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The Earth System and its Co-evolution With Organisms

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Earth, Our Living Planet

The Earth System and its Co-evolution With Organisms

Springer

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Preface

We, the two authors of this book, are both oceanographers, but our scientific and geographic backgrounds are quite different. One of us was initially trained as a chemist, and spent most of his career in France. The other was initially trained as a biologist, and spent the first part of his career in Canada before moving to France. In the latter country, one of us was based on the Atlantic Ocean and the other on the Mediterranean Sea. We first met in the multidisciplinary context provided by the French national research organization CNRS (Centre National de la Recherche Scientifique). Talking together, we realized that we shared a common interest in topics that went beyond our own scientific domains.

In 2004, Louis Legendre published a book on the discovery process entitled *Scientific Research and Discovery: Process, Consequences and Practice* (International Ecology Institute, Oldedorf-Luhe) followed by an abridged electronic edition in 2008 (https://www.int-res.com/articles/eebooks/eebook16.pdf). In 2008, Philippe Bertrand published a book on the evolution and functioning of the Earth System entitled *Les Attracteurs de Gaïa* (Publibook, Paris). We were each interested in each other's books, and talked from time to time about some of the general topics following from our works. One theme that emerged from our discussions was the general lack of analyses in the scientific literature of the conditions that had led organisms and ecosystems to take over the Earth System during the course of the history of the planet. We explain in Sect. 1.1.1 what we mean by *takeover* in this context.

Indeed, there is a large body of studies on the emergence of life on Earth and its further diversification into billions of species, both extinct and extant. These studies involve such scientific disciplines as molecular and cell biology, developmental and evolution biology, genetics, taxonomy, and paleontology. There is another large body of research on the functioning of ecosystems and their perturbations by the ongoing climate change, which involve such disciplines as biogeochemistry, ecology, oceanography, limnology, and climatology. However, less attention is devoted to what lies between the two sets of phenomena, that is, the fact that organisms not only appeared and diversified on Earth, but became so abundant that they modified the physical and chemical environment of the planet and largely took over the functioning of the Earth System. This led us to the question: “Which combination of factors led to this apparently unique development in the Solar System?” We thought that trying to answer this question would be an original contribution to Earth System Science.

Philippe Bertrand had already provided some high-level answers to this deep question in his 2008 book, in a form mainly intended for experienced researchers. For the present book, we decided early (in 2011) to address a more general audience. We looked for a possible Publisher for our future work, and found that the books in Springer’s *Frontiers Collection* were “devoted to challenging and open problems at the forefront of modern science and scholarship [...] written in a manner accessible also to scientifically literate non-specialists”. This corresponded precisely to what we had in mind for our book. In turn, the approach underlying the collection largely determined our approach to the book, including the encouragement to “active academics in all fields to ponder over important and perhaps controversial issues beyond their own speciality.”

As we wrote our manuscript, we investigated numerous domains of astronomy, geology, geophysics, chemistry, climatology, biology, ecology, systems theory, and other disciplines, in which we revisited the territories we had journeyed in the past and also explored new lands. The resulting information influenced the content and structure of the book, and the resulting changes to our original plans led us to explore new domains of knowledge.

The book thus took a life of its own, but we always reined in our exploration of new areas of knowledge to stay on the track of the conditions that have enabled organisms and ecosystems to take over the Earth System. Accordingly, each of the first eight chapters of the book begins with the identification of a connection between organisms and the Earth System, after which information from several disciplines is combined to explain the occurrence of this global connection. The last three chapters are progressively broader syntheses of the materials presented in the previous chapters, which lead to general mechanisms that govern the functioning of the Earth System (Chapter 9), and its evolution from past to present (Chapter 10) and present to future (Chapter 11).

Experts from the many disciplines cited above may well find that we have not delved into certain topics enough and taken too many shortcuts. However, we have deliberately written our book for non-specialists, namely scientifically literate members of the general public, students, and colleagues from various scientific and non-scientific disciplines who would be fascinated by the interactions between astronomical, geological, environmental, biological phenomena and ecological characteristics of the planet that led to the unique Earth System.

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Nice, France Louis Legendre

Acknowledgments

We first want to thank our patient and obliging draughtsman, Mohamed Khamla, who drew or modified most of the figures in this book. His contribution was essential, and we thank the Director of the *Institut de la Mer de Villefranche* for allowing him to devote innumerable hours to our book. We are particularly indebted to nine colleagues who each pre-read some chapters of our manuscript, namely Maryam Cousin, Muriel Gargaud, Satoshi Mitarai, André Monaco, Tom Pedersen, Claude Pinel, Richard B. Rivkin, Carolyn Scheurle, and Marie-Thérèse Vénec-Peyré. Their thoughtful suggestions greatly helped us improve our final text. We also thank the colleagues who provided us with information or assistance at various times during the writing of our book, in particular Leif Anderson, Andrew C. Clarke, Francisco Chavez, Katherine Clark, Christina De La Rocha, Peter J. Edmunds, Martine Fioroni, Jean-Pierre Gattuso, David M. Karl, Robert Knox, Nianzhi Jiao, Robbert Misdorp, Purificación López-García, Sophie Rabouille, Florian Rastello, Bruce H. Robison, Christian Sardet, David Schindler, Morgane Thomas-Chollier, and Paul Tréguer. We are also very grateful to the researchers and institutions cited in the figure credits for giving us permission to use their illustrations. Alexis Vizciano has been our kind and helpful Editor from our first contact with Springer to the publication of the book. Last but not least, during the many years between the conception of this book and its publication, we benefited from the constant support and wise advice of Marie-Soline Bertrand and Mami Ueno-Legendre, without whom this book would not have become a reality.

Contents

Chapter 1
The Living Earth: Our Home in the Solar System and the Universe

1.1 The Living Planet Earth

1.1.1 Focus and Organization of This Book

This book investigates the billion-year takeover of planet Earth by its organisms and ecosystems (see Information Box 4.2 for a definition of *ecosystem*). By *takeover*, we mean the progressive changes brought about by organisms and ecosystems to the chemical, geological and/or physical conditions of the Earth's environment, and the feedbacks of the latter into ecosystems (see Information Box 6.2). One example is the oxygenation of the atmosphere by the photosynthetic activity of organisms, which led to the development of the ozone layer, which in turn provided the protection from harmful solar radiation that allowed the occupation of continents by plants, which produced even more oxygen (see Sect. 9.4.3). We use *takeover* as a metaphor to stress the roles of organisms in the Earth System (defined two paragraphs below), in a way similar to Darwin borrowing in 1859 the word *selection* from animal husbandry and plant breeding to characterize the mechanism of biological evolution, although artificial selection in husbandry is guided whereas natural selection is not.

This takeover is unique in the Solar System, and we explain it by the existence of interactions between a small number of key environmental and biological mechanisms. In this book, we take the existence of organisms on Earth since almost 4 billion years for a fact, and we do not consider the origin of life on the planet (1 billion = 1,000 millions = 10^9; also 1 milliard). We focus on the conditions that allowed the organisms to diversify, and build up the huge biomasses that allowed ecosystems to successfully occupy all the Earth's habitats. Other, very interesting books examine hypotheses concerning the intriguing questions of how and where life appeared on Earth. Here instead, we investigate the conditions that allowed the initially very small number of cells to give rise to the innumerable

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organisms and huge biomasses that ultimately took over the whole planet. We show that the establishment of organisms and the development of ecosystems on Earth have been conditioned by the conditions that led to the formation of the planet in the Solar System, in our galaxy the *Milky Way*, and more generally in the Universe (Sect. 1.4.1).

