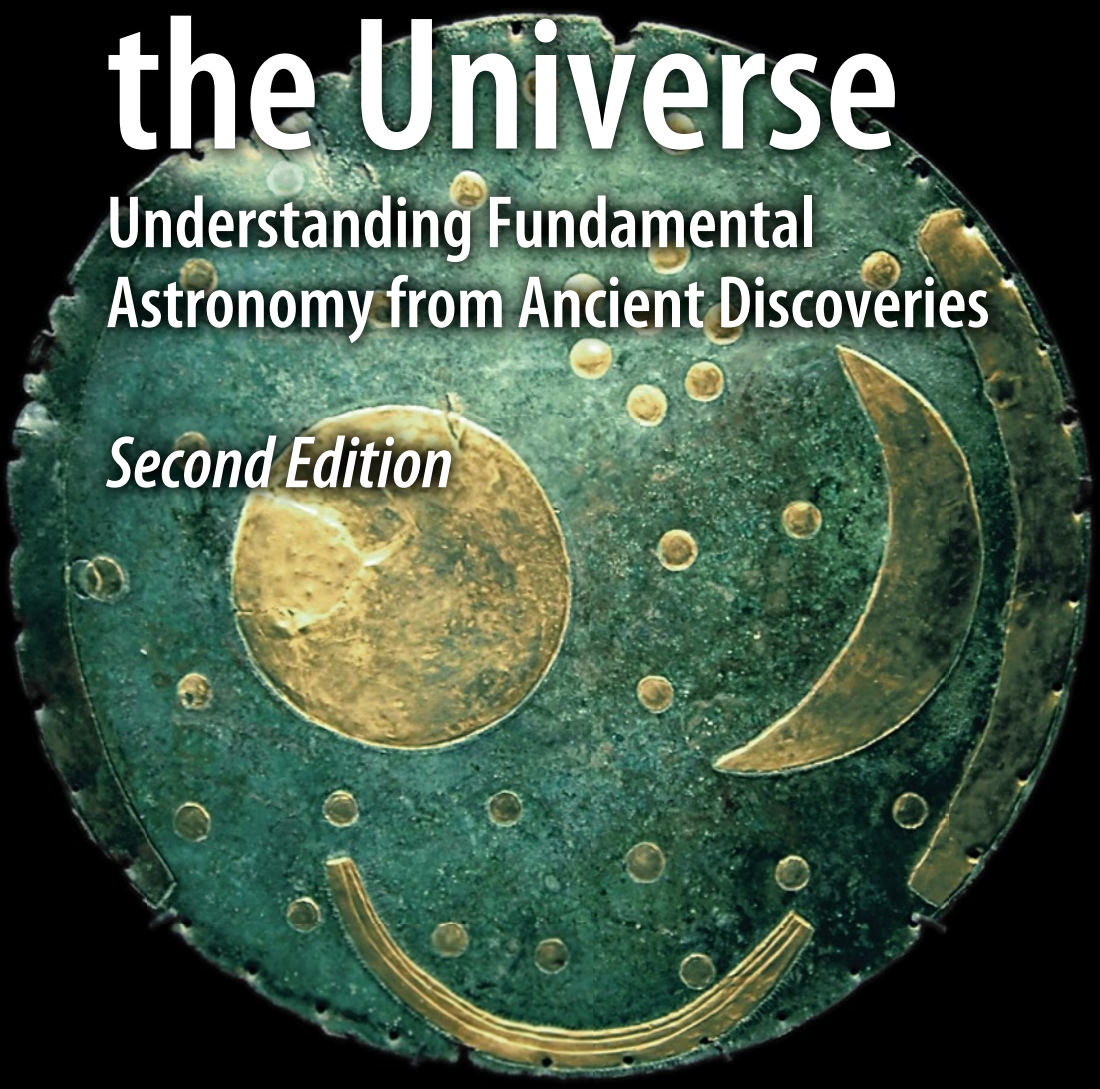
Sun Kwok

# Our Place in the Universe

## Understanding Fundamental Astronomy from Ancient Discoveries

*Second Edition*



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## Understanding Fundamental Astronomy from Ancient Discoveries

