Conceptions of Cosmos

From Myths to the Accelerating Universe: A History of Cosmology

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INTRODUCTION

The term 'cosmology' derives from Greek, essentially meaning the rational or scientific understanding of the *cosmos*, a word which to the ancient Greeks carried connotations such as 'order', 'regular behaviour' and 'beauty' (it is no accident that the words 'cosmology' and 'cosmetology', or 'cosmos' and 'cosmetics', are so similar). The wildly ambitious claim that the universe can be described rationally—that it is a cosmos, not a *chaos*—had its origin in ancient Greek natural philosophy, which consequently must occupy a central place in any comprehensive history of cosmology. Although in Chapter 1 I refer briefly to the cosmological views of non-Western cultures, the present book is concerned with the development of the scientific understanding of the universe, which effectively means that it is a contribution to the history of science in the European cultural tradition. Incidentally, although attempts to understand the universe in scientific terms go back to the very birth of science, until the twentieth century the word 'cosmology' was rarely used in a scientific context. The first books that carried the word in their titles date from the 1730s. As will become clear, cosmology did not have a professional identity until after the Second World War. Strictly speaking, there were no 'cosmologists' before that time, only scientists who ocassionally dealt with questions of a cosmological nature. Although it is a bit anachronistic to refer to these scientists as 'cosmologists', it is a convenient label and I have made no particular effort to avoid it.

The domain of cosmology is a frightening concept, the *universe* or the cosmos in the sense of everything that has (or has had, or will have) a physical existence, whether matter, energy, space, or time. I use the two words 'cosmos' and 'universe' synonymously, and also do not distinguish them from the word *world*. In German and the Scandinavian languages this all-encompassing concept is sometimes known as 'all'; compare the German *Weltall*. Cosmology in the traditional sense refers principally to the study of the structure of the universe, what in the seventeenth century was often known as *cosmography*, a term which stresses the mapping of the universe and which could also refer to what we would consider as geography today. Indeed, when Ptolemy's famous geographical work (*Geographia*) was first translated into Latin in 1406, it carried the title *Cosmographia*. Whereas cosmology and cosmography were sciences dealing with a static world, *cosmogony* means literally the study of how the universe came to be what it is and so includes a temporal dimension. However, the term is not widely used any longer, and today the evolutionary aspects of the universe, including its so-called creation, are included under the label 'cosmology'.

Confusingly, cosmogony and cosmography often referred to the planetary system (its formation and description, respectively) rather than the universe as a whole, as may be exemplified by Petrus Apianus' *Cosmographia* of 1524 and Henri Poincaré's *Hypothèses cosmogoniques* of 1913. Neither of these works was about cosmology, in the present meaning of the term. *Cosmophysics* may come closer, but this was originally a name employed for a mixture of astrophysics, meteorology, and geophysics, with little concern for the universe at large. The term may first have been used by the German Johannes

Müller, the author of *Lehrbuch der kosmischen Physik* (1856), and in 1903 the Swedish chemist Svante Arrhenius published a massive work in two volumes with the same title. Neither Müller nor Arrhenius had much to say about physical cosmology as we understand the subject today.

It should, further, be pointed out that the word 'cosmology' is sometimes used in a sense very different from the scientific study of the universe. One may, for instance, speak of communist cosmology, romantic cosmology, or the cosmology of Australian aboriginals, in which case one refers to the world view of the corresponding group or era (in German, *Weltanschauung* rather than *Weltbild*). The world views of individuals, periods, or societies may be related to the more narrow, astronomically oriented meaning of cosmology, but this is not generally the case. For instance, the philosopher Stephen Toulmin published in 1982 a book with the title *The Return to Cosmology*, an analysis of leading intellectual 'cosmologists' such as Arthur Koestler, Teilhard de Chardin, and Jacques Monod, none of whom have contributed to the study of the physical universe. Likewise, the fact that Alfred Whitehead's *Process and Reality* of 1929 was subtitled *An Essay in Cosmology* does not make it relevant to astronomers and physicists trying to understand the world. Nor is that the case with the Russian philosopher Peter D. Ouspensky's *A New Model of the Universe*, first published in 1914.

In a wider historical perspective, cosmology as a world view or an ideology cannot be cleanly separated from cosmology as a science. Indeed, the latter largely grew out of the former, and consequently the historian has to deal with both. Even when focusing on the scientific aspects of cosmology, as I do, one cannot ignore the philosophical and religious dimensions, which for a long time were inextricably connected with scientists' efforts to unravel the secrets of the universe. This connection was particularly strong in the old days, especially before the Enlightenment period, after which it weakened. However, it never disappeared completely and probably never will. (Those who believe that cosmology has nowadays severed its links to philosophy and religion should consider the anthropic principle and so-called physical eschatology, topics which will be discussed in Section 5.3.)

From an epistemic and sociological point of view, cosmology is a peculiar science, unlike any other. Historians have traditionally investigated its development either from the perspective of the history of ideas and culture or as part of the history of astronomy. There certainly is a tight connection between astronomy and cosmology, but in my view it would be a mistake to look at cosmology as merely a subfield of the astronomical sciences. This is not the case today, and it was not the case in the past. In fact, for long periods of time astronomers wanted to have as little as possible to do with questions of cosmology and cosmogony, fields they were happy to leave to the philosophers. It has been my intention to write a history of how scientists—or, until fairly recently, natural philosophers—explored and thought of the universe and how they, in the process, changed the very meaning of it. Astronomers always played a most important role in this development, but they were not alone. Contrary to most other histories of cosmology, I pay close attention to reasoning based on physics and chemistry. Mathematical modelling compared with astronomical observations may have been the single most important approach to the study of the universe, but there have always been people who considered the heavens in material terms, as something chemists and physicists could investigate. 'Physical cosmology' is generally believed to be an invention of the second half of the twentieth century, something only made possible by the discovery in 1965 of the cosmic microwave background, but this view I believe is contradicted by history.

There is no one way to write the history of cosmology, just as there is no one way to write the history of any other field of science (or branch of history in general). I have chosen to present the development rather broadly, to include physical and philosophical perspectives alongside the unavoidable astronomical perspectives. As far as chronology is concerned, I highlight the twentieth century, which is given as much space as the entire previous development. I believe this is justified for at least two reasons. For one thing, the history of pre-twentieth-century cosmology is well covered by the existing literature. For another thing, and more importantly, scientific cosmology has changed drastically since the early part of the twentieth century (more precisely, since 1917), which marked a new and revolutionary phase in the age-old study of the universe. The development since Einstein's breakthrough during the First World War, and even more so since the 1960s, has been so remarkable—and so sketchily covered by historians—that it needs to be given high priority. It goes without saying that this is no easy job and that my account can undoubtedly be criticized. It is an especially difficult task to cover recent developments, not only because they are so varied and confusing, but also because it is difficult to judge their historical significance. But this is a general problem for any kind of recent historiography.[1] In any case, I feel that a somewhat inadequate and objectionable historical account of modern cosmology is better than no history. It is about time that historians of science discovered the immense richness of modern cosmology, and it is my hope that this book may be a modest contribution to changing the state of affairs.

The structure of the book is, by and large, chronologically organized. The earliest cosmological views we know of, those of the Mesopotamian and Egyptian cultures, were cosmogonies rather than cosmographies. They were mythical tales of how the world and the gods came into existence, to be followed by the first humans. This is dealt with in Chapter 1, which proceeds to consider the Greek cosmos, first in its speculative–philosophical version and next as developed into a scientific model by Eudoxus, Aristotle, Hipparchus, Ptolemy, and others. The Aristotelian–Ptolemaic picture of the world was, in a Christianized version, adopted by the theologian–philosophers of the Middle Ages, who turned it into a pillar not only of knowledge but also of faith. The stable medieval world picture was, however, challenged by Copernicus' heliocentric system of 1543, an innovation which heralded the coming of a new age. The Copernican universe was immensely larger than the traditional universe, yet the two rival world systems had much in common, including their shared conception of the stellar system as a huge spherical shell populated with countless stars. Also, both systems presupposed that the universe had a centre and that the heavenly bodies moved uniformly in circles, a view which was finally abandoned a couple of decades after Kepler introduced ellipses as the true planetary orbits.

Chapter 2 describes some of the advances in astronomical and cosmological knowledge from Newton in the 1680s to Hubble in the 1920s, a long period in which progress occurred by astronomical observations rather than theoretical innovations. Newton's universal law of gravitation became the cornerstone of theoretical astronomy and the basis of the first scientific (or scientific-looking) cosmogonies in the magnificent style of Kant and Lambert. In the second half of the eighteenth century an evolutionary perspective made its entry into cosmology, a trend which continued in the nebular world view of the following about 1820 it becomes rare to find references to God in scientific works on the cosmos.

The invention of spectroscopy in 1860 introduced for the first time a physical (and chemical) dimension to cosmology, providing new and fruitful ways to deal with the riddle of the nebulae. At the same time, the laws of thermodynamics were used to discuss the long-term development of the universe, its fate in the far future, and its possible origin in an unknown past. These discussions of a more speculative nature were not of great concern to the astronomers, who preferred to use their telescopes to obtain positive knowledge about the universe in its present state. By the turn of the century, one of the great questions concerned the size of the Milky Way and the distribution of the nebulae. These difficult problems, epitomized in the 'Great Debate' of 1920, were solved when it became possible to determine the distances to some of the nebulae. It turned out that they were at vast distances, island universes majestically floating around in the vast sea of space.

The work done by observational astronomers was of little relevance to Einstein's development of the general theory of relativity and its subsequent transformation into a theory of a closed universe. As we can see today, but which was far from obvious at the time, Einstein's work marked a watershed in the history of cosmology, easily comparable to the Copernican revolution. The main part of Chapters 3 and 4 deal with aspects of the amazing consequences of Einstein's cosmological field equations. The static nature of the universe had a paradigmatic status in early relativistic cosmology, to the extent that the first theories of an evolving universe were ignored. Only in 1930, when Hubble's observations were combined with the theoretical insights of Friedmann and Lemaître, did the expanding universe become part of mainstream cosmology. We may be tempted to identify the expansion of the universe with relativistic cosmology, and also to think that it led automatically to the notion of a finite-age universe, but history shows otherwise. Cosmologists could favour a universe with an origin in time without subscribing to general relativity; and those in favour of the relativistic theory of the expanding universe could deny that it had a definite age.

The emergence and development of the Big Bang theory of the universe, from the mid-1940s to the late 1970s, forms the main part of Chapter 4. In the early 1950s, Gamow and his collaborators had developed a sophisticated model of the early universe based on nuclear physics, the first version of hot Big Bang cosmology. The theory came to a halt, though, and it took more than a decade until it was developed further and became generally accepted. An important reason for the non-linear development of cosmology in that period was the emergence of a strong rival theory of the universe in the form of the steady-state cosmology of Bondi, Hoyle, and Gold. The controversy between this theory and relativistic evolutionary theories is a classical case in the history of cosmology, described in greater detail in my *Cosmology and Controversy* of 1996. New observations, in particular the discovery of the cosmic microwave background radiation in 1965, killed the steady-state theory, which by 1970 was no longer taken to be a serious alternative by the majority of astronomers and physicists. The hot Big Bang theory quickly became the paradigm of the new cosmology, a field which for the first time emerged as a scientific discipline with its own standards and rules for solving problems. It short, cosmology became a scientific profession.