The environment we consider is planet Earth within the whole Solar System (see Information Box 3.3 for a definition of *system*). We compare Earth with the billions of astronomical bodies that exist in our Solar System (yes billions, as explained below; see Sect. 1.2.2), and find that our planet has a number of unique characteristics. We look at hidden relationships among the suite of nested systems made of ecosystems, the Earth System, the Solar System, and the Universe. The *Earth System* consists of the atmosphere (air), the hydrosphere (liquid water), the cryosphere (ice), the lithosphere (rocks), and the biosphere (organisms), as well as the physical, chemical and biological processes within and among them. The study of Earth as a complex, adaptive *system* (see Information Box 3.3) is called *Earth System Science* (ESS). This book does not systematically refer to the ESS, but is very much a contribution to it. The book of Shikazono (2012) provides further reading on the ESS.

A first example of the unique characteristics of Earth is the presence of a significant atmosphere with a high concentration of free oxygen (O_2). Some other bodies in the Solar System also have significant atmospheres, but contrary to these bodies where the atmospheric concentration of O_2 is very low or even nil, the percentage of O_2 in the Earth's atmosphere is high: 21% by volume. This reflects the presence on Earth of organisms able to break up water molecules and release the O_2 they contain. It is the high concentration of O_2 in the Earth's atmosphere that allowed ecosystems to occupy the emerged lands. A second example is the generally moderate temperature that prevails at the Earth's surface, which varies within a relatively narrow range during the course of a day, and does not seasonally reach extreme values except in geographically limited regions. This narrow temperature range was one of the conditions that allowed organisms to establish themselves durably on Earth, and ecosystems to prosper. A third example is the existence on Earth of a large amount of liquid water, which is the key fluid of organisms. There is increasing evidence that water is also present on some other planets of the Solar System and also on some moons and dwarf planets and in comets, but contrary to these bodies where water is not liquid at the surface (or, at least, not permanently), more than 70% of the Earth's surface is covered with stable reservoirs of liquid water. A fourth example is the continual modification of the Earth's surface by large-scale motions of the rigid but mobile pieces of the crust (called *plates*) that together make the outermost shell of Earth. The success of ecosystems on Earth is intimately connected with the slow, large-scale motions—called *plate tectonics*—of these slabs of crust, as tectonic activity plays a key role in the recycling of carbon and other chemical elements essential to organisms. This recycling takes place among the ocean, the seafloor, the continents and the atmosphere, at geological time scales of millions of years.

Our analysis of the above and other characteristics of Earth in Chaps. 2–8 uncovers major *hidden connections* between ecosystems, planet Earth, the Solar System and the Universe. These connections have shaped the organisms and ecosystems in the forms they exist on Earth, and involve environmental characteristics of the planet as well as geological and astronomical characteristics of the Earth System and the Solar System. In the following chapters, we explore the principal environmental characteristics of Earth: the presence and retention of the atmosphere; the thermal and overall habitability of the planet for organisms; the prevalence of liquid water; the availability of the chemical building blocks of organisms; and the natural greenhouse effect. The geological and astronomical characteristics we consider include: the mass, rotation, gravity, geological activity and magnetic field of Earth; the motions of Earth around the Sun; the existence of the Earth-Moon system; actions of various bodies of the Solar System on Earth; and the role played by the gravitational pull of stars.

This chapter considers successively five aspects of the Earth System in the context of the Solar System: organisms, which are subject to evolution (Sect. 1.1.3); the Solar System, which is the homeland of Earth in the Universe (Sect. 1.2); Earth with its sister planets and their consorts (Sect. 1.3); brief history of the Universe (Sect. 1.4); and brief history of Earth (Sect. 1.5). The chapter ends with summary of key points concerning the connections between organisms, Earth, the Solar System, and the whole Universe (Sect. 1.6).

Sections 1.2–1.5 provide evidence of the following key interconnections between Earth, its organisms and ecosystems, and the cosmic environment:

Some connections of Earth with asteroids and comets, over distances of hundreds of millions of kilometres and times of billions of years, have largely determined the evolution of organisms and ecosystems.

Different astronomical characteristics of Earth, such as its short day-and-night rotation cycle and moderate axial tilt (angle between the planet's axis of rotation and the plane of its orbit around the Sun), have created conditions suitable for the establishment and the development of organisms and ecosystems on the planet.

Some aspects of the 13.7 billion-year evolution of the Universe explain key characteristics of Earth.

There has been a *co-evolution* of Earth and its organisms over the last 3.8 billion years.

Chapters 2–8 examine seven major hidden connections between ecosystems, planet Earth, the Solar System and the Universe. Chapter 9 explains how the interactions among several components of the Earth System create feedback loops that contribute to stabilize the environment of the planet. Finally, Chap. 10 weaves the threads spun in Chaps. 1–9 into a 4.5 billion-year tapestry called *The Legends of the Eons* (Fig. 10.1), and Chap. 11 looks at conditions of present Earth that contribute to the deterioration of this tapestry, and explore some aspects of the possible future state of the planet.

1.1.2 The Long Geological Times

Planet Earth and the Solar System are very ancient. As a consequence, this book often refers to very large numbers of years, that is, thousands, millions (thousands of thousands), and even billions (thousands of millions) of years. Such long durations are seldom used in day-to-day life, and could sometimes be confusing to readers.

Figure 1.1 summarizes the timescales of billions and millions of years, with reference to some of the key points in the history of the Earth System examined in this book. The billion-year timescale (left) identifies key events in the Earth System (left side) and the four phases of the atmosphere (right side). The million-year timescale (right) identifies the five mass extinctions of organisms documented by fossils (left side) and key events in the Earth System (left side).

Planet Earth is about 4.6 billion years old, and the oldest time generally considered in this book is 4.5 billion years, corresponding to the formation of Earth-Moon system (see Sect. 1.5.1). The references to the long timescales of billions, millions and thousands of years in this book follows some general rules:

When we refer to the very long period of 4.5 billion years, we generally express the time as a fractional number of billions of years, or equivalently hundreds of millions of years. For example, complex organisms began their occupation of emerged lands some time earlier than 0.4 billion or 400 million years before present (see Sect. 1.5.4).

When we refer to periods of millions of years, we generally express the time as a multiple or a fractional number of millions of years. An example of the first is the above reference to 400 million years. An example of the second is the Quaternary Ice Age in which we are currently living and which was marked by a succession of glacial and interglacial episodes that started 2.6 million years ago (see Sects. 1.3.4 and 4.5.2).

When we examine events that occurred in the last millions of years, we generally express the time as hundreds or tens of thousands of years. For example, there have been 30–50 successive cycles of glacial and interglacial episodes since the beginning of the Quaternary Ice Age, and their duration was initially around 40,000 years and then 100,000 years (see Sect. 4.5.4).

The same three units of time (100 million, 10 million, and 100,000) also correspond to the precision of the time values cited in this book. Billions of years have an uncertainty of 100 million (or 0.1 billion) years, for example 4.5 ± 0.1 billion years. Hundreds of millions of years have an uncertainty of 10 million years, for example 400 ± 10 million years. Millions of years have an uncertainty of 100 thousand (or 0.1 million) years, for example 4.6 ± 0.1 million years. These precisions are not stated throughout the book, for simplicity.