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# Preface

There is a common perception among the general populace that astronomy is impractical and irrelevant. This could not be further from the truth. For thousands of years, astronomy was an extremely practical subject, and our ancestors relied on their astronomical knowledge to conduct their daily lives. Most ancient people were far more familiar with the behavior of the Sun, the Moon, and the stars than the average person is today. Astronomy also motivated intellectual thought and had a major impact on the social development of the human race throughout history. Our evolving perception of our place in the universe helped bring about important social changes over the last two thousand years.

This book is not just about astronomy. It uses the historical development of astronomy to illustrate the process of rational reasoning and its effect on philosophy, religion, and society. Because celestial objects followed regular patterns, astronomical observations gave humans some of the first hints that Nature was understandable. The complicated nature of these patterns also challenged our intellectual powers.

In our education system, science is often presented to our students as a series of facts. In fact, 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.

I tried to achieve these goals as follows. I begin with a description of basic observations, summarize the patterns observed and the problems they pose, and discuss the suggested theories and their implications. The pros and cons of these theories are evaluated alongside alternate theories. This approach differs from typical science textbooks, which usually take an axiomatic approach by first stating the correct theory and deriving the deductions before comparing them with experimental results. I hope this historical approach allows students to better understand the scientific process and learn from this process when they tackle real-life problems in their careers.

We live in the most prosperous times in human history. It is convenient to assume that everything important happened recently and that events from the distant past do not matter. It is also easy for us to forget or dismiss the wisdom and achievements of our ancestors. A simple survey of modern university students will reveal that most of them believe we discovered the Earth was round only a few hundred years ago. But in fact the Earth's shape was well known as long as 2500 years ago.

With naked eye observations and some very simple instruments, ancient astronomers found out a great deal about our world. By observing celestial objects, they deduced that the Earth was round. They could explain the changing times and locations of sunrise. They had a reasonable empirical model to forecast eclipses. In spite of the apparent erratic motions of the planets, their positions could be predicted accurately with mathematical models hundreds of years into the future. Although ancient civilizations occupied only a small fraction of the surface of the Earth, they had a very good estimate of the size of the entire Earth. They could even determine the size of and distance to the Moon.

Modern humans' disconnection from Nature also means that some common knowledge from ancient times has been lost. Many people today believe that the Sun rises in the east every day, but it was common knowledge among our ancestors that the direction of sunrise changes every day. The regular yet complex apparent motion of the Sun was the main motivator for the development of rational thought.

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. The classes also help students appreciate our own culture and global issues.

I developed this course and taught it from 2010 to 2016. 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. In order to convey the concepts effectively without mathematics, I relied strongly on graphical illustrations and animations. Computer simulations were used to show apparent motions of celestial objects in the sky. These illustrations greatly helped students visualize the complexity of such motions.

For more technical readers, I have added some mathematics in this book, most of which is presented in the Appendices. Nonmathematical readers can skip these parts. To focus on the evolution of concepts, I have deliberately omitted certain details. For example, the apparent motions of the Sun and Moon are even more complicated than I have presented here. My goal is to reach a broad readership.

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.

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 have been told all the modern notions but have never learned how we arrived at those conclusions. To learn about the process of discovery, they have to give up their preconceptions, which can be hard for some students. One example is the question "How do we know that the Earth revolves around the Sun?" When I posed this question to students, the most common answer I got was "This is what I was told by my teacher." In this book, we try to retrace historical steps to find out how we got to this conclusion.

In addition to lectures, we had weekly tutorials, quizzes, assignments, computer laboratory exercises, a planetarium show, and exams. The planetarium show was developed with the assistance of the Hong Kong Space Museum 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 so that students could have firsthand 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.