Chapter 5 summarizes the most important developments since about 1980. On the theoretical side, the inflationary scenario of the very early universe led to a minor early-universe cosmology. Even more important was that the standard Big Bang model of the 1970s began to lose its status as observations indicated that the universe was in a state of accelerated expansion. It was believed for theoretical reasons that the energy-mass density was critical, but even when the large amounts of hypothetical dark matter were taken into account it was not enough. By the end of the millennium many cosmologists believed that the main part of the universe consisted of a 'dark energy', which was possibly a form of quantum vacuum energy. Most remarkably, in this way Einstein's controversial cosmological constant made a dramatic comeback on the cosmological scene. Progress in cosmology during the last couple of decades has been mainly observation-driven, yet at the same time interest in highly theoretical and in part speculative areas of cosmology has flourished. In the final sections I offer a characterization of some of the more speculative areas which, whatever their scientific merits, have greatly appealed to the public. They have helped make modern cosmology a fashionable science far beyond the world of research cosmologists.

It goes without saying that the book covers the development of cosmology incompletely. There are many names, events, and themes that are not included, and some that are mentioned only too briefly. At the end of the book I take up a few themes which are best treated in a broad, non-chronological perspective, such as the importance of technological innovations for the progress of cosmological knowledge. I also comment on various questions of a more philosophical nature, not in order to 'philosophize' about cosmology but because they have been recurrent themes in the historical development of cosmology. In 1996, after having been in the business of cosmology for some thirty years, Stephen Hawking wrote:

> Cosmology used to be considered a pseudoscience and the preserve of physicists who might have done useful work in their earlier years, but who had gone mystic in their dotage. . . . However, in recent years the range and quality of cosmological observations has improved enormously with developments in technology. So this objection against regarding cosmology as a science, that it doesn't have an observational basis, is no longer valid.[2]

Hawking was right about the last part—observations of cosmological relevance have improved enormously—but his appreciation reveals an inadequate understanding of the history of cosmology, to put it gently. As this book demonstrates, cosmology as a science dates back much farther in time than the 'recent years' Hawking talked about. I see no reason why Aristotle's cosmology, or that of later researchers such as Copernicus, Newton, William Herschel, and Hugo von Seeliger, was not 'scientific'. Granted, their cosmologies were not very scientific by our standards, but then, how will cosmologists five hundred years from now look upon the current relativistic Big Bang theory of the universe?

Notes

1. On the problems and promises associated with writing the history of contemporary science, see Söderqvist 1997.
2. Hawking and Penrose 1996, p. 75.

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FROM MYTHS TO THE COPERNICAN UNIVERSE

1.1 Ancient cosmological thought

Cosmology, in the elementary sense of an interest in the natural world and the heavenly phenomena, predates science and can be traced back several thousand years before humans learned to write and read. The cave dwellers knew how to communicate by means of pictures, as we know from the fascinating artwork found in the Lascaux caves in France and the Altamira caves in Spain, for example. Some of this cave art possibly had an astronomical significance. There are drawings that may symbolize the Sun and others that have been interpreted as depictions of the phases of the Moon. If so, they provide evidence that *Homo sapiens* had a sense of wonder about the universe more than 10 000 years ago.

Evidence of a different kind, and relating to a later period in pre-literary culture, comes from the arrangements of large stones—megaliths—that are found many places in Europe, most notably in Great Britain, and which date back to around 3500 BC. The most famous of these impressive megalithic documents is undoubtedly Stonehenge in southern England. For what purpose was the enigmatic Stonehenge projected and constructed? Nobody knows for sure, but today it is widely accepted that it partly served astronomical purposes, that it was a huge megalithic observatory or 'an astronomical temple', as John Smith suggested as early as 1771. More than a century later, the idea appealed to the prominent astrophysicist Norman Lockyer, who was convinced that the Egyptian pyramids had astronomical orientations and saw no reason why that shouldn't be the case with Stonehenge as well. In 1906 he argued his case in a book titled *Stonehenge and Other British Monuments Astronomically Considered*, but the book failed to convince the majority of astronomers and archaeologists. Lockyer may be considered the father of archaeoastronomy, but it was only in the 1960s that the field took off, revived in particular by the British–American astronomer Gerald Hawkins. Appropriately, his classic papers of 1963 and 1964, 'Stonehenge decoded' and 'Stonehenge: a Neolithic computer', appeared in *Nature*, the journal that Lockyer had founded nearly a century earlier.

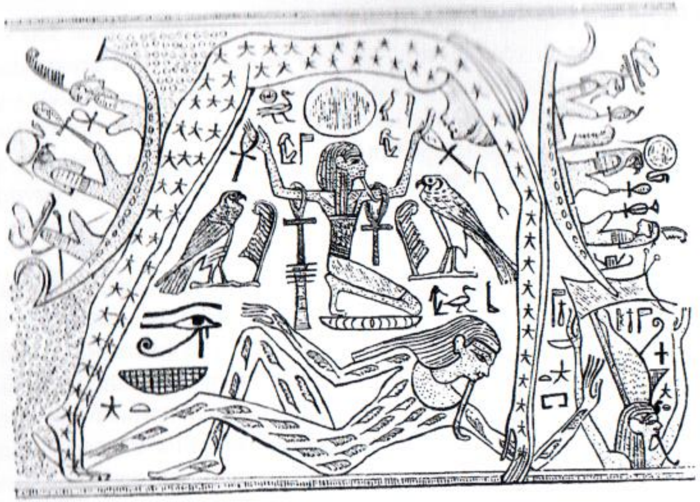
Hawkins's arguments in favour of British archaeoastronomical activities aroused a good deal of controversy but also attracted positive responses and helped to create an interest in the field. Among the early supporters of archaeoastronomy was Fred Hoyle, the eminent astrophysicist and cosmologist, who entered the debate in 1966, and in 1977 gave a full presentation of his ideas in his book *On Stonehenge*. During the last couple of decades, archaeoastronomy has flourished, and claims that at least some of the megalithic monuments were observatories of a kind are today generally accepted.[1] It seems that humans, even in pre-literary times, had a keen interest in astronomical phenomena and constructed sophisticated tools to study celestial motions. Unfortunately, archaeoastronomy tells us little about the cosmological views of Neolithic man, his conception of the structure of the universe, and how it came into being.

The ancient Egyptians thought of the world as consisting of three parts. The flat Earth, situated in the middle, was divided by the Nile and surrounded by a great ocean; above the Earth, where the atmosphere ended, the sky was held in its position by four supports, sometimes represented by poles or mountains. Beneath the Earth was the underworld, called Duat. This dark region contained all things which were absent from the visible world, whether deceased people, stars extinguished at dawn, or the Sun after having sunk below the horizon. During the night, the Sun was thought to travel through the underground region, to reappear in the east next morning.

Although the universe of the Egyptians was static and essentially timeless, apparently they imagined that the world had not always existed in the form in which they knew it. Theirs was a created world, the creation being described in cosmogonies, of which there existed at least three different versions.[2] Common to them is that they start with a state of primeval waters, a boundless, dark, and infinite mass of water which had existed since the beginning of time and which would continue to exist in all of the future. Although the gods, the Earth, and its myriads of inhabitants were all products of the primeval waters, these waters were still around, enveloping the world on every side, above the sky, and beneath the underworld.

To the Egyptians, the universe and all its components were living entities, some of them represented as persons. The original watery state of chaos was personified as the god Nun, who, in one of the cosmogonies associated with Heliopolis ('the city of the sun'), gave rise to Atum; according to other versions, Atum emerged out of the primeval waters, as a hill or standing upon a hill. Atum was the true creator-god, and he created out of himself—by masturbation, according to one source—two new gods, one personified as Shu, god of the air, and the other as Tefenet, goddess of rain and moisture. A passage from the Book of the Dead expresses the first creation as follows: 'I am Atum when I was alone in Nun; I am Re in his [first] appearances when he began to rule that which he had made,. . .[meaning that] Re began to appear as a king, as one who existed before Shu had lifted [heaven from Earth], when he [Re] was on the primeval hillock which was in Hermopolis.' The Earth and the sky came next, represented by the deities Geb and Nut, respectively. However, the Earth and the sky had not yet been created as separate parts, for initially they were locked closely together in a unity. It was only when Shu raised the body of Nut high above himself that the heavens came into existence; at the same time Geb became free and formed the Earth. The creation story continues with the emergence of a variety of new gods, but what has been said is enough to give an impression of the nature of the Egyptian cosmo-myths.

Another text, dating from the old kingdom in Memphis (about 2700–2200 BC), likewise includes Nun as the original god of the waters, but it differs from the other cosmogonies by speaking of an even more original god or spirit, Ptah, who is described more abstractly as a cosmic eternal mind, the maker of everything. Ptah was the one god, a cosmic intelligence and creator who was responsible for all order in the universe, physical as well as moral. Atum and the other gods were said to emerge from Ptah, or be contained in him, Atum being the heart and tongue of Ptah. According to the text, 'Creation took place through the heart and tongue as an image of Atum. But greatest is Ptah, who supplied all gods and their faculties with [life] through his heart and tongue—the heart and tongue through which Horus and Thoth took origin as Ptah.'[3]



;. 1.1 The Egyptian creation story. Shu, the god of air, separates Earth and heaven, personified by Geb and the goddess Nut, who are dressed in leaves and stars, respectively. The daily journey of the Sun is represented by a god in a boat traversing the sky from east to west. Reproduced from J. Norman Lockyer, *The Dawn of Astronomy* (London: Cassell and Co., 1894), p. 35.

Many of the features of Egyptian cosmology, as sketched here, can be found in other cient cosmologies, both in the Near East and elsewhere. Generally, these depict the universe as a dynamic entity, something which was created and is full of life, change and activ- —cosmology and cosmogony were intertwined and parts of the same story. On the other nd, the extant texts have disappointingly little to say about the geometry of the universe, aspect which came to be central in scientific cosmology but which was of no importance the Egyptians or other ancient cultures. For example, the Egyptian texts tell us nothing out the spatial location of Duat, except that it is symmetric to the visible world. As has ready become clear, the universe of the ancients was thoroughly mythological and it ould be a grave mistake to try interpreting it in scientific terms. Gods, often personified, ere the central players in the cosmologies of the ancient world. Not only were objects, rces, and places associated with such gods, the same could also be the case with abstract oncepts such as time and victory (which in Greek mythology were identified with the god hronos and the goddess Nike).

Mesopotamian cosmology was essentially a mythological tale, and the tale has some imilarities with that told in Egypt. The universe was ruled by three gods, each with their eparate domain. Heaven was ruled by Anu, the Earth and the waters around and below it vere the domain of Ea, and Enlil was the ruler of the air in between (the names here are hose used by the Babylonians; the earlier Sumerian names were different). Although Anu vas thought of as a kind of father god, he only ruled the universe as part of a triumvirate, ogether with Ea and Enlil. Not unlike the Egyptian cosmology, the gods were descended

Fig. 1.2 The Sun (Samas), the Moon (Sin), and Venus (Ishtar), placed in the centre of a Babylonian monument from the twelfth century BC. The three celestial bodies are surrounded by a heavenly army of animals. Reproduced from Schiaparelli 1905, p. 80.

from a primeval chaos of waters, in this case a mingling of salt water and sweet, associated with the goddess Tiamat and the god Apsu, respectively. Again in conformity with the Egyptian myths, what came to be the domains of Anu and Ea were originally tied together and only became separated after Enlil moved heaven away from the Earth. The Mesopotamian universe also included an underworld, ruled by a god or a goddess.