Finally, it should be noted that the word *period* has three different meanings in this book, depending on the context. First, a *period* is generally a length or a

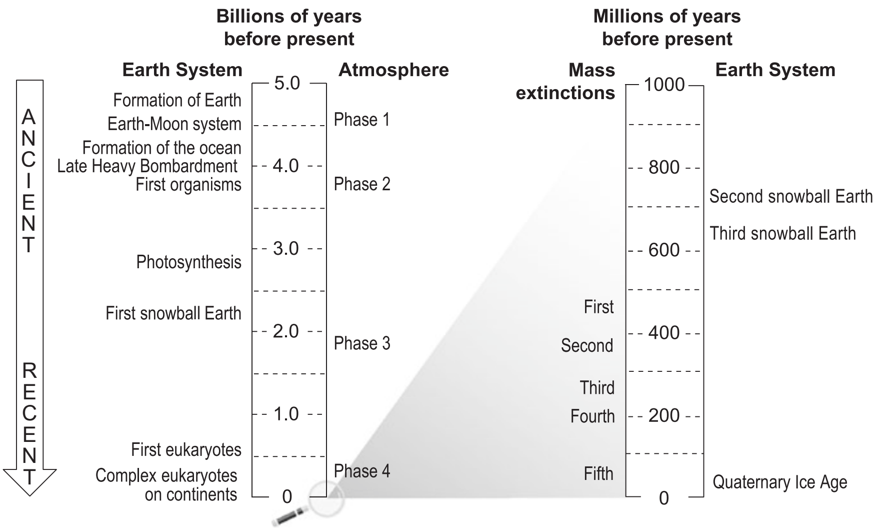

Fig. 1.1 History of the Earth System, with identification of key events described in this and subsequent chapters. Note the two different timescales: billions (*left*) and millions (*right*) of years before present. Credits at the end of the chapter

portion of time, as in the above paragraphs. Second, a *period* can be the interval of time between successive occurrences of the same state or event in cyclical phenomena, such as the movements of Earth and other astronomical bodies on their orbits (see Sects. 1.2.2 and 1.3.2). For example, the *orbital period* of Earth around the Sun is 1 year. Third, the word *period* can also designate a major division of geological time, as in Table 1.3. One example is the *Quaternary period*.

1.1.3 The Characteristics of Organisms

A central characteristic of Earth is the all-pervading occurrence of organisms over the planet. Life forms may well exist in various places in the Universe and even close to us in the Solar System, but Earth is, so far, the only astronomical body where organisms and ecosystems are known (by us) to be present. Furthermore, Earth is the only known astronomical body whose characteristics bear the signature of ecosystems. Organisms are ubiquitous in almost all Earth's environments, and they continually interact with physical, chemical and geological processes of the planet. These interactions between the organisms and the environment take place within and among the oceans, the seafloor, the continents and the atmosphere, and they largely determine the functioning of Earth.

Information Box 1.1 General Features of Organisms on Earth The definition of life is elusive, and many researchers, including biologists, physicists and philosophers have tried in the past to define life with varying success. Further reading on this topic is provided by the books of Schrödinger (2012, first published in 1944), Pross (2012), and Schulze-Makuch and Irwin (2018). Other researchers have proposed to try instead to identify the general features of organisms on Earth, such as in the scheme illustrated in Fig. 1.2.

The Earth's organisms comprise the three essential features shown schematically in Fig. 1.2, and a fourth not in the figure: *first*, the software, namely the genetic information encoded in nucleic acids; *second*, the hardware, consisting of the biochemical compounds (carbohydrates, lipids and proteins) and membranes of the cells, and the components (tissues and organs) and structure (body systems) of the bodies of multicellular organisms (that is, organisms consisting of more than one cell); and *third*, the flux of energy. The latter keeps organisms alive, meaning that organisms maintain their high level of internal organization through a continual intake and dissipation of energy: when the flux of energy stops, they die. An organism is alive only if it exhibits all three components shown in Fig. 1.2: software, hardware, and energy transfer (details on these three components are given in Sects. 6.1 and 6.2). In addition and *fourth*, organisms are capable of replication or reproduction, by either cell division or the production of *gametes* (germ cells in sexual reproduction) that allows them to perpetuate and multiply. Reproduction led to the development of large biomasses of organisms that were subject to biological evolution, which resulted in the massive and diversified ecosystems that progressively occupied the planet. Examples of the above are given in Chap. 6 (see Sect. 6.2.5).

Any list of general characteristics of organisms on Earth, such as those above, raises a number of philosophical questions about the definition of life. For example, viruses outside living cells have the software (genetic instructions) for the construction of new viruses, but they lack the hardware (machinery) to do it and they exhibit no energy flow. Because they lack these two properties (Fig. 1.2), viruses should be considered as inert particles, but they become alive when they infect a cell where they co-opt hardware and energy flows to produce new viruses (reproduction). Such considerations are important philosophically, and could also become crucial someday if humanity is confronted by extraterrestrial life that differs from terrestrial life. However, such concerns are outside the scope here, which focuses on the durable establishment of organisms on Earth and their takeover of the whole planet during about 4 billion years of biological evolution. Readers interested in exploring the general aspects of life can delve into the many books, articles and websites that investigate them.

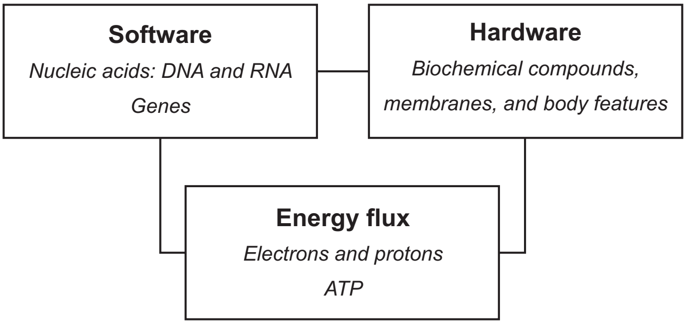

Fig. 1.2 Schematic representation of three key components of organisms on Earth. A fourth component (not illustrated in this figure) is replication or reproduction (see Information Box 1.1). Credits at the end of the chapter

Important biological and philosophical questions concerning the origin of life in the Universe and its evolution on Earth are addressed in many studies and books, among which those of Meinesz and Simberloff (2008) and Whittet (2017) provide further reading on this topic. The present book takes instead the existence of life on Earth for a fact, and focuses on the conditions that allowed organisms (see Information Box 1.1) to establish themselves durably on Earth and develop large biomasses there. During their conquest of Earth over the last billions of years, the ecosystems became one of the main factors that largely governed the evolution of the whole planet, and they will likely continue to determine its fate during billions of years to come. How did the above conditions developed and persisted over the first 4.6 billion years of Earth's existence, and in particular during the last 3.8 billion years in which ecosystems have progressively dominated the planet? This history did not occur elsewhere in the Solar System as far as we know. How is it that it happened on planet Earth?

1.2 The Homeland of Earth in the Universe: The Solar System

1.2.1 The Multifaceted Solar System

The homeland of Earth is the *Solar System*, which consists of the Sun, the eight planets and the billions of other astronomical bodies that move around it. We sometimes tend to imagine that our home planet, Earth, is quite isolated in the Universe, with our astronomical neighbourhood being limited to the Moon and a few closest planets. However, the reality is quite different since the Solar System is populated by billions of objects of many different types. These include the Sun, the planets and their moons (also called *natural satellites*); the word *moon* without

Information Box 1.2 The Astronomical Unit (AU) The distance between the centre of Earth and the centre of the Sun is 149,597,870,700 km. This distance defines what is called the *astronomical unit* (AU). Hence 1 AU = 150 million km.

The distance from the Sun to the outer edge of the Solar System is not certain, and may be around 100,000 AU. In order to develop an intuitive idea of such a distance, let us imagine that the distance between Earth and the Sun is 1 cm. Taking this distance of 1 cm as reference, the outer edge of the Solar System would be located 1 km from the Sun.

capital *m* is a synonym of *natural satellite*, and *Moon* with capital *M* is the name of Earth's moon. The objects found in the Solar System also include dwarf planets, meteoroids, asteroids, comets, centaurs and interplanetary dust. We will become acquainted with all these objects in the remainder of this chapter.