I wish to thank Wai Wong, who skillfully drew many of the figures in this book. Anisia Tang and Sze-Leung Cheung helped with background research and contributed to the laboratory exercises. I thank Gray Kochhar-Lindgren, Director of the HKU Common Core Program, and Y.K. Kwok, Associate Vice President (Teaching and Learning), for their unyielding support for my course. Tim Wotherspoon and Bruce Hrivnak provided helpful comments on an earlier draft. I thank Ramon Khanna, my editor at Springer, for encouraging me to publish this book. I am particularly grateful to my wife Emily and daughter Roberta for reading various drafts of this book and giving me critical comments.

I also wish to thank the University of British Columbia for its hospitality during my sabbatical leave when this manuscript was completed.

I first became interested in this subject during my second year of undergraduate study at McMaster University, where Prof. Bertram Brockhouse (Nobel Prize in Physics, 1994) introduced me to Kepler's work in his Philosophy of Science course. His teaching made me realize that physics is more than just mechanical calculations; it is a subject with philosophical and social implications.

Vancouver, Canada Sun Kwok
2016

# 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 1000 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. He is the author of many books, including *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), and *Stardust: the Cosmic Seeds of Life* (Springer, 2013). 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*.

He currently serves as the President of Commission F3 Astrobiology of the International Astronomical Union (IAU). He has previously served as President of IAU Commission 34 Interstellar Matter, Vice President of IAU Commission 51 Bioastronomy, chairman of IAU Planetary Nebulae Working Group, and an organizing committee member of IAU Astrochemistry Working Group. Sun Kwok is currently the Chair Professor of Space Science at the University of Hong Kong. He previously served as Director of the Institute of Astronomy and Astrophysics, Academia Sinica in Taiwan, Killiam Fellow of the Canada Council for the Arts, and Professor of Astronomy at the University of Calgary in Canada.

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# Chapter 1
# Humans and the Sky

People have asked the question: "How important are we?" since the beginning of our existence. Humans are not alone. We are surrounded by Nature. Nature consists of all forms of life: animals, birds, trees, and insects. It also includes non-living entities such as rivers, lakes, oceans, rocks, and mountains. Ancient humans developed some idea of the extent of their world by examining their surroundings. They could also expand their visible horizons by moving around, and their knowledge of the world depended on how far they could travel on foot. By exchanging information with other travelers, they became aware of the existence of other villages. Those who lived by the sea could see the vastness of the oceans.

However, they knew that the world on Earth was not everything. They could see the Sun, the Moon, and the stars and speculated that other worlds were out there, much further away than people could travel. If we define everything in existence as "the Universe", then the question "How large is our world within the whole Universe?" has been with us since we developed the ability to think.

We are also curious about our existence on the temporal scale. How long was the world around before humans? Can we look at the world today and determine its age? How long have we existed? With the development of language, stories were passed from one generation to another. With the invention of writing, we inherited a record of past events. From these oral and written histories, ancient humans knew that their world had existed for generations, spanning hundreds if not thousands of years. Our direct experiences, coupled with recorded history, gave us the knowledge of our world.

Our world is variable—some things come and go and change on different time scales. Clouds appear and disappear in the sky and change color and shape. Thunder and lightning appear out of nowhere and last for seconds. Periodically we have rain and snow. Spectacular sky displays such as aurora can be seen at night in the extreme northern and southern locations of the Earth. There are also catastrophes that can have devastating consequences. Typhoons, hurricanes and tornados wreak havoc along their paths, volcanoes erupt at unpredictable times, and earthquakes and tsunamis strike without warning.

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However, not all natural events are random. On a perfectly reliable schedule, day changes to night and seasons come and go in recurring cycles. These phenomena happen on a regular basis and can be relied upon to occur without fail.

Away from our immediate surroundings are the heavens and the celestial objects that occupy them. Humans, and even some other animals, are familiar with the two most luminous objects in the sky, the Sun and the Moon. When the Sun goes down, thousands of stars appear in the sky. At night, ancient people watched the heavens and noticed that five points of light behave differently from the rest of the stars. These five objects, which we now call planets, change their positions and move among the stars. A bright band of light lies across the sky, and it is now named the Milky Way. In Chinese, the Milky Way is called the "Silver River" which seems to dissect the sky and separate stellar constellations. What makes these celestial phenomena special is their regularity. They move and change, but they follow a fixed pattern which can be learned and predicted.