It is well known that the Mesopotamian civilizations came to include a sophisticated sci-
entific astronomy, more highly developed than that of the Egyptians. In view of this, it is
remarkable that the world picture of the Babylonians remained mythological and that their
mathematical astronomy had almost no impact at all on their cosmology. The clay tablets do
not discuss the shape of the Earth, but it was evidently thought to be a flat disc. There are
only a few glimpses of astronomical knowledge in the creation myth known as *Enuma Elish*,
the earliest known version of which was composed around the middle of the second millen-
nium BC but is based on material going further back in time. One of these glimpses relates to
the Moon as a timekeeping device. The Moon is portrayed as a god wearing a crown which
changes in shape through the month, corresponding to the lunar phases. The young warrior
god Marduk, city god of Babylon, not only organized the calendar, but also 'bade the Moon
come forth; entrusted night to her.' He 'made her a creature of the dark, to measure time; and
every month, unfailingly, adorned her with a crown. "At the beginning of the month, when
rising over land, thy shining horns six days shall measure; on the seventh day let half [thy]

own [appear]. At full Moon thou shalt face the Sun. . . [But] when the Sun starts gaining thee in the depth of heaven, decrease thy radiance, reverse its growth.'[4]

Finally, it is worth pointing out that the world picture of the Jewish people, as reconructed from various passages in the Bible, was essentially the same as that of the gyptians and the Babylonians. According to the Italian astronomer Giovanni Schiaparelli, ho in 1903 published a book on the subject,[5] it can be summarized in a drawing such as at given in Fig. 1.3. The flat, disc-shaped Earth is surrounded by a sea; beneath the arth, there are wells and fountains connected with the upper part of the Earth as well as ith the great deep, called Tehom. The Earth rests on pillars, and above it is the sky or rmament. Waters are to be found not only on the Earth or beneath it, but also above the rmament. After all, on the second day of creation, God commanded, ' "Let there be a ome to divide the water and to keep it in two separate places"—and it was done. So God ade a dome, and it separated the water under it from the water above it. He named the ome "Sky" ' (Genesis 1:6–7). It is from this heavenly water that the rain, formed by water the clouds, comes. The Jews' equivalent to the Egyptian Duat, the underworld and bode of the dead, was called Sheol. The only difference is that Sheol includes a deep cave hich houses a kind of hell for those who have lived a particularly immoral life. On the ther hand, the writers of the Bible did not think in diagrams or pictures, and one should ot try to make a definite world view out of the Old Testament. That is just not what the ible is about.

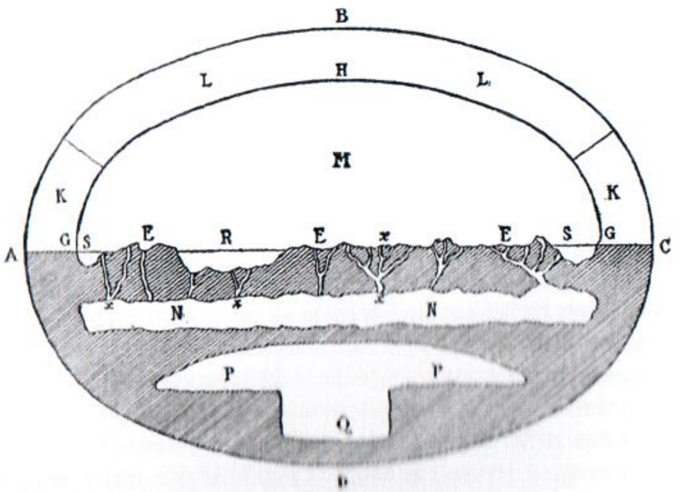


Fig. 1.3 Schiaparelli's reconstruction of the universe of the the Old Testament. The Earth (EEE) is surrounded by a sea (SS), and its surface is connected by streams to a large underground water deposit (NN). Above the Earth is the heavenly tent (ABC), supported by a solid vault (GHG). The space LL contains the waters in heaven, the source of rain. Beneath is the underworld Sheol (POP), the land of the dead. From Schiaparelli 1905, p. 33.

Egyptian and Babylonian astronomy and cosmology influenced to some extent Greek thought and thereby became linked to the European tradition, out of which scientific cosmology would eventually emerge. But there were other old cultures and these, too, had their conceptions of the universe. In ancient India there were four distinct traditions of cosmology, each of them exceedingly complicated, often fantastic, and rarely exhibiting much consistency. The reason may have been that there was no tradition in India of abandoning a theory or idea just because a new one had been accepted; rather, new ideas were added to the existing belief system by aggregation and inclusion. The complexity of the cosmological traditions makes it impossible to describe them in brief.[6] Suffice it to mention a theme from the *Rig-Veda*, written around 1500 BC, which also occurs in the later Vedic literature, namely, that the world started when fire and water came to meet. In one of the hymns of the *Rig-Veda*, it is said that originally there was nothing, neither existence nor non-existence. 'Darkness was in the beginning hidden by darkness; indistinguishable, all this was water. That which, coming into being, was covered with the void, that One arose through the power of heat.'[7]

Early Chinese astronomy differed in several respects from that of ancient Greece, notably by admitting that the heavens could change. New stars and novae were duly recognized when they appeared. Astronomical inscriptions related to divination practices have been found on a large number of animal bones and shells, dating back to about 1400 BC. Some of these records refer to solar and lunar eclipses, some to comets, and others to stars. One of these oracle bones records a 'guest star' near the star Antares. As to the world picture, the Kai Thien school of the third century BC conceived of the Earth as an inverted bowl lying within a similar but larger bowl, representing the heavens. The two bowls shared the same axis, around which the celestial bodies revolved. At the bases of the bowls, the space between them was filled with water. Remarkably, this model was supplied with precise dimensions (for instance, the distance between the two concentric domes—or between the Earth and the heavens—was about 43 000 km).

According to the later Hun Tian cosmology, the heavens formed a system of celestial spheres, essentially a cosmological model of the type that had been developed by Greek astronomers. A book from the first century AD says that the world is like a hen's egg, with the central Earth like the yolk of the egg. Of more interest is the somewhat later Xuan Ye school, according to which the celestial bodies floated freely around in an infinite space. The world view of this school included a kind of physical cosmology with a certain affinity to the ideas of the Greek atomists. A description of the Xuan Ye school from the early fourth century AD gives this account:

> They said that the heavens were entirely empty and void of substance. When we look up at them, we can see they are immensely high and far away, without any bounds. . . . The Sun, Moon, and company of stars float freely in empty space, moving or standing still, and all of them are nothing but condensed vapour. . . . The speed of the luminaries [the Sun, Moon, and the five brighter planets] depends on their individual natures, which shows they are not attached to anything, for if they were fastened to the body of heaven, this could not be so.[8]

1.1.2 *Cosmogonies and theogonies*

As we have seen, the ancient cosmologies were primarily concerned with how the world and its inhabitants (gods and humans) came into existence. They were cosmogonies and,

...ce of the crucial role played by the gods, at the same time theogonies. Most of the cosmogonies share some common features, among them a starting point in some undifferentiated, perhaps chaotic state which separates into two or three opposites, such as the Earth, and sky. A variant of this theme is included in the opening verse of Genesis:

> In the beginning, when God created the universe, the Earth was formless and desolate. . . . Then God commanded, 'Let there be light'—and light appeared. . . . Then He separated the light from the darkness. . . . Then God commanded, 'Let the water below the sky come together in one place, so that the land will appear'—and it was done. He named the land 'Earth' and the water which had come together he named 'Sea'.

However, this scenario differs from most other cosmogonies not only in its monotheism, but also in the absence of any primordial state. The initial elements, such as 'darkness' and 'water', are not pre-existing and active principles, but God's creations. It should also be noted that Genesis does not speak of nothingness as the 'state' out of which God created the universe. In later Christianity, *creatio ex nihilo* would become a dogma, but the notion is not mentioned explicitly in the Bible; it was only introduced in the second half of the second century by the church, which wanted to emphasize in this way God's absolute sovereignty.

Dating from roughly the same time as the Book of Genesis, Hesiod's *Theogony* offers the Greek version of how the world and the gods came into existence. Unsurprisingly, there are considerable similarities with the cosmogonies known from Mesotopamia and Egypt. Although the *Theogony* is mainly a cosmogony, it also comprises a picture of the structure of the universe, however crude. The Earth (flat, of course) is surrounded by a river or ocean, and above the Earth there is a hemispherical heaven, separated from the Earth by a gap which is bright by day and dark by night; beneath the Earth, dark and gloomy Tartaros is located, an underworld symmetric to heaven. We are informed about the size of the universe, as measured by the distance from the Earth to Tartaros, in the following way: 'A bronze anvil falling nine days and nights from heaven would reach Earth on the tenth. And a bronze anvil falling nine days and nights from Earth would reach Tartaros on the tenth.' Hesiod's account of the earliest gods is, at the same time, an account of how the main components of the physical world were created. Contrary to the Jewish creation story, there is no creator, but an initial state of chaos, which, without any cause or explanation, develops into a heaven and a sky. First night (Nyx) and darkness (Erebos) are produced, and then day (Hemera) and bright air (Aither):

> First of all Chaos came into being. Next came broad-breasted Gaia [Earth],. . . and murky Tartaros in a recess of the broad-roaded earth, and Eros . . . From Chaos there came into being Erebos and black night. From night, Aither and Hemera came into being . . . Gaia first brought forth starry Ouranos [heaven] equal to herself, to cover her all about in order to be a secure dwelling place forever for the blessed gods.[10]

Note that the original chaos has not always been there, but 'came into being'. Hesiod's text provides no answer to the question of what the chaos emerged from or how it happened. Historians believe that in the *Theogony* Chaos does not refer to a formless and structureless fluidum, as in the later meaning of the term, but to the gap between the Earth and the sky.

Apart from giving an account of the origin of the universe, many of the ancient cosmo-mythologies included accounts of the end of the world, typically by some cosmic catastrophe represented by a huge battle between the good and evil forces of nature. The catastrophe did not necessarily imply an absolute end of the world, though, for some of the cosmogonies were recurring cosmogonies, with a new world arising out of the ashes of the old. In some cultures, notably in India, the process was thought to go on endlessly, with an eternal change between creative and destructive phases. This is the archetypical conception of the cyclical universe, an idea which has fascinated humans throughout history and can be found in mythical as well as scientific cosmologies right up to the present.

The Hindus had a predilection for large numbers, which they used in elaborating cosmic cycles of vast proportions. A single cycle of the universe, called a *mahayuga*, consisted of 12 000 divine years, each of a duration of 360 solar years, thus totalling 4.32 million years. Two thousand such cosmic cycles made up one day of Brahma, called a *kalpa*. The life of Brahma, corresponding to 100 Brahma years, was also the lifetime of the lower part of the universe, 311 trillion (3.11×10^{14}) years—or 23 000 times the age of the modern Big Bang universe. And Hindu cosmology operated with even larger numbers.

Cyclical conceptions of the universe can be found in many other civilizations. Although there was no unique Greek idea of time, the notion of cyclical time, or a cyclical universe, was entertained by several Greek philosophers. According to a Greek historian, writing about 40 BC, there were two competing views with respect to time and the universe: 'One school, premising that the cosmos is ungenerated and indestructable, declares that the human race has always existed, and there was no time when it began to reproduce itself. The other holds that the cosmos has been generated and may be destroyed, and that men similarly first came into existence at a definite time.' [11]

1.1.3 *Ionian natural philosophy*

Historians sometime speak of the period between 600 BC and 450 BC as 'the first scientific revolution'. By this grand name they refer to the emergence of a group of Greek (or Ionian) thinkers who initiated a paradigmatic change in humanity's understanding of the natural world: they approached nature in a new way, asked different questions than previously, and provided different kinds of answers. These Ionians and Milesians were were not only philosophers, they were also natural philosophers. They believed that the world could be understood rationally or, rather, naturalistically, that it could become the subject of human reasoning. The Olympian gods were still there, but they were no longer held responsible for natural phenomena. The Ionian philosophers, also known as the Presocratics, thought of the world as a cosmos, a structure of matter and forces bound together by law-like connections into a harmonious whole. It followed that they endeavoured to explain natural phenomena as instances of general patterns of explanation, not as individual phenomena, each with its own explanation.

