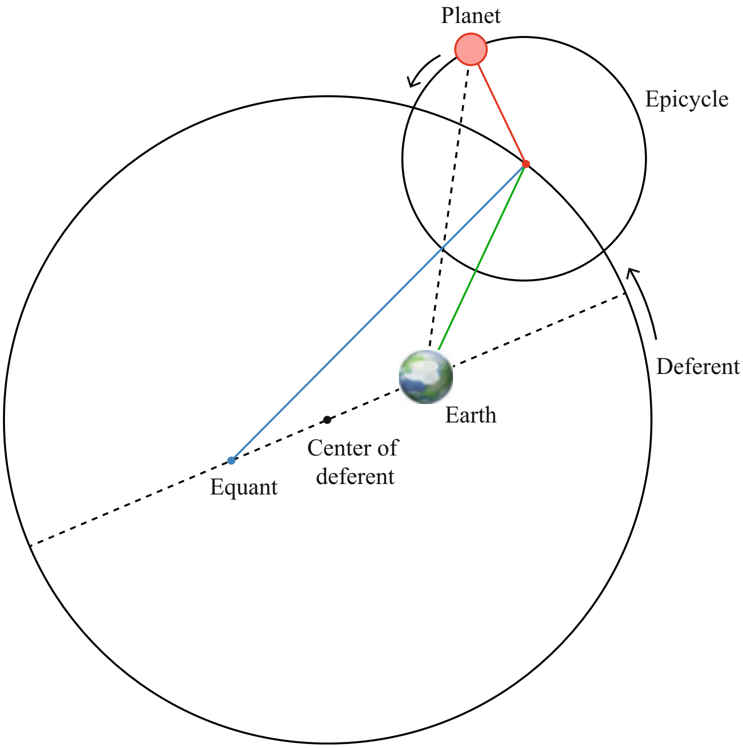

Fig. 1.5 The use of eccentric, epicycle, and equant in Ptolemy's model of planetary motion. The Earth and the equant are placed at equal distances on opposite sides of the center of the deferent. The planet moves uniformly around the center of the epicycle which revolves around the deferent centered on a point eccentric from the Earth. The angular speed of the center of the epicycle is uniform relative to the equant point

Given the complexity of the motions of the Sun, the Moon, and the planets, Ptolemy faced a formidable task. The high degree of accuracy of his model's predictions – which can quantitatively forecast the positions of the Sun, the Moon, and the planets hundreds of years into the future – is a testament to the model's success. Ptolemy's book *Almagest* represents the pinnacle of Greek science and stood for 1500 years before being challenged.

1.4 The Copernican Model

Aristarchus (310–230 B.C.) was the first person to suggest that the Sun, not the Earth, is the center of the Universe. Using his measurement that the Sun is 20 times farther away from the Earth than the Moon is, he estimated that the Sun is seven times larger than the Earth (Sect. 12.2, Vol. 1). He argued that it was unreasonable to