From time to time, seemingly unpredictable celestial events occur. Light from the Sun and Moon diminishes during eclipses. Streaks of light race through the sky in the form of meteors. New celestial objects with long tails (comets) appear, move across the sky, and last for months. Some stars (novae) brighten suddenly and remain bright for months. Do these transient celestial events carry messages? Do they foretell disasters (as comets were believed to do) or carry good news (like the star of Bethlehem)?

Some of our ancestors pondered why the celestial bodies existed. The Sun is an essential part of our existence that provides light and warmth, while the Moon provides illumination at night. Were they created for our convenience? The stars have no apparent use other than as a celestial display of beauty. Were they created for our amusement as a demonstration of supernatural power?

As remote as celestial objects may seem, they are strongly connected to us. Human activities are synchronized by the daily motion of the Sun. We work during the day when the Sun is up and sleep during the night when the Sun is down. Before artificial lighting, there was not much one could do at night. Tides are controlled by the Moon, and agriculture depends on the seasons. Sailors used the stars to navigate the vast ocean, and Polynesians crossed the Pacific with little guidance except the stars.

Our ancestors were very conscious of the heavens and paid great attention to the motion of celestial bodies. The changing phases of the Moon were important because a full moon provides much more illumination for nocturnal human activities. Seafaring communities knew that the appearance of the Moon is related to tides. People also thought that the Moon could affect our minds. The English words "moonstruck" and "lunatic" probably originated from this belief.

In spite of the importance of the Sun, fascination with the cosmos begins after dark when thousands of shining stars are revealed. Stars of different brightness seem to be distributed randomly in the sky. Humans often saw patterns in this randomness, and different cultures developed different sets of patterns called constellations. The Sumerians, who occupied the Mesopotamian region around the Tigris-Euphrates rivers (modern day Iraq) are widely credited with inventing

the first writing system. Records of Sumerian constellations traced back to around 3000 B.C. include the Eagle, Bull, Fish, and Scorpion. These constellation names were passed down to the Greeks and are still in use today as the constellations Aquila, Taurus, Pisces, and Scorpius.

Many ancient cultures regarded themselves as special, a chosen people. They believed that they were here for a reason and that everything else (animals, plants, rivers, lakes) existed for their use or enjoyment. Even celestial objects, such as the Sun, the Moon, and stars, seemed to revolve around them. It was therefore natural to believe that we were at the center of the Universe and that supernatural beings (a god or gods) put us here.

Are we at the center of the Universe? We believe that humans are more advanced and more intelligent than other living plants and animals, but are we special or unique? Are there others who are like us or more advanced than we are? Does life exist elsewhere in the Universe? Are there extraterrestrial intelligent beings? Attempts to answer these questions have dominated intellectual thinking throughout history. How did we come to our present understanding of our place in the Universe?

## 1.1 Repeating Days and Nights

Our most obvious aspect connection to the heavens is the separation between night and day. The Sun rises and sets every day, and our environment changes from light to dark. The length of the day has a significant influence on our everyday lives. Since we needed to see to interact with our surroundings, most human activities were confined to the day time. The biological functions of our bodies are adjusted to the length of the day. Our pattern of work and sleep was developed in response to the motion of the Sun. We reserve a fraction of our day for sleep, which usually takes place during the night.

We defined the day as the period when the Sun is above the horizon, and night as the period when the Sun is below the horizon. The Moon, when present at night, provides illumination when the Sun is absent.

As the Sun disappears below the horizon, stars appear in the night sky. Our ancestors realized very early that stars are not created at night. They are always there. The only reason that stars are not visible during the day time is that the Sun is too bright—it simply outshines the light from the stars.

As our ancestors watched the constellations, they could see them rise and set move throughout the night. They realized that stars also have a daily cycle. They rotate around the Earth about once a day.