Most or all of the objects in the Solar System likely result from the condensation, more than four billion years ago, of interstellar gas (mostly hydrogen) and dust that previously occupied the region of space that is now the Solar System. In this chapter and following ones, we will see that various types of Solar System bodies played key roles in the past, and continue to do it today, in the development and maintenance of the conditions that allowed organisms to establish themselves durably and prosper on Earth. The interactions of these astronomical bodies and Earth contributed to the progressive build-up of large biomasses of organisms.

All the bodies in Solar System share certain common characteristics since they were all formed from the same *solar nebula* (a nebula is a cloud of gas and dust in outer space). However, other characteristics of these bodies can be very different depending on where and how they formed within the nebula and their history since formation. Similar to what travellers often do when they visit a new city for the first time, we will now take a general tour of the Solar System, before focussing on Earth and its ecosystems.

1.2.2 The Huge, Diverse, and Life-Bearing Solar System

Within the immense Universe, our Solar System homeland is very small. Indeed, the universe contains a very large number of galaxies (perhaps more than 2 trillions), of which our own galaxy, the Milky Way, is only one. The name *Milky Way* describes the galaxy seen from Earth. Indeed, far from city lights, our galaxy is seen in the night sky as a hazy band of light formed from 100 to 400 billion stars. The name comes Greek mythology, where the Milky Way is a trail of milk sprayed by the queen of the gods Hera when she was suckling baby Heracles (Hera and Heracles correspond to Juno and Hercules in Roman mythology).

Information Box 1.3 The Variety of Objects in the Solar System There is a wide variety of objects in the Solar System. The names of some of the most cited Solar System objects in this book are defined here, in alphabetical order. The names of other objects are defined in the text when they are first used.

Asteroid. A non-satellite body that fulfils only criterion (1) of a planet (see *Planet* below). An asteroid is also called *small Solar System body* or *minor planet*.

Centaur. A non-satellite body that has characteristics of both comets and asteroids.

Comet. Small, icy Solar System body that releases gases when passing near the Sun. This release of gases produces a visible atmosphere around the comet (called coma), and also sometimes a tail trailing it.

Dwarf planet. A non-satellite body that fulfils criteria (1) and (2) of a planet, but not criterion (3) (see *Planet* below).

Meteoroid. Same as an asteroid, but smaller.

Moon. An astronomical body that orbits a planet or a dwarf planet. The word *moon* without capital *m* is synonym of *natural satellite*, whereas *Moon* with capital *M* is the name of the moon of Earth.

Planet. Astronomical body that fulfils the following three criteria: (1) it is in orbit around the Sun, (2) it has a sufficient mass to achieve a round shape, and (3) it has cleared the neighbourhood around its orbit of other material (meaning that the planet has become gravitationally dominant around its orbit).

Galaxies are systems of millions to billions of stars, each surrounded with billions of bodies of various sizes and compositions, plus gas and dust, which are held together by gravitational attraction (see Sect. 6.6.1). Our own galaxy contains between 100 billion and 400 billion stars, of which our Sun is only one. And the Solar System contains billions of objects, of which our Earth is only one. These mind-bogglingly large numbers should not, however, distress us. Indeed, Earth is, so far, the only place in the Universe where we know that organisms have taken over a planetary body, and its homeland, the Solar System, is huge and contains a fascinating variety of astronomical objects (see Information Boxes 1.2 and 1.3).

This book focuses on the unique *Living Earth*, an expression explained at the end of this chapter (see Sect. 1.6). Further reading is provided by the book of Vita-Finzi (2016), for a compact history of the Solar System, and that of Cohen and Cox (2019), for an illustrated tour of the planets and other astronomical bodies of the Solar System.

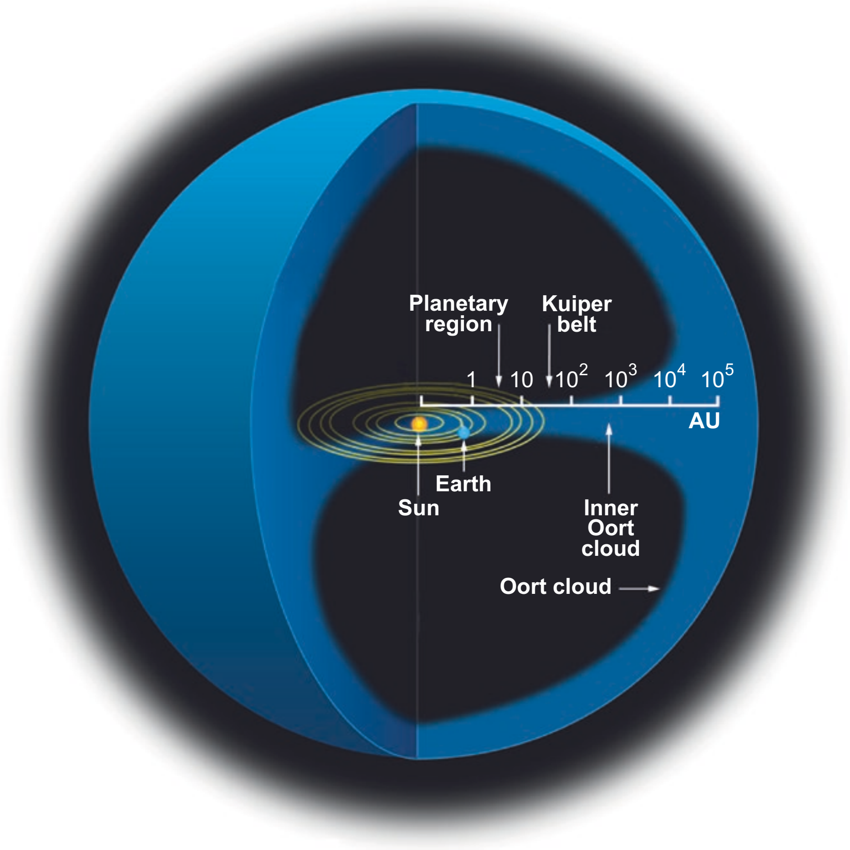

Fig. 1.3 Schematic representation of the Solar System: the Sun, at the centre; the orbits of the eight planets (planetary region); the Kuiper Belt; and the Oort cloud. Each interval in the distance scale from the Sun corresponds to a factor of 10: Earth is 1 AU from the Sun (Information Box 1.2), and the outer edge of the Solar System may be 100,000 AU. Credits at the end of the chapter

The Solar System consists of the *heliosphere*, which is the region of space influenced by the Sun (see Sect. 8.4.2), and the *Oort cloud* (Fig. 1.3). The existence of the Oort cloud beyond the heliosphere in interstellar space is predicted by models, but has not been supported by direct observations so far (Fig. 1.3). The heliosphere comprises the *planetary region*—with the eight planets, their moons, and the asteroid belt—and the Kuiper belt.