According to tradition, the first of the natural philosophers—the first 'physicist' if one likes—was Thales of Miletus. He allegedly predicted a solar eclipse in 585 BC, although this is undoubtedly more myth than historical reality. This wise man had a high reputation among the Greeks, who said that he thought hard about how to explain celestial phenomena. Perhaps he thought too hard, for Aristotle reports that once while Thales was studying the heavens, he fell into a well. 'A clever and delightful Thracian serving-girl is said to have made fun of him, since he was eager to know the things in the heavens but failed to notice what was in front of him and right next to his feet.'[12]

A Milesian follower of Thales, Anaximander, postulated an eternal and spatially unlimited principle or medium, an indefinite something called *apeiron*, out of which the present world order grew by a process of separation. He wanted to explain how the diversity of the world had emerged out of the undifferentiated and indeterminate *apeiron*; characteristically for the new spirit of enquiry, he refrained from invoking the intervention of the gods. Anaximander's explanation may appear obscure and unconvincing, but his question—how can the formation of a complex world out of an originally simple state be understood?—would remain central to cosmological thinking. Indeed, it is still a central question.

Anaximander also speculated about the structure of the world, including its dimensions, and again he avoided mixing his cosmology with mythology. He assumed that the shape of the Earth was cylindrical ('like a stone column'), with the height of the cylinder being one-third of its breadth. Humans and other inhabitants of the Earth would occupy one of the plane surfaces. As to the size of the Sun and its distance from the Earth, 'Anaximander says that the Sun is equal to the Earth, and the circle . . . on which it is carried is 27 times the size of the Earth.' He further held that the Earth is at the centre of the universe, and gave a kind of symmetry argument to the effect that the Earth therefore had to be immobile (for why should a central body move in one direction rather than any other?). It is not clear if Anaximander, in saying that 'the Sun is equal to the Earth', also implied that the two celestial bodies had the same physical composition. But Anaxagoras, a later philosopher in the Ionian tradition, did believe as much, since he claimed that the Sun, far from being divine, was just a hot stone. He likewise surmised that the Moon was Earth-like, with mountains, plains, and ravines. Because of his heretical view, he was prosecuted and exiled from Athens, where he lived. Anaxagoras adopted the flat Earth, but his explanation of why the Earth stays aloft in the middle of the universe (rather than falling down) differed from that of Anaximander. According to Anaxagoras, the Earth was supported by air, which he described as an ocean upon which the Earth rested.

Among the Presocratic philosophers should also be mentioned Empedocles, born around 490 BC, who was the first to suggest that all matter consisted of four basic and unchanging elements, namely earth, water, air, and fire. Because Aristotle adopted his view, it came to serve as the foundation of matter theory, alchemy, and much else for a period of nearly two thousand years. Empedocles stated that originally the elements were mixed, but eventually some vortex mechanism caused a separation of them, first separating off the air and next the fire. 'He declares that the Moon was formed separately out of the air that was cut off by the fire.' As to the Sun, he seems to have believed that it was either a vast aggregation of fire or a reflection of fire. Empedocles realized that the Moon was not a luminous body, but that it reflected the light from the Sun, and also that a solar eclipse occurred when the Moon stood between the Earth and the Sun. Like other natural philosophers, he came up with an explanation for the immobility of the Earth. According to Aristotle, Empedocles explained the stable, circular motion of the stars and planets by their great velocity. 'For when the cup [filled with water] is whirled in a circle, the water, whose natural movement is downward, does not fall down, even though it is often underneath the bronze.' Empedocles seems to have believed that the swift rotation of the heavens prevented the Earth from moving.

Empedocles' cosmos, materially consisting of the four elements, was governed by two gods or motive forces called 'Love' and 'Strife'. Since the elements had always existed, there was no need to explain how they originally came into existence. Depending on the

influence of either of the two cosmic forces, the universe alternated in a cyclical pattern.[13] Thus, when Love dominated, the elements were mixed up into a uniform mass; and at the time of Strife's complete dominance, they were fully separated from one another and arranged in concentric spheres. Only in between the two extremes was the universe hospitable to life-generating processes, as we experience them. The changes between dominance by Love and Strife proceeded eternally, corresponding to continual creations and destructions of the world. However, the two forces were not simply creative and destructive, for the conditions of life demanded a certain balance between them. The cycles were symmetric, so that the events in one phase were repeated in the opposite phase, but in reverse time order (a process from birth to death will be followed by one from death to birth). The periods of the cycles would be very long, but Empedocles did not specify their length.

During the Presocratic period, the emphasis was upon explaining what was known, whereas there was little interest in extending the empirical basis by means of new observations. Moreover, the explanations that the Presocratic philosophers came up with were crude analogies of a purely qualitative nature. Indeed, from a later perspective the explanations of Anaximander, Anaxagoras, Empedocles, and their kindred spirits appear primitive and speculative. But what matters is not their answers, but their questions and the conditions they posited for acceptable explanations.

1.1.4 *Pythagoreans and atomists*

Whereas Pythagoras is a somewhat shadowy figure who left nothing in writing to posterity, the philosophical school he founded in southern Italy was influential throughout antiquity.[14] The early Pythagoreans formed a secret religious fraternity and they continued to emphasize religious and mystical aspects of their philosophy rather than scientific aspects. Nonetheless, their thoughts came to exert a strong influence on early Greek science. In the present context, we only need to draw attention to their original idea of associating numbers with material substances, an idea which pointed the way to a mathematization of physics and cosmology. It is not very clear what the Pythagoreans meant by relating numbers to things (but then, presumably, it was not meant to be clear). Some of them apparently claimed that things *are* numbers, which clearly is an implausible claim; others may have meant, less implausibly, that material objects resemble numbers and that physical phenomena can be explained by numbers.

The Pythagoreans were aware of the five regular polyhedra, also known as the Platonic bodies, and claimed that the element earth was made from the cube, fire from the tetrahedron, air from the octahedron, and water from the icosahedron; the fifth of the regular bodies, the dodecahedron, they associated with the whole of the cosmos, which they believed was spherical and limited in extent. They were among the first to adopt a spherical Earth, a conceptual innovation which dates from around 430 BC. Even more remarkably, some of the Pythagorean thinkers removed the Earth from its privileged position in the centre of the universe. According to Philolaus, one of Pythagoras' successors in Italy, the central place was occupied by a fire—'the guard of Zeus'—around which rotated the planets and the stars. It is to be noted that Philolaus' cosmos was not heliocentric, as he did not identify the central fire with the Sun, which he took to revolve around the centre. Furthermore, he postulated a dark 'counter-Earth' which moved opposite to the real Earth and with the same period of revolution. The Earth described a circle around the central fire, which was, however, invisible to us because humans only lived on the side of the Earth that was turned away from the centre of revolution. Another Pythagorean, Ecphantus (who may or may not have been a real person), was said to have maintained that the Earth performed a daily rotation around its axis from west to east.

The reason for the introduction of the counter-Earth was numerological, not astronomical. According to Aristotle, the Pythagoreans held that the number 10 was perfect, and for this reason they maintained that there must be 10 celestial bodies. Taking the Earth, the Moon, the Sun, the planets, and the sphere of the fixed stars they counted nine, and by including the counter-Earth they got the right number. The order of the bodies was as mentioned, with the counter-Earth innermost and followed by the Earth, the Moon, etc. Aristotle was not impressed by Pythagorean cosmology, which he found to be speculative and unrelated to observations. As he wrote in *De caelo*, 'They are not inquiring for theories and causes with a view to the phenomena, but are forcing the phenomena to fit certain theories and opinions of their own, and trying to bring them into line.'[15] All the same, some 2000 years later Copernicus would refer to Philolaus' pyrocentric world model for support of the idea that the Earth is a circularly moving planet.

According to Aristotle, the atomistic school of natural philosophy was founded by Leucippus, a philosopher possibly from Miletus. However, atomism is usually associated with the better-known Democritus from Abdera in Thrace, a contemporary of Socrates and with the reputation of being a prolific author. Leucippus may have been a pupil of Zeno and somewhat older than Democritus. Both of the founders of atomistic natural philosophy are rather shadowy figures, known only through the works of later authors.

The basic idea of ancient atomism was the postulate that all that truly exists in the world is atoms, indivisible and invisible particles which move incessantly in an unlimited void, a cosmic vacuum. Whereas the atoms are being, the void is non-being. Although Democritean atomism is often represented as a monistic theory, it operated with non-being as well as being, and the non-being void was ascribed an ontological status somewhat similar to that of the being atoms. This is what lies behind Democritus' paradoxical statement that 'nothingness exists'. The atoms were uniform in substance and differed only in size and shape. Because there were an infinite number of shapes, there were an infinite number of different atoms too. Material objects were formed by chance congregations of atoms, which first resulted in compounds or, anachronistically, 'molecules'. The process might also give rise to a vortical motion with larger and slower objects tending toward the middle, whereas smaller and faster objects tended toward the periphery. Out of such vortices entire worlds might originate. The general idea of ancient atomism was to explain the complexity of the phenomenal world solely in terms of atoms moving in a void, to reduce observed qualities and changes to changes in the relative position of atoms which were themselves qualityless and eternal.

Atomistic philosophy included a particular cosmological view in which a distinction was made between the infinite world at large and world systems within it, sub-universes, which were limited in space and time. Our cosmos was just one out of an infinite number of roughly similar systems, some larger and some smaller; like the other world systems, ours had come into being and would one day perish. 'There are an infinite number of universes [*kosmoi*] of different sizes. In some there is no Sun and Moon. In some the Sun and Moon are larger than ours and in others there are more. . . . Some are growing, some are at their

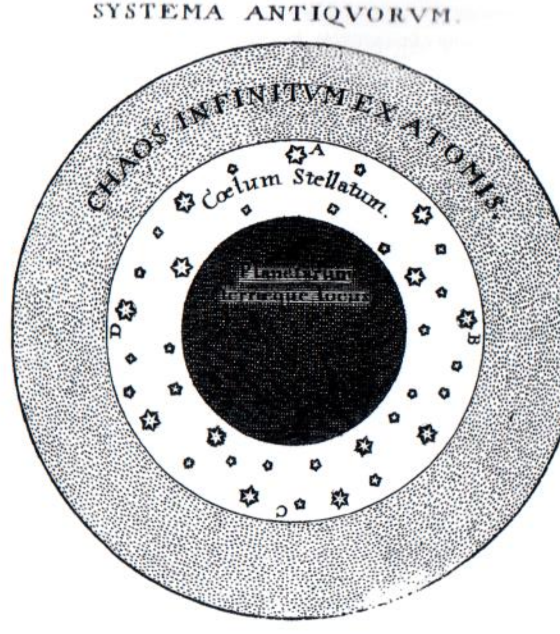


Fig. 1.4 Democritus' atomisfic universe as depicted in a book published in England in 1675. The dark central area is made up of the Earth and the planets, surrounded by a thick stellar sphere. Outside the stars is the infinite chaos of randomly moving atoms. Although pictured as a shell, it is supposed to have no outer limit. From Heninger 1977, p. 193.

peak, and some are declining, and here one is coming into being, there one is ceasing to be. They are destroyed when they collide with one another.'[16]

As to the arrangement of the celestial bodies, Democritus placed the Moon nearest the Earth, then the Sun followed, and outside it the fixed stars; the planets were said to 'have different heights'. Leucippus believed that the Sun was farthest away. The two philosophers agreed that the Earth was at the centre of our universe, while for the world at large there was not, of course, any central place. Contrary to the Pythagoreans, Democritus did not accept a spherical Earth, but suggested that it had an oval shape with a length one and one-half times its width.