## 1.2 Cycles of the Seasons

In addition to this daily cycle of day and night, people were also keenly aware of a longer cycle which we call the seasons. They divided the periodic variations of hot and cold into four roughly equal seasons: spring, summer, autumn, and winter. Seasons repeat themselves and spring always returns after winter. Nomadic people needed to move their animals to different pastures in the winter. As soon as people began farming, an accurate knowledge of the seasons was essential to decide when to plough, sow, and harvest.

Our ancestors knew that the daily and seasonal cycles are related. Summer has longer days and shorter nights and winters have shorter days and longer nights. The lack of sunlight, as well as cold temperatures, reduces the work that can be performed during the winter, and crops are much less likely to grow. These variations are more extreme in the temperate zones than in the tropics. Since many ancient civilizations (e.g., the Mesopotamian, the Chinese) were in temperate zones, these seasonal changes were very obvious to them.

Animals also adapt to the changing seasons. With the coming of winter, birds migrate, animals grow thick coats, and some even go into hibernation. Ancient observers knew that the paths of the Sun across the sky vary according to the seasons. The Sun is certainly related to or even responsible for the seasons, and it is quite obvious that heavens have a major effect on all living beings on Earth.

## 1.3 Early Sky Watchers

The practical needs mentioned above made our ancestors pay careful attention to the heavens. The cosmos are not static. Celestial objects change positions in the sky. The Sun, the Moon, and the stars are constantly moving, and their motions never stop. Why do they move? If the Sun exists to provide us with light and warmth, why doesn't it just stay in one place?

The motions of celestial objects provided the first motivation for rational thinking. Humans are intelligent beings. Humans, or more technically homo sapiens (Latin for "wise man"), are the only species on Earth that can develop tools and machines, transform our surroundings to adapt to the changing environment, and find new means of living. Most importantly, we are the only species that can comprehend the meaning of our surroundings and theorize about their origins. Many animals are capable of observations and awareness. But we do not just observe, we try to find out why.

There is plenty of anthropological evidence to suggest that ancient people were interested in the sky. Artifacts and cave art shows that people observed the sky and defined themselves within the universe since early prehistory. A carved bone from an eagle's wing found in France and dated to ~30000 B.C. has been interpreted as markings the changing phases of the Moon. The Lascaux Cave in France, dating

back to 15000 B.C., contains markings associated with astronomical objects such as stars and constellations. Man-made objects with astronomical connotations can be traced back more than 3500 years. Written texts mentioning astronomical events such as eclipses, comets, planetary conjunctions inscribed on animal bones and tortoise shells from 900 to 1600 B.C. have been excavated in China.

Figure Fig. 1.1 shows the Nebra Sky Disk discovered near Nebra, Germany which is dated to around 1600 B.C. The Sun and the crescent Moon are clearly represented in the disk. The other small circles represent stars, and a group of stars between the Sun and the Moon is believed to represent the Pleiades (Seven Sisters) star cluster. The arc on the right and another missing one on the left indicate the sunrise and sunset locations along the horizon from winter solstice to summer solstice. If this interpretation is correct, then people of the Bronze Age were already aware of the changing location of sunrise and sunset over the year. The creators of the Nebra Sky Disk knew not only about celestial objects, but also about their behavior patterns.

## 1.4 Worship of the Sun

To ancient people, the Sun was the most important object in their lives. Every day begins with the Sun rising over the horizon, providing light for humans to gather food and warmth for them to survive. Their greatest fear was probably that somehow the Sun would fail to appear the next day. They prayed to the Sun for its continued blessing and Sun worship was common among many cultures. Ra was

**Fig. 1.1** The Nebra Sky Disk. Symbols representing the Sun, the Moon, stars, the star cluster Pleiades, as well as the changing positions of the rising Sun can be found on the disk. Photo ©Anagoria, Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported (https://creativecommons.org/licenses/by-sa/3.0/deed.en) license

the god of the Sun for the Egyptians, as Apollo was to the Greeks. Surya was the solar god to the Hindus and Sun worship was a major part of Aztec mythology. Japan considers itself the land of the rising Sun, and the Sun goddess was the major deity of the Shinto religion. There is ample evidence that the Sun represented a major part of ancient culture and religion.