The Sun is at the centre of the Solar System, and like the other stars in the Universe, it continually radiates energy coming from the fusion of atoms in its core, primarily hydrogen (see Information Box 3.2). Most of this energy is radiated as light and heat (see Information Box 2.7). The diameter of the Sun is 1.4 million kilometres, or 109 times that of Earth. Its mass is 333,000 times that of Earth, and

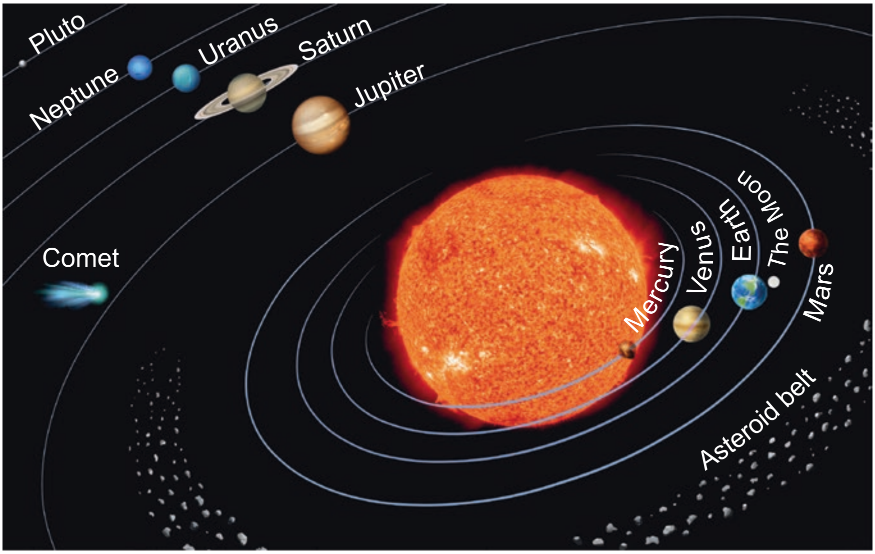

Fig. 1.4 Solar System. Illustrated in this figure: the Sun, the four rocky planets and our Moon, the asteroid belt, the four gas giant planets, dwarf planet Pluto (largest object in the Kuiper belt), and a comet. The scale is very far from reality. Credits at the end of the chapter

represents over 99% of the total mass of the Solar System. The Sun formed from the solar nebula about 4.6 million years ago, and when the first organisms appeared on Earth billions of years ago, the Sun was much cooler than it is now, this phenomenon giving rise to the *faint young Sun paradox* (see Sect. 3.7.1). Since then, the Sun warmed up to its present temperature, and is expected to continue to warm in the future. As a result, the Earth's environment is expected to become too hot for organisms within one to several billion years (see Sect. 11.3.5).

The Sun is orbited by eight planets divided in two groups of four, in order of increasing distance from the Sun: Mercury, Venus, Earth and Mars (*inner planets*, also called *terrestrial* or *telluric planets*), and Jupiter, Saturn, Uranus and Neptune (*outer planets*, also called *giant planets*) (Fig. 1.4). Most of the planets are accompanied by one or several moons.

The four inner and four outer planets are separated by a region of smaller astronomical bodies, the *asteroids*, called the *asteroid belt* (Fig. 1.4). The eight planets and their 205 moons are examined below (see Sects. 1.3.1–1.3.5). The asteroid belt contains more than half a million bodies of various shapes, called *asteroids* (see Information Box 1.3), and is located between about 2.1 and 3.3 AU from the Sun. Some of the large asteroids have their own moons, and almost 300 such moons have presently been identified in the asteroid belt. About half the mass of all the matter in the asteroid belt is made by four large asteroids named Ceres, Vesta, Pallas and Hygiea. Asteroid Ceres possibly contains liquid water (see Information Box 5.4). The objects in the asteroid belt are rocky remnants left over from the early formation of the Solar System about 4.6 billion years ago, and it is thought that Vesta and Ceres narrowly missed becoming planets. If these two asteroids had become large enough to join the planets, there would now be 10 planets in the Solar System.

Outside the orbit of planet Neptune, which is farthest from the Sun, there is a region called the *Kuiper belt*, which is similar to the asteroid belt but 20 times wider. It extends from the orbit of Neptune (30 AU from the Sun) to about 100 AU (15 billion kilometres). It contains some small bodies made of rocks and metals like those in the asteroid belt, but most objects in the Kuiper belt are frozen masses of volatile substances such as methane, ammonia and water. The adjective *volatile* identifies substances that evaporate easily at normal temperature and pressure (see Sect. 2.1.2). The Kuiper belt also contains three known dwarf planets (see Information Box 1.3), called Pluto, Haumea and Makemake, named respectively after the god of the underworld in Greek and Roman mythology, the goddess of fertility and childbirth in Hawaiian mythology, and the creator of humanity and god of fertility in Easter Island mythology. It is interesting to note that Pluto was formerly known as the ninth planet of the Solar System, but was reclassified as a dwarf planet by the International Astronomical Union in 2005 because it did not meet the third criterion of planets (see Information Box 1.3). Even if the Kuiper belt is located very far from Earth and most of its objects are small, more than 1300 bodies have presently been observed individually and identified as *Kuiper belt objects*. The overall number of objects in the Kuiper belt is not known, but it could be hundreds of millions or more.

Comets (see Information Box 1.3) are icy astronomical objects that move between the outer reaches and the inner region of the Solar System. They are remnants from the formation of the Solar System 4.6 billion years ago, and they mostly consist of ice and rocks, often coated with organic material. There are thousands of known comets, but it is thought that there are hundreds of billions of them, originating from both the heliosphere and the Oort cloud (described two paragraphs below). Comets are grouped in two broad types—short period and long period—based on the time taken by a comet to complete one orbit around the Sun, called the *orbital period*.

Short-period comets originate from the Kuiper belt. The qualifier *short-period* comes from the fact that these icy bodies orbit the Sun in less than 200 years. Given their short period, many comets have been recorded repeatedly in historical chronicles for thousands of years, reflecting in part that the passage of comets in the sky was often interpreted by astrologists and people in general as a divine sign. *Long-period comets* take thousands of years to orbit the Sun, and their occurrence led astronomers to propose the existence of the Oort cloud.

The *Oort cloud* is seen as a thick bubble of icy debris surrounding the heliosphere beyond the Kuiper belt. Although the Oort cloud has not been directly observed as yet, it is assumed that it occupies the region of space between 1000 and more than 100,000 AU (15 trillion kilometres) from the Sun, and contains hundreds of billions and even trillions of icy bodies. It has been proposed that long-period comets are icy bodies of the Oort cloud pulled into unique orbits by gravitational perturbations caused by stars passing near the Solar System. Astronomers divide the Oort cloud in a disk-shaped inner cloud and a spherical outer cloud (Fig. 1.3).

The number of astronomical objects of the different types in the heliosphere (not counting dust) is at last several billions, from the large Sun to the smallest rocky and icy debris. Earth is thus in good company. We will see in this book that life-bearing Earth was affected by many of its Solar System neighbours during the course of their long common history.

Despite the fact that asteroids and comets come from very far away from Earth, these Solar System bodies have very special significance for organisms because most of the water on this planet—a condition for the durable establishment of organisms and the development of ecosystems—may have been brought by asteroids or comets that impacted the surface of Earth a long time ago. While this issue is debated in the scientific community (see Sect. 5.3), it stresses the importance of the distant asteroid and Kuiper belts and Oort cloud as the sources of the water that contributed to the development of ecosystems on Earth.

It has also been hypothesized that comets carried to Earth already made organic compounds, which may have contributed to the emergence of the first organisms. The provision of water and organic compounds by comets could have also happened on other water-rich bodies of the Solar System, where life may thus exists presently or may have existed in the past. If so, comets were one of the main agents that prepared Earth for the widespread existence of organisms on the planet. Hence Earth's ecosystems may have largely benefited from inputs carried by asteroids and comets over huge distances and very long time periods.

1.3 Earth, Its Sister Planets, and Their Consorts

1.3.1 The Neighbourhood of Earth: The Planets

Robotic spacecraft exploration of the Solar System continually brings new information on its planetary bodies, and what is presented here reflects the current consensus on their composition and functioning, which is likely to change at least partly in the years to come. For example, the books published before 2005 reported nine planets including Pluto, now assigned to the dwarf planet category (see Sect. 1.2.2, above). The remaining eight planets of the Solar System are divided in two distinct groups (Fig. 1.4).