In the atomists' conception of the universe, there was no room for design, purpose, or divine agency. All that existed were material atoms moving randomly in a void. This does not mean that the atomists denied the existence of the gods, but they did deny that the gods had anything to do with natural processes. Some four hundred years after Democritus, the Roman poet Titus Lucretius Carus wrote his famous text *De rerum natura*, in which he presented his own version of atomism. Although this version derived more from Epicurus than from Democritus, in general it agreed with ancient atomist cosmology. Here is Lucretius' description of the cosmos:

All that exists, therefore, I affirm, is bounded in no direction; for, if it were bounded, it must have some extremity; but it appears that there cannot be an extremity of any thing, unless there be something beyond, which may limit it. . . . Now, since it must be confessed that there is nothing beyond the WHOLE, the whole has no extremity; nor does it matter at what part of it you stand, with a view to being distant from its boundary; inasmuch as, whatever place any one occupies, he leaves the WHOLE just as much boundless in every direction.

Having argued in this way for an infinite universe, Lucretius proceeded with arguing for an infinity of inhabited worlds:

Further, when abundance of matter is ready, and space is at hand, and when no object or cause hinders or delays, things must necessarily be generated and brought into being. And now, if there is such a vast multitude of seminal-atoms as the whole age of all living creatures would not suffice to number, and if there remains the same force and nature,. . . you must necessarily suppose that there are other orbs of earth in other regions of space, and various races of men and generations of beasts.

Lucretius further explained that although the cosmos is infinite in space, it is of finite age and 'there will be an end to the heaven and the Earth'. He based his argument on the shortness of human history, which he found to be inexplicable if the world had always existed:

If there was no origin of the heavens and Earth from generation, and if they existed from all eternity, how is it that other poets, before the time of the Theban war, and the destruction of Troy, have not also sung of other exploits of the inhabitants of Earth? How have the actions of so many men thus from time to time fallen into oblivion? . . . But, as I am of opinion, the whole of the world is of comparatively modern date, and recent in its origin; and had its beginning but a short time ago.

Not only did the universe have a beginning, it was also decaying, on its way to an end. Lucretius spoke of a cosmic deterioration, a theme which can be followed throughout the history of cosmological thought. 'The walls of the great world, being assailed around, shall suffer decay, and fall into mouldering ruins. . . . It is vain to believe that this frame of the world will last for ever.'[17] As has become clear, the atomist cosmology followed the trend in Presocratic natural philosophy in being grand and speculative. It included many visions, including the bold proposal of many worlds, that are still considered interesting by modern cosmologists.

1.2 The Greek cosmos

During the centuries after 400 BC, natural philosophy partly transformed into science. For the first time Greek thinkers focused on observations of nature and attempted to construct explanations or models that agreed quantitatively with the observations. In no area was the new kind of science pursued with more vigour and success than in astronomy. Yet, as the science of the heavens became more mathematical and better founded in observational data—in short, more scientific—the more narrow did it become. Whereas interest in cosmology and cosmogony had flourished among the Presocratic philosophers, such speculations declined drastically in the long period between Plato and Ptolemy.

Two points are worth emphasizing. First, cosmogony, in the strict meaning of the term, practically came to a halt. Scientists and natural philosophers rarely addressed questions concerning the origin of the universe or how it had developed into its present state. From Aristotle onwards, most astronomers tacitly assumed that the world had always existed and that it would continue to do so into an indefinite future. Of course, granted this assumption, there was no room for cosmogony. The second point I want to mention is that the meaning of 'the universe' (or 'cosmos') changed. It was still everything physical in the world, but in astronomical practice the universe tended to be identified with the seven planets encircling the Earth. Although the fixed stars belonged to the universe too, there was little that astronomers could do about them except to count and classify them. (The first classification into magnitudes was due to Hipparchus, who divided the stars into six classes with the most luminous belonging to magnitude 1, and the least luminous belonging to magnitude 6.) The narrower view and the emphasis on mathematical models meant that cosmology became peripheral to the astronomers' research programme, a state of affair that was to continue throughout the Middle Ages and the Renaissance.

This is not to say that cosmology vanished from the scene of Greek science, only that it was given little priority and, when it was cultivated, appeared in different forms than previously. Among the more interesting cosmological theories in the period were those of Aristotle, Aristarchus, and Ptolemy. Most astronomers preferred to leave cosmology to the philosophers, and here we do find an interest in the subject along lines similar to those of the Presocratics. The Stoics, for example, were much interested in cosmological questions, but did not combine them to any extent with astronomical knowledge. To mention but one aspect of Stoic cosmology, they held a cyclical world view in which the formation and destruction of the cosmos was associated with thermal phenomena. The world was a gigantic sphere oscillating through cycles of expansion and contraction in the void surrounding it. Chrysippus, a leader of the Stoic school in Athens in the third century BC, is said to have believed that 'after the conflagration of the cosmos everything will again come to be in numerical order, until every specific quality too will return to its original state, just as it was before and came to be in that cosmos.'[18]

1.2.1 *Aristotle's world picture*

Although Plato discussed astronomical issues in several of his writings, his attitude was idealistic in the sense that he denied the epistemic value of observations. The cosmos could be comprehended mathematically, by pure thought, whereas empirical investigations would only obscure the truth; they would at most lead to a 'likely story' of the real world. In the *Republic*, he insisted that astronomy should be pursued as if it was geometry. 'We shall dispense with the starry heavens, if we propose to obtain a real knowledge of astronomy,' he wrote.

All the same, according to tradition Plato was the first to state what soon became the basic problem of astronomy and an approach to this science of huge importance. According to Simplicius' *Commentary on Aristotle's De Caelo*, a work written in the early part of the sixth century AD, Plato suggested that the business of the astronomers was to reduce the apparent motions of the planets (including the Sun and the Moon) to uniform, circular motions—to 'save the phenomena'. It is now believed that the demand for uniformity and circularity of celestial motions was a later innovation, which cannot be found in Plato and to which he did not subscribe.[19] The principle was to shape the paradigm that would dominate astronomy and cosmology until the time of Kepler, over a period of two thousand years. Whatever Plato's priority, it was a pupil of his who first answered the challenge, that is, who first proposed a single system which accounted for the observed motions of the planets in terms of circular orbits.

Eudoxus of Cnidos had for a short period stayed with Plato at his Academy in Athens, and later in life he constructed a system of revolving concentric spheres which accounted for many of the observed features of the heavens.[20] None of Eudoxus' writings have survived, but the basic content of his world model is known from later writers, Aristotle and Simplicius in particular.[21] Eudoxus considered each of the heavenly bodies as a point on the surface of one of several interconnected spheres, which were all concentric—or 'homocentric'—with the Earth at the centre. He imagined the spheres to turn around different axes and with different speeds, but in accordance with Plato's paradigm he only allowed uniform revolutions. In the case of the five planets, he made use of four spheres, the outer one of which represented a motion around the Earth with a period of 24 hours. For the Sun and the Moon, he postulated three spheres.

Among the irregular motions that had to be explained was the fact that some of the planets appeared to reverse their motion and then, after some time, continue their regular course towards the east. Such retrograde motion was considered most undignified for a heavenly, divine body, and hence something that had to be explained as apparent only. This Eudoxus' model succeeded in doing, if only in a qualitative and incomplete way, and it also largely accounted for another disturbing irregularity, the planets' variation in latitude. Because the model had only two parameters that could be varied, one corresponding to the speeds of revolution and the other to the inclination of the spheres, it was, however, unable to give the right motions of the planets.

In his *Introduction to Astronomy*, a work from around 70 BC, the Stoic philosopher Geminus gave an excellent exposition of the research programme adopted by Eudoxus and his followers. 'Their view was that, in regard of divine and eternal beings, a supposition of such disorder as that these bodies should move now more quickly and now more slowly, or should even stop, as in what are called the stations of the planets, is inadmissible.' Interestingly, Geminus drew an analogy to the social norms of his time:

Even in the human sphere such irregularity is incompatible with the orderly procedure of a gentleman. And even if the crude necessities of life often impose upon men occasions of haste and loitering, it is not to be supposed that such occasions inhere in the incorruptible nature of the stars [planets]. For this reason they defined their problem as the explanation of the phenomena on the hypothesis of circular and uniform motion.[22]

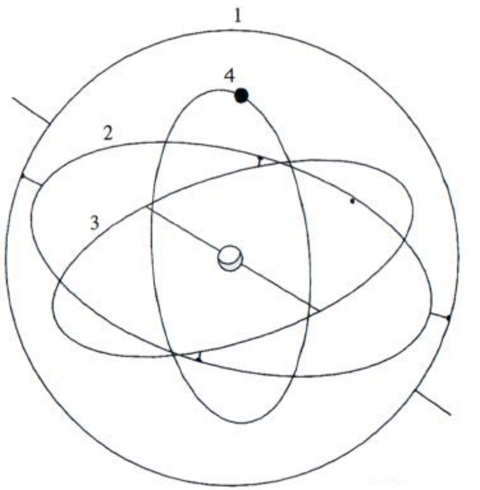


Fig. 1.5 Planetary mechanism based on Eudoxus' model with four concentric spheres.

In a commentary on Aristotle, Geminus, as quoted by Simplicius, further spelled out the difference between physics and astronomy, as these disciplines were conceived in Greek antiquity:

It is the business of physical inquiry to consider the substance of the heaven and the stars, their force and quality, their coming into being and their destruction, nay, it is in a position even to prove the facts about their size, shape, and arrangement; astronomy, on the other hand, does not attempt to speak of anything of this kind, but proves the arrangement of the heavenly bodies by considerations based on the view that the heaven is a real κόσμος [kosmos], and further, it tells us of the shapes and sizes and distances of the Earth, Sun, and Moon, and of eclipses and conjunctions of the stars, as well as of the quality and extent of their movements.[23]

This was a distinction that would last for about eighteen centuries and have a crucial impact on the histories of astronomy and cosmology. Whereas Eudoxus needed 26 spheres to account for the workings of the heavens, Callipus of Cyzicus, a near-contemporary of Aristotle, refined the model by adding seven more spheres (one each for Venus, Mars, and Mercury, and two each for the Sun and the Moon). Eudoxus and Callipus seem to have conceived their world models purely geometrically and the celestial spheres to be merely theoretical entities.

The homocentric model adopted by Aristotle was a modification of the models of Eudoxus and Callipus, but at the same time it marked an important change in the research programme in that Aristotle introduced a physical perspective. His spheres were corporeal, not mathematical constructs, and his planets and stars were physical bodies attached to a series of interconnected rotating shells. This made him propose a mechanism to explain *why* the bodies moved as they did. According to Aristotle, the spheres of an outer planet were physically connected with those of an inner planet, a model which forced him to introduce some countermeasures in order to reproduce the observed motions. In his *Metaphysics*, he wrote: 'If all the spheres combined are to give an account of the phenomena, then for each planet there must be other spheres . . . which counteract and restore to the same position the first sphere of the innerlying planet, for only in this way will the whole system produce the required motion of the planets.'[24] There clearly was a cost to Aristotle's physicalization of the cosmos, namely a drastic increase in complexity. No fewer than 55 spheres were now needed, 22 of them introduced to restore the independence of the seven planetary systems.

Aristotle's great innovation was to provide a physical model of the actual heavens in agreement not only with the postulate of uniform circular motion but also with the general principles of his natural philosophy. This connection was a leading theme in his famous treatise on the heavens, known by its Latin title *De caelo*. Perhaps the most important feature in Aristotle's cosmos was that it was a two-region universe, as he drew a sharp distinction between the sublunar and the superlunar world. The first region, covering the Earth and the air up to the Moon, was composed of bodies made up of the four Empedoclean elements with their natural motions, which were rectilinear, either towards the centre of the Earth (earth and water) or away from it (air and fire). Beyond the Moon, the celestial bodies moved naturally in eternal, uniform circular motions, without being subject to the terrestrial laws of physics. The stars, planets, and celestial spheres were composed of an entirely different kind of matter, an ethereal, divine substance or fifth element, *quinta essentia* in Latin. Unlike the matter of the sublunar world, the heavenly ether was pure and incorruptible. Whether in the sublunar or superlunar region, a void could not possibly exist, and hence the universe was a plenum.