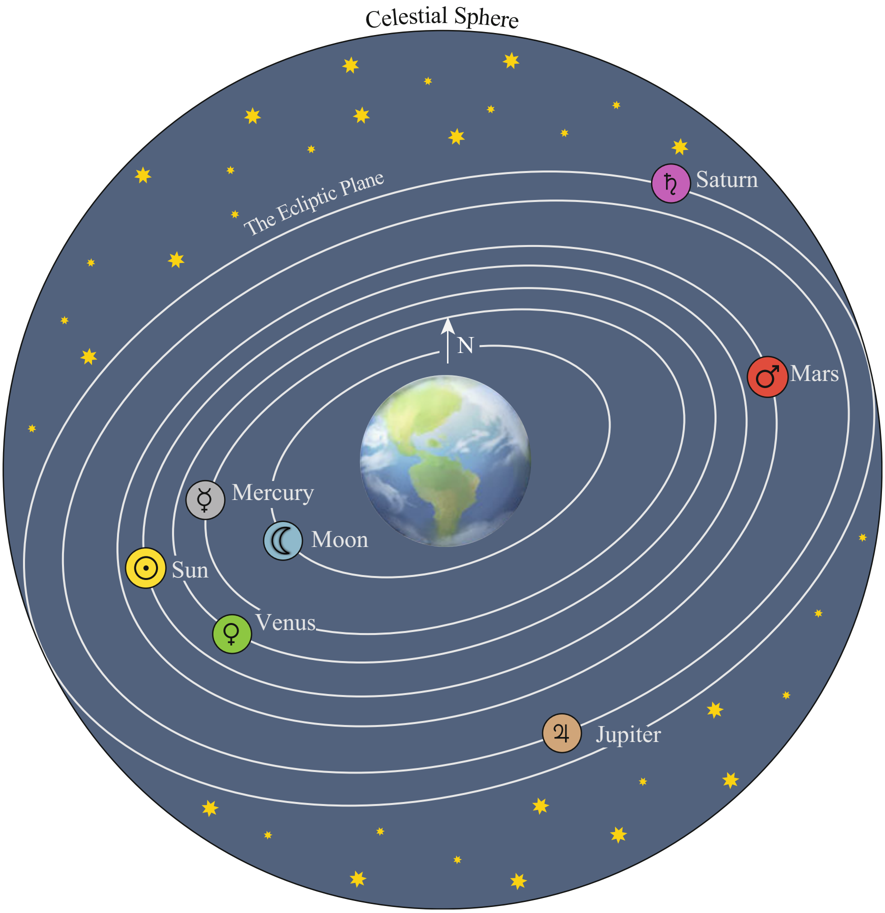

Fig. 1.6 Schematic diagram of Ptolemy's cosmological model. The celestial sphere upon which all stars lie revolves around a stationary Earth once a day. The Sun, the Moon, and the five planets revolve around the Earth on the plane of the ecliptic also once a day. In addition, these seven celestial objects also move relative to the stars with different periods. The plane of the ecliptic is inclined with respect to the equator of the Earth. The epicycles are not shown in this diagram. The sizes of the planetary orbits and the celestial sphere are not to scale. The Earth should be just a point in comparison to the size of the celestial sphere

assume that a larger body (the Sun) should revolve around a smaller body (the Earth). The heliocentric model was taken up by Nicolaus Copernicus (1473–1543). Copernicus considered the concept of equant in Ptolemy's model as violating the spirit of uniform circular motion and proceeded to seek an alternative without the use of the equant. Copernicus placed the Sun near the center of the Universe, with the Earth and the other five planets revolving around it. The only object that revolved around the Earth is the Moon.

Although Copernicus's model was not more accurate and had more epicycles than the model of Ptolemy, he did remove some unexpected coincidences in Ptolemy's model such as the alignment between the lines connecting the planets to the centers of their epicycles being always in parallel with the line connecting the Earth and the Sun, and the planets revolving around the centers of their epicycles at the same rate as the Sun revolves around the Earth (Sect. 15.3, Vol. 1). Copernicus's model also has the esthetic advantage of providing a natural explanation for the retrograde motions of the planets. From the observed synodic periods (time from conjunction to conjunction or from opposition to opposition) of the planets, he was able to derive the true periods of revolution (sidereal periods) of the planets (Sect. 16.1, Vol. 1). The heliocentric model also naturally explains why the superior planets (Mars, Jupiter, and Saturn) are brightest during opposition, without assuming artificial periods for their epicycles (Sect. 15.3, Vol. 1). Most significantly, Copernicus can predict the relative distances between the planets and the Sun, therefore resolving the ambiguity in the order of Mercury and Venus in Ptolemy's model (Sect. 16.2, Vol. 1).

1.5 Immutability of the Heavens

One of the essences of Aristotelian cosmology is the immutability of the heavens. This was further entrenched into the Christian doctrine that the fixed stars came into existence at the time of Creation and were everlasting and unchanging. In 1572, Tycho Brahe (1546–1601) noted the appearance of a new star in the constellation Cassiopeia. Tycho carefully measured the separations of the new star from nearby stars as the stars move from horizon to near the zenith and to the opposite horizon. He found no change in the separations, suggesting that the new star was located far above the Moon and was part of the fixed stars. The appearance of this new star represented a clear violation of the principle of the immutability of the heavens.

1.6 A Physical Universe

Like Ptolemy's model, Copernicus's model relies purely on geometry to describe the motions of celestial objects. All objects move in perfect circles and at uniform rates. By removing both assumptions, Johannes Kepler (1571–1630) greatly simplified Copernicus's model. From Tycho's accurate measurements of Mars's apparent motion in the sky, Kepler found that its orbit around the Sun is best described by an ellipse, with the Sun located in one of the two foci of the ellipse (his first law of planetary motion). He also found that the revolution speed of a planet varied during its orbit, and did so in relation to its distance to the Sun (faster when they are near the Sun and slower when they are far from the Sun). The varying speeds of Mars's and the Earth's motions around the Sun can be summarized by his second law which