Planet Mercury is closest to the Sun, followed by Venus, Earth and Mars. Earth is the largest of these four relatively small planets. They all have hard, rocky surfaces and are thus *rocky planets* (Table 1.1).

Farther from the Sun are, in order of increasing distance, Jupiter, Saturn, Uranus and Neptune, the latter being the farthest planet from the centre of the Solar System (Table 1.1). These four planets are mostly made of gas, and because they are very large, they are called *giant planets*. While they probably have rocky cores, the largest two, Jupiter and Saturn, are called *gas giants* because they are

Table 1.1 Key characteristics of the eight planets of the Solar System. Most characteristics of the four rocky planets, which are relatively close to the Sun, are different from those of the two massive gas giants, which are further away, and the two ice giants, which are the most distant. https://solarsystem.nasa.gov/planetinfo/charchart.cfm

Planet[a]	Distance from the Sun (AU)[b]	Diameter (1000 km)	Mass (10^{24} kg)	Mean density (kg cm^{-3})	Orbital period (Earth years)	Rotation period (Earth days)[c]	Axial tilt (°)	Surface temperature (°C) min/max	Surface atmospheric pressure (atm)
Four rocky planets (also called terrestrial or telluric planets)									
Mercury	0.4	4.8	0,3	5427	0.2	59	0	−173/+427	10^{-14}
Venus	0.7	12.1	4.9	5243	0.6	−243[d]	2.7[e]	+462/+462	92
Earth	1.0	12.7	6.0	5513	1.0	1.0	23.4	−88/+58	1.0
Mars	1.5	6.8	0.6	3934	1.9	1.0	25.2	−153/+20	0.006
Two gas giant planets									
Jupiter	5.2	140	1898	1326	11.9	0.4	3.1		
Saturn	9.5	116.0	568	687	29.4	0.4	26.7		
Two ice giant planets									
Uranus	19.1	50.7	87	1270	84.0	−0.7[d]	82.2[f]		
Neptune	30.0	49.2	102	1638	164.8	0.7	28.3		

[a]Another object of the Solar System, Pluto, was considered as a planet until 2005, but is now classified as a dwarf planet. Pluto's distance from the Sun is 39.5 AU, and its mass is 0.01×10^{24} kg, or 0.002 time that of Earth

[b]Average distance between a planet and the Sun, with corresponds to half of the average length of the longest axis of the elliptic orbit of that planet (called *semi-major axis*)

[c]The planets, except Venus and Uranus, rotate from west to east (as most other Solar System bodies including the Sun)

[d]The negative sign indicates that the planet rotates from east to west

[e]Tilt seen from the north: 177.3°. Because of Venus rotates from east to west, its tilt away from the plane of the ecliptic is 180° − 177.3° = 2.7°

[f]Tilt seen from the north: 97.8°. Because Uranus rotates from east to west, its tilt away from the plane of the ecliptic is 180° − 97.8° = 82.2°

mostly composed of gases hydrogen and helium. The other two giant planets, Uranus and Neptune, are called *ice giants* because the materials incorporated into the planets during their formation were in the form of ice. Uranus and Neptune are mostly composed of volatile chemical elements heavier than hydrogen and helium, namely oxygen, carbon, nitrogen and sulphur, probably because the gravity exerted by their smaller masses was less efficient than that of Jupiter and Saturn at capturing light atoms of hydrogen and helium.

The eight planets differ widely in terms of distance from the Sun, size (diameter), mass, density (mass per unit volume), and other characteristics (Table 1.1). These particular and contrasting features contribute to the explanation, in following chapters, as to why Earth, while sharing some of the characteristics of other planets, was the only one on which organisms both established themselves durably and built up large biomasses.

The planets were formed more than 4.6 billion years ago by the accretion of matter from the solar nebula, and by successive collisions and/or fragmentations of the initial bodies. The *accretion* of a planet is the phenomenon by which its mass, under the influence of gravitational attraction, gradually increased by agglomerating surrounding matter. The latter was present in the forms of gas, dust debris and larger-sized objects. The present Earth did not completely form at that time. Indeed, Earth had two parent planets, which both emerged from the solar nebula. The collision of these two planets—called *proto-Earth* (or *Gaia*) and *Theia*—produced the Earth-Moon system about 100 million years after their formation (see Sect. 1.5.1). In the Greek mythology, Gaia was the goddess of Earth, and her daughter Theia was the mother of the Greek goddess of the Moon, called *Selene*. As a consequence, the name of Selene's mother, Theia, was given to the astronomical body involved in the formation of the Moon. The name *Gaia* is also used in the scientific literature to designate Earth viewed as a self-regulating system: see, for example, the book *The Ages of Gaia* of James Lovelock (1995).

Earth and the other seven planets (and most of the other Solar System bodies) revolve around the Sun along elliptic paths called *orbits*. Because the path of a planet around the Sun is not circular, its distance to the Sun changes continually with time, and the amount by which its orbit deviates from a perfect circle is called *eccentricity* (Table 1.1). Hence a circular orbit has an eccentricity of 0 (Fig. 1.5a). Over the course of one Earth year, the distance between Earth and the Sun varies between 147 and 152 million kilometres, with an average value of 150 million kilometres. The eccentricity of the Earth's orbit is calculated as follows: $(152 - 147)/(152 + 147) = 0.0167$. The eccentricity of the Earth's orbit is close to zero, which means that the Earth's orbit around the Sun is almost circular, but not perfectly so.

It is reported in the news from time to time that Earth will nearly encounter (or has nearly encountered) a relatively large object, such as a comet or an asteroid, whose path around the Sun will cross (or has crossed) that of our planet. The eccentricity of the orbit of these *Near Earth Objects* (NEOs) is much larger than that of Earth. For example, the eccentricity of Halley's comet, whose visits to the inner Solar System every 75–76 years have been recorded in archives since a long time (perhaps as early as 467 years before the Common Era), is 0.9671 (Fig. 1.5a). The very large