Aristotle's cosmos enjoyed general respect in the ancient world, but it was not beyond criticism. Xenarchus of Seleuchia, who was a contemporary of Cicero, wrote a treatise entitled *Against the Fifth Substance*, in which he challenged two of Aristotle's basic notions, the existence of a fifth element and the circular motion of the celestial bodies. Among his arguments against the heavenly ether was that the hypothetical substance was superfluous. He denied that a simple or perfect body by its nature would follow a circular path, as claimed by Aristotle and most other astronomers. For, as Xenarchus argued, in circular motion those parts nearer to the centre move with a smaller linear velocity than those nearer to the periphery, whereas a simple body must necessarily have the property that all its parts move with the same velocity.

Although Aristotle held that the Earth was located at the centre of the universe, this was in a geometrical sense only. Contrary to the Pythagoreans, he saw no reason to identify the geometric centre with the true or 'natural' centre of the universe, understood in a physical and ontological sense. On the contrary, in *De caelo* he suggested that this more elevated status belonged to the sphere of the fixed stars, from where motion was transmitted to the interior parts of the world. That which contains is more precious than that which is contained, he wrote. Thus, one may say that Aristotle operated with two centres of heavenly motion, an idea which was taken over into the medieval conception of the universe. Not only was the stellar sphere of a nobler nature than the corruptible Earth, it was also the origin of universal time and closer to the unmoving prime mover (corresponding to God).

Based as it was on Eudoxus' homocentric model, Aristotle's system shared most of its weaknesses, the most serious of which was its inability to account for the variations in brightness shown by some of the planets. It was well known that the brightness of Venus and Mars varied considerably during their course, which is easily explained if their distances from the Earth change. However, it followed from the premises of the homocentric system that the planets must always be at a constant distance from the Earth. This and other problems were pointed out by Autolychos only a generation after Eudoxus and later also by Simplicius, who quoted Sosigenes, a contemporary of Julius Caesar. 'Nevertheless the theories of Eudoxus and his followers fail to save the phenomena', Sosigenes is said to have said. The inability to explain the variable brightness was the main reason why the homocentric model, whether in the version of Eudoxus or of Aristotle, did not survive for long.

Aristotle did not only establish a kind of physical astronomy, he was also much concerned with the greater questions of cosmology. One of these questions related to the temporal aspect of the world. Had it once come into existence? Would it come to an end? In his famous dialogue *Timaeus*, Plato discussed these questions, although in a form far away from a scientific discourse. According to Plato, the world had come to be, it was created. He pictured the creation as made by a 'demiurge', a divine craftsman who first made the soul of the cosmos and subsequently its body, the two fitting perfectly. Moreover, Plato made clear that there could be only one world, not many images of the ideal world. He stated that the stars and planets were divine and in perpetual motion, and 'whatever is in perpetual motion is immortal'. The creation of the world was not *ex nihilo*, for the demiurge made the cosmos as a copy of an eternal and divine original, a kind of pre-existing universe-idea.[25] Since Plato formulated his creation story as a myth, one should be careful not to read into it later ideas of cosmic creation, whether in a theological or a scientific sense. Most modern interpreters warn that *Timaeus* should be read metaphorically rather than literally.

At any rate, Aristotle disagreed with his former teacher and vehemently denied that the universe was created and also that it was spatially infinite. On the contrary, he argued that the universe as a whole was ungenerated as well as indestructible, in short eternal. A spatially infinite world was impossible, for by its very nature the world revolved in a circle, and Aristotle argued that such motion was impossible for an infinite body as it would lead to an infinite velocity. This conclusion would not hold true in a universe consisting of a finite material cosmos surrounded by an infinite void; but such a picture (which was adopted by some Stoic philosophers) ran counter to Aristotle's notion of space as volume filled with matter. According to Aristotelian natural philosophy, a large empty space was ruled out by definition. What was enclosed by the outermost sphere included everything. In opposition to some earlier philosophers, Aristotle maintained that the universe was unique, eternal, and all-inclusive:

> The world in its entirety is made up of the whole sum of available matter . . . and we may conclude that there is not now a plurality of worlds, nor has there been, nor could there be. This world is one, solitary and complete. It is clear in addition that there is neither place nor void nor time beyond the heaven; for (*a*) in all place there is a possibility of the presence of body, (*b*) void is defined as that which, although at present not containing body, can contain it, (*c*) time is the number of motion, and without natural body there cannot be motion.[26]

As to the central body, the Earth, Aristotle argued that it was spherical and immobile, neither of which claims was controversial. Although the celestial spheres would move naturally, Aristotle introduced in his *Physics* an 'unmoved mover', a spiritual something at the outermost part of the universe which he conceived as the ultimate source of all celestial movement. However, he did not develop the topic, nor did he provide any explanation of how the transmission of movement took place. In his *De caelo*, Aristotle referred briefly and somewhat cryptically to the question of the Earth's axial rotation 'as is stated in the *Timaeus*'. This passage has been discussed endlessly, from Plutarch in antiquity, through Thomas Aquinas in the Middle Ages, to scholars in the twentieth century. Did Plato really assume a rotating Earth? It is pretty certain that he did not, for other reasons, because such a notion would have been wholly inconsistent with his astronomical system. Plato shared the standard view of the Earth sitting motionless in the centre of the universe.

Aristotle's assumptions about a finite and eternal cosmos, and his denial of a vacuum, were not generally accepted in ancient Greece and Rome. For example, they were opposed by the Stoics and Epicureans, who not only returned to Presocratic ideas of cosmic evolution but also operated with versions of an infinite universe. As we have seen, Lucretius' exposition of cosmology in *De rerum natura* was most un-Aristotelian.

The Stoic school, which included Chrysippus and later Poseidonius as prominent members, developed a cosmology where the element fire was essential and was seen as the source of the other three elements. They agreed with Aristotle that there could be no void within the material world, but not that an extra-cosmic void was impossible. On the contrary, they supposed that 'beyond the cosmos there stretches an infinite, non-physical world'. Stoic philosophers pictured the universe as slowly pulsating, performing cycles of condensation and rarefaction. An extra-cosmic void would not cause matter to dissipate into the void, as Aristotelians argued, for 'the material world preserves itself by an immense force, alternately contracting and expanding into the void following its physical transformations, at one time consumed by fire, at another beginning again the creation of the cosmos'.[27]

The problem of the eternity of the world (or the Earth) remained a matter of dispute, especially among Stoic philosophers, who objected to Aristotle's thesis with empirical arguments based on the observed surface of the Earth. They reasoned that erosion is a unidirectional process and if it had been at work for an infinite time, all mountains and valleys would by now have been planed down; they clearly are not, and hence the Earth must have existed only over a limited span of time. This argument against the eternity of the world was developed by the Stoic philosopher Zeno of Citium around 300 BC and reported by Theophrastus as follows:

> If the Earth had no beginning in which it came into being, no part of it would still be seen to be elevated above the rest. The mountains would now all be quite low, the hills all on a level with the plain . . . As it is, the constant unevenness and the great multitude of mountains with their vast heights soaring to heaven are indications that the Earth is not from everlasting.[28]

This is the first time we meet a theme that would come to occupy a prominent position in cosmological thinking more than two thousand years later: there exist in nature unidirectional processes—whether given by erosion, radioactivity or entropy increase—that speak against an eternal world (see Section 2.4). Faced with the Stoics' argument, proponents of Aristotelian physics postulated that corruptive geological processes were counteracted by generative processes, but they were unable to provide a satisfactory account, based on Aristotle's matter theory, of how these compensating processes operated.

1.2.2 *Aristarchus and the dimensions of the universe*

It has always been an important task of astronomers and cosmologists to determine distances in the universe, from the surface of the Earth to objects as far away as possible. It is also one of the most difficult tasks.[29] How big was the universe of the ancient Greeks? Nobody knew, for there were no ways in which the distances to the stars and the planets (except the Sun and the Moon) could be measured. In fact, not even the order of the planets could be unambiguously determined, except that the sphere of the fixed stars was obviously the farthest away from the Earth, and the Moon was the closest. Yet the Greeks were not totally at a loss and they did make some progress in determining cosmic distances, if only in the neighbourhood of the Earth.[30]

Alexandria and Syene (now Aswan) in southern Egypt are located roughly on the same meridian. In the third century BC, Eratosthenes, director of the famous library in Alexandria, estimated the distance between the two cities to be 5000 stades. Assuming that the Sun was sufficiently distant that its rays could be treated as if they were parallel, he concluded from a simple measurement that the circumference of the Earth was close to 250 000 stades. We do not know the value of the stade he used, but if one stade equals 157.7 m, as often assumed, the result corresponds to 39 370 km, in excellent agreement with later determinations. However, the numerical agreement may to some extent have been fortuitous and should not be given much weight. What matters is that from the time of Eratosthenes the order of magnitude of the size of the Earth was known and generally accepted.

Aristarchus of Samos, Eratosthenes' senior by some 40 years, was an accomplished mathematician and astronomer. In his only extant writing, *On the Sizes and Distances of the Sun and Moon*, he undertook to establish the relative distances of the Sun and Moon from the Earth and also to determine the sizes of the Sun and Moon.[31] His main method was to measure the angle between the directions from the Earth pointing towards the Moon and the Sun at the moment when the Moon was observed to be exactly half illuminated (Fig. 1.6). He found the value 87° and, from lunar-eclipse observations, which he used to determine the sizes of the Sun and Moon, he found that the Moon's apparent diameter was 2°. Here, in the words of Aristarchus, is what he concluded:

> 1. The distance of the Sun from the Earth is greater than eighteen times, but less than twenty times, the distance of the Moon [from the Earth].
> 2. The diameter of the Sun has the same ratio [as aforesaid] to the diameter of the Moon.
> 3. The diameter of the Sun has to the diameter of the Earth a ratio greater than that which 19 has to 3, but less than that which 43 has to 6.[32]

Aristarchus' conclusions were wide of the mark. The reason was errors in his two basic data values, which should have been 89°50′ and ½° rather than 87° and 2°. His method was clever and correct, but his results wrong; or, as a historian has expressed it, it was 'a geometric success but a scientific failure'.[33]

As a result of his wrong data, Aristarchus obtained values that were much too small, especially for the Earth–Sun distance, where his result was wrong by a factor of no less than 65 (Table 1.1). Nonetheless, his methods were sound, and a refined use of them later led Hipparchus to a much better value of the distance between the Earth and the Moon (the distance to the Sun was also much improved, if still off the mark by a factor of 9.5).

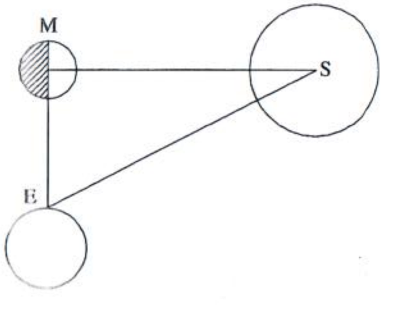


Fig. 1.6 Aristarchus' method for determining the relative distances of the Sun and the Moon. An observer on the Earth E sees the Moon M when it is in its first quarter and measures the angle MES, from which the ratio EM : ES follows.

Table 1.1 Ancient values of mean distances and sizes of the Moon and the Sun expressed in diameters of the Earth. Adapted from Heath 1959, p. 350.