Some simple observational facts about the Sun were known to every ancient civilization as early as 4000 years ago. First, every day the Sun rises on one side of the horizon, reaches a certain altitude, and descends onto the opposite side of the horizon. Second, the location of sunrise and sunset are different every day. Third, the times at which it rises and sets are different every day. Fourth, the amount of time it stays in the sky is different every day.

Before 1000 B.C., the Babylonians and the Egyptians began systematic observations of the Sun's motion. From the shadow of a vertical stick planted in the ground, they could measure the direction of the Sun. From the length of the shadow, they could measure how high the Sun rose in the sky. These observations were the first quantitative astronomical measurements. Ancient people knew precisely how the maximum altitude of the Sun (as indicated by the length of the Sun's shadows) changes with the seasons. The direction of sunrise could also be linked accurately to the seasons.

Anthropological evidence of ancient people's interest in the motion of the Sun can be found in artifact such as the Trundholm Sun chariot found in Denmark, dated to ~1400 B.C. (Fig. 1.2). The bronze disk being pulled by a horse is believed to signify the motion of the Sun across the sky. The fact that there are two sides of the disk has been suggested to represent the motion of the bright Sun from east to west

**Fig. 1.2** The Trundholm Sun chariot on display at the National Museum of Denmark. Photo ©Malene Thyssen, Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported (https://creative.commons.org/licenses/by-sa/3.0/deed.en) license

during the day, and the return from west to east during the night while presenting the dark side to Earth.

Ancient monuments were constructed to mark the changing positions of sunrise at different times of the year. Stonehenge, built between 3000 and 1500 B.C., was designed to quantitatively and precisely determine the location of sunrise on a day of special significance. This was a momentous undertaking at the time as the stones were transported from Wales, about 200 km away. Another example of such a circular stone arrangement is the Callanish Stones on the Isle of Lewis in Scotland, built between 2900 and 2600 B.C. Thirteen primary stones each 1–5 m tall, are arranged in a circle about 13 m in diameter. Although the arrangements of the stones have been suggested to mark the cycles of the Sun and the Moon, the astronomical purpose of the stones is less definite than in the Stonehenge case.

In the Americas, the Plains Indians built the Big Horn Medicine Wheel in Wyoming for similar purposes. Its spokes and other features are aligned with the risings and settings of the Sun and other stars. Native Americans used the setting point of the Sun (as marked against the mountain landscape) as a calendar. The Mayan people constructed the Sun Temple in Dzibilchaltun, Mexico, which on two special days in the spring and the autumn the Sun will shine through its central doorway. At other times of the year, the Sun appears to the right or left, which is either further to the north or south. The Caracol temple in Chichén Itzá, Yucatan, Mexico (Fig. 1.3) was built around 1000 A.D. partly to keep track of the seasons and the heavens. The many windows of the building were designed to align with astronomical events. Narrow shafts were used to align with the equinox sunset, lunar extremes, and the planet Venus.

## 1.5 The Orderly Heaven

The heavens are governed by repeating patterns over different time scales. It is clear that the behavior of the heavens is orderly. It is also highly predictable. After the Sun sets, it will rise again the next day. Spring always returns after a hard winter. The Moon repeats its cycle of changing phases without fail, and stars that have disappeared from view will always return.

The regularity of the motions of celestial objects was nothing short of a miracle to ancient people. They took these patterns as messages from gods. Stonehenge and other monuments were built to celebrate these celestial events and to pay tribute. These instruments allowed a few wise men to predict future celestial events, impressing the common folk. Just imagine the awe and respect a priest would command when he successfully predicted the date upon which the Sun would rise along a certain line of stones.

Our everyday encounters with Nature such as rain, cloud, storms, and thunder, seem random and unpredictable. However, the behavior of celestial objects follows regular patterns. This distinction between heaven and Earth was entrenched in the thinking of early people. The presence of patterns in Nature as demonstrated by the