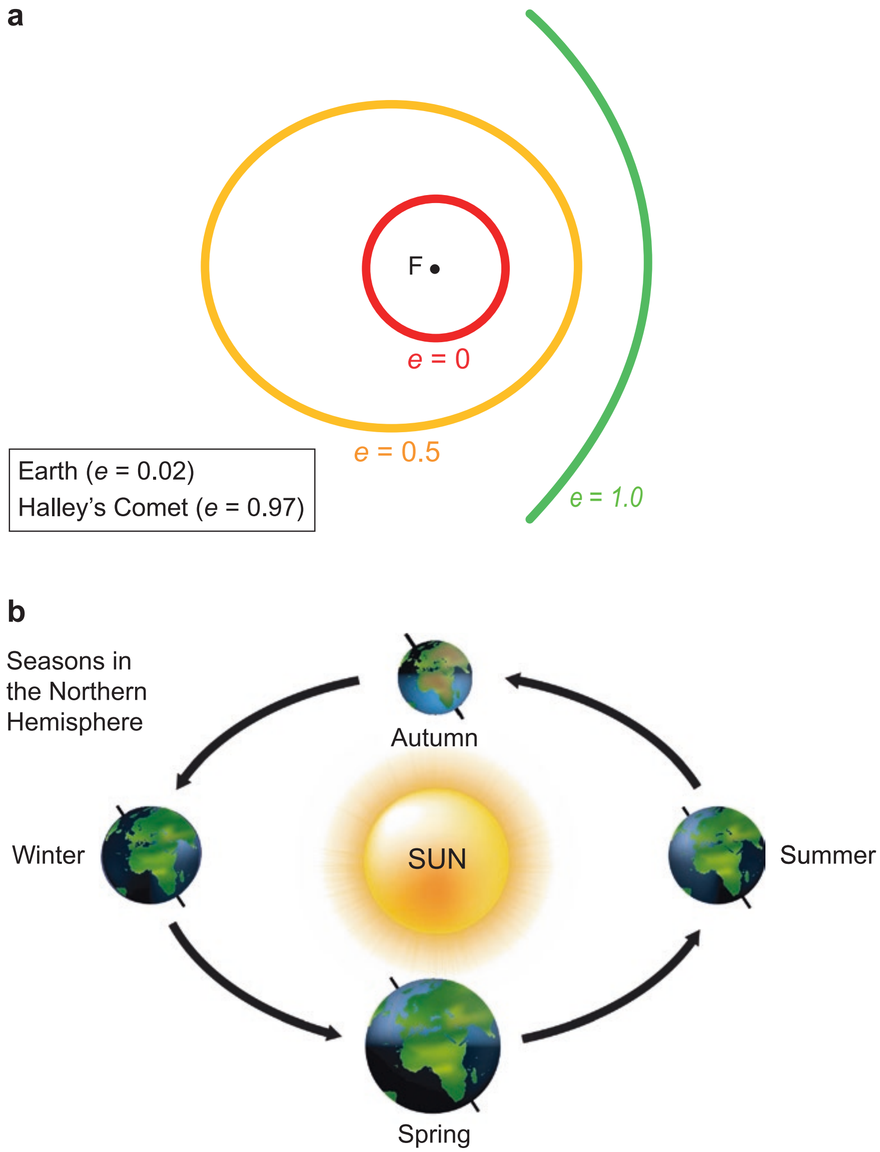

Fig. 1.5 Elliptical orbits. **a** Effect of eccentricity (e) on the shapes of three ellipses with the same focus (F) and $e = 0$, 0.5 and 1.0, respectively. The ellipses with $e = 0$ (circle) and 1.0 provide an idea of the real shapes of the orbits (not represented) of Earth and the Halley's comet, respectively. **b** Positions of Earth on its orbit at the time of the summer and winter solstices and spring and autumn equinoxes in the Northern Hemisphere. The elliptical form of the orbit in panel b is strongly exaggerated (compare with panel a). The effects of the positions of Earth on the seasons are detailed in Fig. 3.3. Credits at the end of the chapter

eccentricity of comets is explained by a destabilisation of their initial orbits by gravitational perturbations originating from inside or outside the Solar System.

The approaching NEOs are detected with increasingly powerful telescopes. Because the NEOs have very elongated elliptic orbits, their cycle of appearance within the range of our present means of detection may be very long, and it is thus difficult to calculate precisely the risk that Earth be hit by any one of them. Given that human civilisation could be seriously damaged if Earth were hit by a very large NEO (see Sect. 4.5.3), some space agencies and a number of governments are trying to improve the early detection of NEOs. These agencies and governments are also considering the development of technical means for possibly deflecting the trajectory of a NEO that would represent a major danger for Earth. In the distant past, Earth was often hit by very large NEOs, with consequences described below (see Sect. 1.5.1 and Information Box 1.6).

1.3.2 Rotation Period, Orbital Period, and Orbital Cycles (Eccentricity, Axial Tilt, and Axial Precession)

The day-and-night cycle corresponds to the time it takes for a planet or an asteroid to make one revolution around its axis, and this time is called *rotation period*. The rotation period of Earth is exactly 24 h when the Sun is taken as reference (this defines the duration of the solar day), whereas it is 23 h and 56 min when the duration of day is measured by reference to very distant objects, such as the *fixed stars* (that is, any star other than the Sun). The Earth's rotation period is the shortest among the four rocky planets, and that of Venus is the longest with 243 Earth days (Table 1.1).

The time taken by Earth to make a complete orbit around the Sun defines the duration of one Earth year. In the Solar System, the *orbital periods* of planets around the Sun range between 0.24 Earth year for the planet closest to the Sun, Mercury, and 164.8 Earth years for the planet farthest from the Sun, Neptune (Table 1.1). Three major characteristics in the orbits of the planets—the eccentricity, the axial tilt, and the precession—are subjected to cyclical variations called *orbital cycles*.

Eccentricity. The amount by which the orbit of a planet deviates from a perfect circle is called *eccentricity* (see Sect. 1.3.1). In fact, the current eccentricity value of 0.0167 cited above for Earth is not constant, and the eccentricity of the planet's orbit varies slightly from a quasi-zero value to about 0.058 over hundreds of thousands of years (Fig. 1.5a). The main component of this variability fluctuates with different periods that combine in an *eccentricity cycle* whose period is about 100,000 years. This cycle modifies the seasonal distribution of the solar energy incident on the surface of Earth with a period of about 100,000 years, which influences the long-term climate of the planet (see Information Box 1.4). This explains why the present duration of the glacial-interglacial episodes experienced by Earth since 2.6 million years, known as *Ice Age*, is about 100,000 years (see Sects. 1.3.4 and 4.5.2).

Information Box 1.4 Weather, Climate, and Climate Change The terms weather and climate are often used nowadays in relation with the ongoing global warming. These two words refer to different timescales.

The word w*eather* refers to changes in the conditions of the atmosphere over the short term. The timescales of weather range from minutes to months.

The word *climate* in the narrow sense refers to the average pattern of weather conditions in a given area over a period ranging from one or a few months to thousands or millions of years. The area may be a region, a continent, and even the whole Earth when *climate* is accompanied by the adjective *global*.

Climate in the wider sense is the state of the climate system. The *climate system* is defined in Chap. 3 as the highly complex system consisting of five major components—the atmosphere (air), the hydrosphere (liquid water), the cryosphere (ice), the lithosphere (rocks), and the biosphere (organisms)—and their interactions (see Sect. 3.5.1). The state of the climate system changes under the influence of its own internal dynamics and because of external forcings, which aspects are examined elsewhere in this book.

To avoid any confusion in the present text, we use *climate* for the average long-term pattern of the weather (narrow sense), and *climate system* for the wider sense of the above five major components, their interactions, and their responses to external forcing. The main variables considered by meteorologists and climatologists are temperature, humidity, atmospheric pressure, wind speed and direction, precipitation, and abundance of atmospheric particles.

The expression *climate change* means a change in the state of the climate in general. In the present text, we use *climate change* for changes in the state of the *climate system*. Various chapters examine past episodes of *natural climate change* and the ongoing *anthropogenic climate change*. The adjective *anthropogenic* means “originating in human activity”. Anthropogenic climate change and ocean acidification, which are two global effects of human activities, are examined in detail in Chap. 11 (see Sects. 11.1.1 and 11.1.3).

Axial tilt. The axis of rotation of a planet on itself is generally not perpendicular to the plane of its orbit around the Sun (called *plane of the ecliptic*), and the angle between the axis of rotation and the plane of the ecliptic is called *axial tilt* or *obliquity* (Fig. 1.6a). On a planet without axial tilt (such as Mercury), all latitudes receive the same insolation year round. Conversely, on planets having an axial tilt, there are seasonal variations in temperature proportional to the axial tilt (Table 1.1). These variations are very small on Venus, and moderate on Earth and Mars.