	Moon, distance from Earth	Moon, diameter	Sun, distance from Earth	Sun, diameter
Aristarchus	9.5	0.36	180	6.8
Hipparchus	33.7	0.33	1 245	12.3
Poseidonius	26.2	0.16	6 545	39.3
Ptolemy	29.5	0.29	605	5.5
Modern values	30.1	0.27	11 728	109.1

Aristarchus is today best known for having proposed a heliocentric system, for which reason he is sometims referred to as 'the Copernicus of Antiquity'. Although Copernicus knew about Aristarchus' world system, he did not refer to it in *De revolutionibus*. Apparently the Polish reformer of astronomy did not think highly of his Greek predecessor, whose ideas did not influence him to any extent.[34] Aristarchus' original text no longer exists, but Archimedes gave a brief account of it in a fascinating work known as *The Sandreckoner*:

Now you are aware that 'universe' is the name given by most astronomers to the sphere whose centre is the centre of the Earth and whose radius is equal to the straight line between the centre of the Sun and the centre of the Earth. This is the common account, as you have heard from astronomers. But Aristarchus of Samos brought out a book consisting of some hypotheses, in which the premisses lead to the result that the universe is many times greater than that now so called. His hypotheses are that the fixed stars and the Sun remain unmoved, that the Earth revolves around the Sun in the circumference of a circle, the Sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same centre as the Sun, is so great that the circle in which he supposes the Earth to revolve bears such a proportion to the distance of the fixed stars as the centre of the sphere bears to its surface.[35]

Aristarchus' reform of the world picture was presumably rooted in his determinations of the relative sizes of the Moon and the Sun. The Moon revolved around the more bulky Earth, which had a volume about thirty times as large as its satellite. If the Sun was some 300 times larger than the Earth in volume, as he had found, it was natural to think of the Sun as the central body instead of the Earth.

Archimedes' interest in the matter was mathematical, not astronomical. That his work was not an attempt to obtain a correct figure for the size of the universe is illustrated by the fact that he intentionally overestimated the cosmic dimensions. For example, he took the Sun to be 30 times as large as the Moon, where Aristarchus had a value of 18–20; and for the circumference of the Earth he used the value 3 million stades, which he knew was much too large. What appealed to Archimedes was the enormous size that must be ascribed to Aristarchus' universe in order to account for the absence of an observed stellar parallax.

Was it possible to express a number greater than the number of sand grains needed to fill up the entire heliocentric universe? In order to solve this problem—clearly of mathematical interest only—Archimedes developed a number system which allowed him to express numbers of gigantic magnitude. His result was that 'a sphere of the size attributed by Aristarchus to the sphere of the fixed stars would contain a number of grains of sand less than 10,000,000 units of the eighth order of numbers'. The number referred to by Archimedes can be written in modern notation as 10^{63}, the first 'very large number' that appears in the history of science. Much later, such dimensionless numbers would become important in cosmology. There is a similarity, if more in spirit than in substance, between Archimedes' number and Eddington's cosmical number 10^{79}, which denotes the number of fundamental particles in the observable universe.[36]

Aristarchus' heliocentric system was not considered a serious rival to the geocentric models and soon went into oblivion. The only astronomer in antiquity who is known to have supported the idea was Seleucus, who lived about 150 BC. It was hard to see the advantages of a system that contradicted common sense and could only account for the absence of a parallax by placing the stellar sphere at a ridiculously far distance from the Earth. There is no indication that Aristarchus worked out the details of his hypothesis, for example that he developed a planetary theory on the basis of a moving Earth, such as Copernicus would do some eighteen centuries later. In addition, it may have added to the theory's lack of acceptability that it was accused of being impious 'for putting in motion the hearth of the universe'. This we know from Plutarch's *On the Face in the Orb of the Moon*, where there is a reference to charges raised against Aristarchus by Cleanthes, a Stoic philosopher. Yet, he also says that Aristarchus was a mathematician, not a physicist (or philosopher), and for this reason his hypothesis should not be taken too seriously. The distinction between the physicist's and the mathematician's view of the universe would later reappear in connection with Copernicus' world system and would in general constitute an important theme in the history of scientific cosmology.

We may get an impression of the cosmological views of the early Roman empire from Pliny the Elder's voluminous compilation *Historia naturalis*, a work consisting of 37 'books' and which exerted a great influence on late antiquity and the Middle Ages.[37] Astronomy, presented in a qualitative way in Book II, was but a small part of the erudite Roman's work, but it may have been representative of what non-astronomers knew and thought about cosmology at the time. Pliny rejected astrology and conceived the world (*mundus*) as 'sacred, eternal, immeasurable, wholly within the whole'. What may be outside it 'is not within the grasp of the human mind to guess'. Pliny was aware that some philosophers had made suggestions about the dimensions of the universe, but these he discarded as 'mere madness', a phrase he also used for attempts to investigate what lies outside the world. The general features of Pliny's universe were in agreement with Hellenistic cosmology in so far that he adopted a spherical, Earth-centred world with the fixed stars at its outer boundary. He had no doubt that the Earth was the central body of the universe, which he substantiated with 'irrefragable arguments' of which the most important was the equal hours of day and night. On the other hand, the Sun was not merely one planets among others, for,

In the midst of these [planets] moves the Sun, whose magnitude and power are the greatest and who is the ruler not only of the seasons of the lands, but even of the stars themselves and of the heaven. . . .[The Sun is] the soul, and more precisely the mind, of the whole world, the supreme ruling principle and divinity of nature. He . . . lends his light to the rest of the stars also; he is glorious and pre-eminent, all-seeing and even all-hearing.

Pliny further accepted the doctrine of the four elements, arranged in such a way that the element fire was nearest the stars, followed by air, which was thought to exist throughout the universe. Of course, in between the immobile Earth and the revolving stellar sphere he placed the seven planets, taking their order to be the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. The Earth was spherical and kept in place by the force of air. It is uncertain if Pliny accepted the Aristotelian distinction between a sublunar, elementary world and a supralunar, ethereal region, as he wrote somewhat ambiguously on the matter. He did, however, agree with Aristotle that the universe was uncreated and eternal. Although he knew of the idea of a cyclical universe repeating itself eternally, he seems to have found the notion unattractive.

1.2.3 *Ptolemaic planetary astronomy*

The troubles that faced the homocentric models of Eudoxus and Aristotle were largely solved with the introduction of an alternative planetary model in the second century BC. It is believed that this alternative was first proposed by the Alexandrian mathematician Apollonius, who is especially known for his unified theory of conic sections, including the circle, parabola, ellipse, and hyperbola. As an astronomer, Apollonius investigated the motion of a planet revolving around a point displaced from the fixed Earth. This *eccentric* model is equivalent to a model in which the planet moves uniformly in a small circle (the *epicycle*), whose center revolves in a larger circle (the *deferent*) with the Earth at its centre. This combination of two circular motions could reproduce the observations of apparently non-circular and non-uniform celestial phenomena.

Apollonius' writings on astronomy have not survived, but his idea was developed by Hipparchus, who was the first to supply it with numerical parameters based on observations. With Hipparchus, the idea was turned into a geometrical model of epicycles and deferents that initiated a new chapter in the history of theoretical astronomy. What was most important was that Hipparchus' solar theory led him to conclude that all the fixed stars had small motions parallel to the ecliptic, a phenomenon known as the precession of the equinoxes. The value he gave for the precession was one degree per century or 36″ per year, which is in reasonable agreement with the true value of 50″ per year. The discovery of the precession turned out to be cosmologically important, as it led Ptolemy to conclude that the stellar sphere needed to be extended with yet another sphere. According to Ptolemy, the precession was due to the stellar sphere, but outside it there was a ninth sphere which caused the daily revolution. The ninth sphere was empty, yet it was the prime mover of the celestial revolutions. He described the two movements in the heavens as follows: 'One of them is that which carries everything from east to west: it rotates them with an unchanging and uniform motion . . . The other movement is that by which the spheres of the stars perform movements in the opposite sense to the first motion, about another pair of poles, which are different from those of the first rotation.'[38]

The zenith of ancient astronomy was reached in the second century AD with the famous *Almagest* by Claudius Ptolemy, an Alexandrian mathematician and astronomer who also wrote important texts on optics, astrology, and geography. The original title was *Megale syntaxis* ('Mathematical Compilation'), and in the Arabic world it became *al-majisti*, meaning 'the greatest', which in medieval Latin was rendered as *almagestum*. In his introduction to the *Almagest*, Ptolemy praised mathematical astronomy as the only science that could provide unshakeable knowledge and, at the same time, was morally uplifting: 'From the constancy, order, symmetry and calm which are associated with the divine, it makes its followers lovers of this divine beauty, accustoming them and reforming their natures, as it were, to a similar spiritual state.'[39] This theme would later play an important role in the Christian world, both in the Middle Ages and during the scientific revolution, but Ptolemy did not elaborate. The *Almagest*, structured in thirteen books, was a mathematically demanding, highly technical work, not a discourse on natural philosophy or cosmic theology.

Whereas Ptolemy adopted Hipparchus' solar theory, he offered a new and much improved theory of the five planets that agreed excellently with observations. His planetary theory was based on a sophisticated use of eccentrics, epicycles, and deferents that allowed him to explain, for example, retrograde motions and the limited elongations of Mercury and Venus (which never deviate from the Sun by more than 23° and 44°, respectively). In Ptolemy's theory, the centre of the epicycle did not move uniformly with respect to either the Earth or the centre of the deferent, but with respect to a point located at the opposite side of the centre and at an equal distance from it. This point is called the *equant*. With the use of the equant, Ptolemy was able to compute planetary positions accurately. On the other hand, it was a technical device that violated the philosophical doctrine of uniform motion and for this reason it later became controversial, first among Islamic astronomers and later in the medieval West. Ptolemy's world system differed technically from Aristotle's, yet it also had much in common with it. Thus, in the beginning of the *Almagest*, Ptolemy stated the physical premises of his theory in terms that Aristotle would have fully agreed with:

> The heaven is spherical in shape, and moves as a sphere; the Earth too is sensibly spherical in shape, when taken as a whole; in position it lies in the middle of the heavens very much like its centre; in size and distance it has the ratio of a point to the sphere of the fixed stars; and it has no motion from place to place.[40]

Not only did the Earth not move from place to place, it also did not rotate around its axis. Ptolemy was aware that the possibility had been discussed by 'certain people'—he most likely thought of Heracleides of Pontus—but he dismissed it as 'ridiculous' and 'unnatural' because it was contrary to experience. Although he recognized that an axial rotation might account for the celestial motions, he argued that it led to consequences incompatible with observations, such as clouds being left behind in a westward direction. Ptolemy's arguments against a daily rotation would later be reconsidered by philosophers in the Middle Ages and the Renaissance.