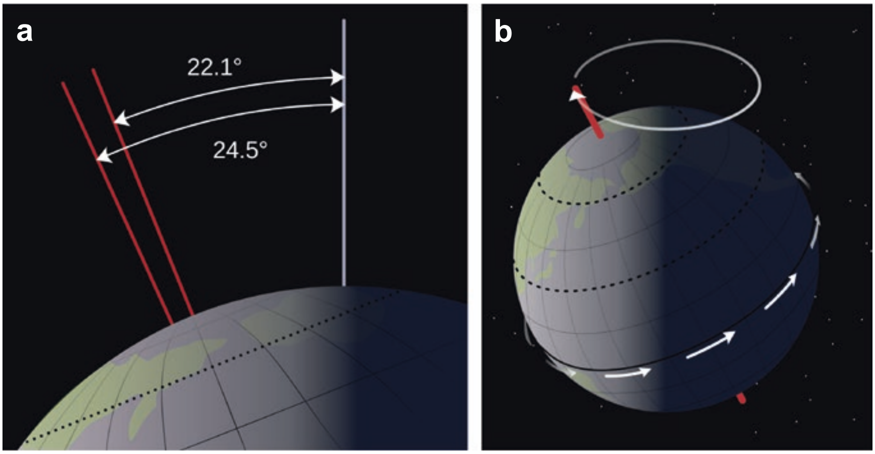

Fig. 1.6 **a** Axial tilt: the tilt of Earth's axis presently varies between 22.1° and 24.5° over a period of 41,000 years. **b** Axial precession: the orientation of the Earth's axis describes a cone in space over a period of 26,000 years. Credits at the end of the chapter

The current axial tilt of Earth is not constant, and varies between 22.1 and 24.5° over a cycle whose period is 41,000 years. It is thought that the axial tilt of Earth stays close to a value of approximately 23° because of the presence of the Moon. Indeed, the formation of the Earth-Moon system about 4.5 billions years ago (see Sect. 1.5.1) stabilized the Earth‘s axial tilt, but it is not known if the relatively stable values of the axial tilt were always near 23°.

Precession. The shape of Earth is not perfectly spherical, and the planet is flattened at the poles and bulges at the equator. Because of the presence of the equatorial bulge, Earth behaves as a slowly spinning top, that is, the axis of rotation of the planet changes its orientation by 1° every 72 years and thus describes a cone in space over a period of 26,000 years. This movement is called *axial precession* (Fig. 1.6b). One of the consequences of this movement is a gradual change in the occurrence of the Earth's equinoxes, and during one *precession cycle*, the Earth's equinoxes move progressively earlier in the year all the way back to the starting time at the end of the cycle. This backward movement in the occurrence of equinoxes is called *precession of the equinoxes*.

The *precession period* of Earth *relative to the fixed stars* (defined above), is 26,000 years. However, gravitational forces that other planets exert on Earth make the elliptical orbit of the planet rotate about the Sun, with the consequence that *the precession period experienced on Earth* is not 26,000 years but instead 21,000 years. The later period is, in fact, the combination of two periods, whose values are 19,000 and 23,000 years. It is explained in Sect. 3.3.2 that the precession of the equinoxes does not change the actual dates of the equinoxes in the current Gregorian calendar.

Although the above aspects of celestial mechanics is a bit complicated, the orbital cycles are important within the context of this book because they are integral components of the Milankovitch cycles. The three orbital cycles provide a key explanation for the succession of glacial and interglacial episodes of the current Ice Age (see Sect. 1.3.4).

1.3.3 Effects of Earth's Characteristics on Liquid Water and the Seasons

Two astronomical characteristics of Earth have favoured the long-term presence of water in liquid form on the planet, which was a key condition for the success of organisms. The *short day-and-night rotation cycle* distributes the solar heat quite uniformly and rapidly all around the planet, which generally prevents the occurrence of temperatures that would be too cold or too hot for the existence of liquid water. Conversely, the very long rotation period on Venus (243 Earth days, Table 1.1) may have contributed to the early loss of water in the history of that planet (see Sect. 5.5.4). The *moderate axial tilt* contributes to the lack of extreme seasonal variations in temperature at most latitudes, which also favours the occurrence of temperatures at which water is liquid. These two astronomical characteristics thus strongly contributed to the successful and long-lasting establishment of organisms on Earth and build-up of large biomasses.

In addition, two axial characteristics of Earth—the axial tilt and the axial precession—also affect the seasons.

The *axial tilt* is responsible for the magnitude of the differences in temperature among seasons. Because the tilt of the Earth's axis is the same year-round (that is, regardless of where Earth is in its orbit around the Sun), the Northern Hemisphere is directed towards the Sun on one side of the orbit in May–July, and away from the Sun half an orbit later in November–January, which causes the existing seasonal changes in Earth's temperature (left and right sides, respectively, of Figs. 1.5b and 3.3). Conversely, the Southern Hemisphere is directed away from the Sun in May–July, and towards the Sun in November–January. This explains why the seasons are opposite in the two hemispheres. Although the seasonal changes are large within a year, the variations in the magnitude of the seasonal differences induced by variations in the axial tilt, for example between glacial and interglacial episodes (see Sect. 1.3.4, below), are generally moderate except at the high latitudes of the two hemispheres. The moderate value of the Earth's axial tilt, which varies between 22.1° and 24.5° over a cycle of 41,000 years, favours generally mild seasonal differences in temperature.

The *axial precession* modifies the seasons in which Earth is closest to the Sun and farthest from it, which increases the seasonal contrast in one hemisphere while decreasing it in the other, and this change occurs over a period of 21,000 years (see Sect. 1.3.2). Currently, Earth is closest to the Sun during the

Northern Hemisphere winter (or the Southern Hemisphere summer), which makes the winters in the Northern Hemisphere generally less severe than in the Southern Hemisphere at comparable latitudes.

1.3.4 Milankovitch Cycles

The position of Earth relative to the Sun varies in the long term over different periods (see Sect. 1.3.2, above): the eccentricity of the Earth's orbit varies over periods that combine in a cycle of about 100,000 years; the Earth's axial tilt varies over a cycle with a period of 41,000 years; and the precession cycle experienced on Earth has a period of 21,000 years (Fig. 1.7). The combined effect of these cycles on the solar heat reaching Earth contributes to explain the succession of glacial and interglacial episodes, called *glaciation* or *Ice Age*, which have affected Earth since the beginning of the Quaternary period 2.6 million years ago. This explanation was proposed in 1920 by the Serbian researcher Milutin Milanković (name generally written *Milankovitch* in English), and the three orbital cycles are consequently now known as *Milankovitch cycles* (see Sect. 4.5.2).

Information on the Quaternary Ice Age is documented by various natural records of Earth such as air bubbles trapped in glaciers and the chemical composition and microfossils of marine sediments. Deciphering these natural records is a very difficult task, similar to decoding ciphers or reading ancient languages. Nevertheless, researchers have progressively accumulated data on a number of climate characteristics that include past atmospheric and oceanic temperatures, sea level, gas composition of the atmosphere, and seawater salinity. The information recorded in marine sediments goes back in time to the beginning of the Quaternary Ice Age and beyond, whereas ice-core records from Antarctica do not go farther than one million years.

The relationships between the changes in solar heat corresponding to variations in the three astronomical cycles in Fig. 1.7 and the Quaternary climate variations are generally not direct. This is because the effects of changes in solar heat on the climate are modulated by a large number of interacting factors. These include: the growth and retreat of forests at continental scales; the uptake and release of climate-active gases (CO_2 and others) by oceans and terrestrial peat; and changes in the reflection of solar energy by the snow and ice cover and by clouds. Paleoclimatologists have incorporated the effects of these factors into complex numerical models that simulate the past climate based on the 100,000-, 41,000- and 21,000-year astronomical cycles. Such models show that the Milankovitch cycles are undoubtedly the major cause of the climatic variations that occurred during the Quaternary period, but these cycles do not fully explain all the recorded events, nor their timing or amplitudes. Research continues on the fascinating links that exist between astronomical cycles that take place over millions of kilometres in the Solar System and changes in the climate of planet Earth at much smaller spatial scales.