The *Almagest* marked the culmination of Greek astronomy, just as Euclid's *Elements* marked the culmination of geometry. However, it was essentially a mathematical theory of the planets revolving around the Earth, and for this reason the *Almagest* is of no particular cosmological significance. As far as cosmology is concerned, another and later of Ptolemy's works is of far greater interest, the *Planetary Hypotheses*.[41]

Ptolemy's physical cosmology was based on Aristotelian natural philosophy, including the doctrines of the five elements and their natural motions. He believed that the ether consisted of tiny spherical particles and that this was a physical argument in support of the sphericity and circular motion of the celestial bodies. Ptolemy agreed that there could be no void in the universe, which became the foundation of his cosmological theory as described in *Planetary Hypotheses*. He found the arrangement of nested planetary spheres he arrived at to be 'most plausible, for it is not conceivable that there be in nature a vacuum, or any meaningless and useless things'.[42] The basic principle of Ptolemy's theory was to arrange the shells of the celestial bodies one within another, with the thickness of each shell being determined by the eccentricity of the planet's deferent circle and the radius of its epicycle. The whole system was arranged in such a way that no empty space appeared between the

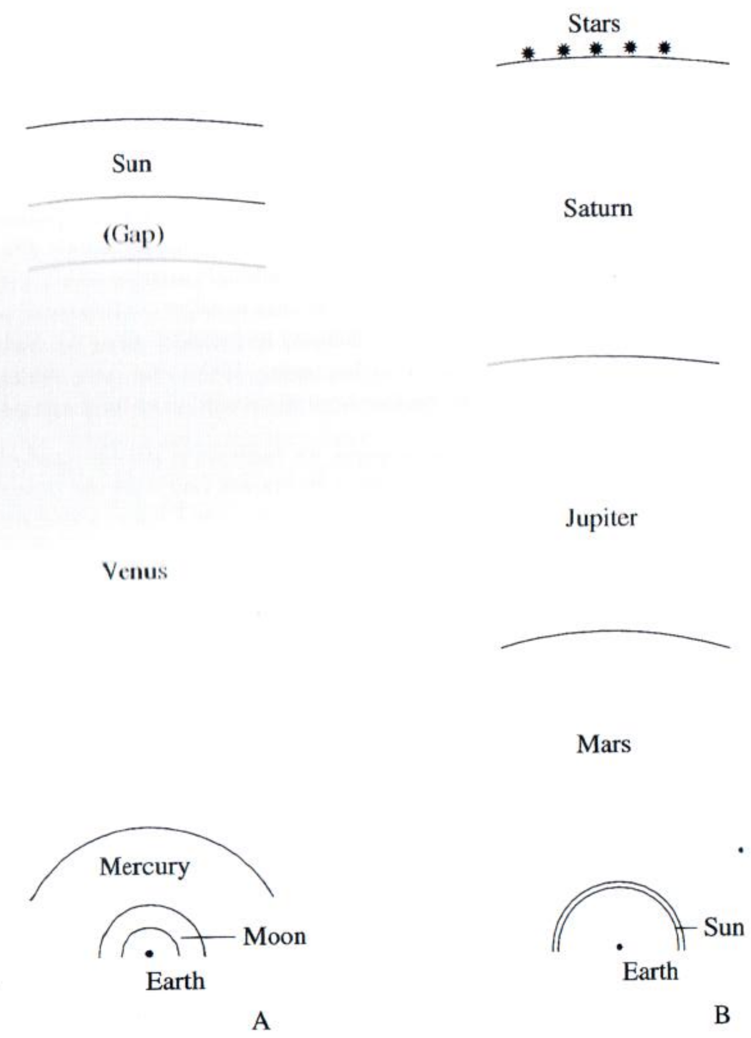


Fig. 1.7 Distances in Ptolemy's cosmology in *Planetary Hypotheses*, drawn to scale. The scale of the left part is 15 times as small as in the right part. Copyright © 1993, from *Encyclopedia of Cosmology* (Hetherington 1993). Reproduced by permission of Routledge/Taylor & Francis Group, LLC.

shells, meaning that the greatest distance of one planet was equal to the least distance of the planet outside it.

The general idea of incorporating epicycles and deferents into the Aristotelian model of nested spheres was anticipated by Theon of Smyrna, a philosopher who lived in the early part of the second century. Contrary to most other philosophers and astronomers, Theon was careful to distinguish apparent from real motions, and he emphasized the need to understand the heavens in physical terms. His epicycles and deferents were not mere mathematical tools, but had a real existence.

The space between the Earth and the Moon was filled with air and fire, and in the *Almagest* Ptolemy determined the Moon's distance from the Earth to vary between 33 and 64 Earth radii. The variation was much too great to fit with observations, which he must have known. However, it was not possible to determine the order of the other planets by means of astronomical data, and Ptolemy therefore had to rely on physical arguments of a somewhat arbitrary nature. Whatever the soundness of these arguments, he concluded in the *Planetary Hypotheses* that following the Moon's sphere there came, in this order, the spheres of Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. The sphere of the fixed stars completed the system. Since the greatest distance of the Moon was 64 Earth radii, this must also be the least distance of Mercury. By means of the theory of epicycles and deferents, as developed in the *Almagest*, he found that the ratio of the least to the greatest distance for Mercury was 34:88, which implied that Mercury's greatest distance was $64 \times (88/34) = 166$ earth radii. The construction of the thicknesses of the remaining planetary shells followed the same procedure and resulted in a cosmological distance scale (Table 2), which Ptolemy summarized as follows:

In short, taking the radius of the spherical surface of the Earth and the water as the unit, the radius of the spherical surface which surrounds the air and the fire is 33, the radius of the lunar sphere is 64, the radius of Mercury's sphere is 166, the radius of Venus' sphere is 1,079, the radius of the solar sphere is 1,260, the radius of Mars' sphere is 8,820, the radius of Jupiter's sphere is 14,187, and the radius of Saturn's sphere is 19,865.

It is to be noted that there is a gap of 81 Earth radii between the maximum distance of Venus and the minimum distance of the Sun. The gap was embarrassing, as it could not consist of void space. Ptolemy argued that it might be reduced by increasing the distance to the Moon slightly, but he nonetheless kept to his numbers, which, he stated, were inescapable.

Table 1.2 Ptolemy's cosmological distance scale. All numbers are in Earth radii

	Least distance	Greatest distance	Mean distance
Moon	33	64	48
Mercury	64	166	115
Venus	166	1 079	622.5
Sun	1 160	1 260	1 210
Mars	1 260	8 820	5 040
Jupiter	8 820	14 187	11 504
Saturn	14 187	19 865	17 026

Having found the cosmic distances expressed in Earth radii, Ptolemy converted them to stades: 'The boundary that separates the sphere of Saturn from the sphere of the fixed stars lies at a distance of 5 myriad myriad and 6,946 myriad stades and a third of a myriad stade.' Expressed in more familiar terms, the radius of Ptolemy's universe was about 570 million stades, or roughly 85 million kilometres. Like other Greek astronomers, he had nothing to say about the thickness of the sphere of the fixed stars. The stars were usually conceived to be at the same distance from the Earth, but it was realized that this was just an assumption with no justification in either theory or observation. For example, in his *Elements of Astronomy*, Geminus wrote that 'we must not suppose that all the stars lie on one surface, but rather that some of them are higher [i.e. more distant] and some lower [less distant]; it is only because our sight can only reach out to a certain equal distance that the difference in height is imperceptible to us.'[43]

Ptolemy went on to determine the sizes of the celestial bodies, which he did from estimates of their apparent diameters. He found that the Sun was the largest of the planets, with a diameter 5.5 times that of the Earth, followed by Jupiter (4.4) and Saturn (4.3). With a diameter of only 0.04 times that of the Earth, Mercury was the smallest planet.

Unlike the *Almagest*, Ptolemy's *Planetary Hypotheses* did not circulate widely. Its content was mostly known from other works, especially by Islamic astronomers. Thâbit ibn Quarra wrote in the ninth century a work that surveyed Ptolemy's cosmology and was partly based on the *Planetary Hypotheses*. Thâbit used Ptolemy's numbers, except that he changed the Sun's least distance to 1079 Earth radii in order to get rid of the gap between the spheres of Venus and the Sun. He kept the Sun's greatest distance (1260 Earth radii) and thus increased the thickness of the Sun's sphere. Such a change had astronomical consequences—it resulted in a solar eccentricity much larger than allowed by observations—but Thâbit chose to ignore these. The important thing was to fill the gap and thus avoid an embarrassing cosmic void.

1.3 Medieval cosmology

The highly developed Hellenistic science, such as that represented by Ptolemy, came to a halt in the late phase of the Roman empire. Since its language was Greek, it remained unknown to most learned people in the early Middle Ages, and it was only after the Greek literature was translated into Arabic that it eventually found its way to Latin-using medieval Europe.

For a long time the best known of the ancient cosmological works was Plato's *Timaeus*, most of which was translated into Latin by Chalcidius, who worked in either the fourth or the fifth century. With the translations in the twelfth century of Aristotle and Ptolemy, the European scene was ready for a change. For nearly four centuries, Aristotle's natural philosophy served as the basis of a stable and harmonious world picture which was strongly influenced by Christian thought. A form of Christianized Aristotelianism became the foundation of a cosmology that gained a paradigmatic status. The medieval cosmos was finite and geocentric, with the seven planets and the stellar sphere revolving around the immobile Earth; the celestial bodies moved with uniform speed in circles or spheres; whereas the terrestrial region was corruptible and made up of the four elements, the heavens constituted a changeless world made of a fifth element unknown on Earth; and, finally, the spheres surrounded one another contiguously, excluding all void or empty space.

The thirteenth and fourteenth centuries witnessed lively discussions of cosmological issues, many of them focusing on possible universes rather than the one actually existing. Could God have created a different universe, say one that violated the doctrines of Aristotelian physics? Could he have created many universes? Because God was omnipotent, his creative power was limited only by what is logically impossible. This kind of scholastic exercise, led to debates of great ingenuity and several remarkable ideas, but when it came to the real universe imagination was much more restrained and only very few scholars dared to question the standard cosmology.

One of the most notable features of the high Middle Ages was that the temporal dimension, which had been largely ignored in Greek cosmology, was brought back into focus. The Christian universe was created by God, which was generally taken to mean that the universe had only existed for a finite period of time. However, although cosmology was thus provided with a temporal marker, that was restricted to the act of creation; there was still no perspective of development. The absolute age of the universe—or of the Earth, a distinction was rarely made—was not an issue of great importance in the Middle Ages, but it was generally conceded that a reliable figure could be derived from Biblical chronology.[44] As early as the late second century, Theophilus of Antioch concluded that creation had taken place in 5529 BC, and Augustine affirmed that this was of the right order of magnitude. During most of the medieval era it was accepted that the world had come into existence by a supernatural act about 6000 years ago, a belief that would persist until well into the eighteenth century.

1.3.1 *Athens or Jerusalem?*

What little was known about the universe in the early Middle Ages included the idea that it was created *in toto* in a supernatural act rather than shaped out of some pre-existing state of matter. It was a true *creatio ex nihilo*. Given that this is a fundamental doctrine of Christianity, and in view of the overwhelming impact of Christian thought on cosmology through a large part of history, it is not irrelevant to repeat that *creatio ex nihilo* is nowhere explicitly stated in the Bible, neither in the Old nor in the New Testament. It is a doctrine not to be found in the earliest form of Christianity, when the form of creation was rarely a matter of discussion. Only in the second half of the second century can the doctrine be found in its strict sense, as an ontological and theological statement that expresses the contingence of the creation and the omnipotence and absolute freedom of God.[45]

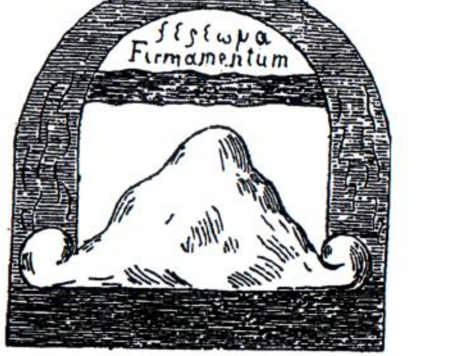
St Augustine went a step further by arguing that cosmic creation did not only mean that God caused the universe to exist, but also that creation was timeless and implied a continual existence of the world. He may have been the first to state that, paradoxically, the created universe has always existed. When the doctrine of creation out of nothing was first formulated, it quickly became accepted as almost self-evident. Church fathers of the third century, such as Tertullian, Hippolytes, and Origen, all found *creatio ex nihilo* to be a fundamental doctrine that must necessarily be true. When it was officially accepted by the fourth Lateran Council in 1215, it had been widely adopted for a millennium.

The early Middle Ages—roughly the period from 400 to 800—witnessed a drastic decline in science, including astronomy and cosmology. The new spiritual power, the Christian church, had no unified view of what little was still known about Greek science, but for a time it expressed strong hostility towards any form of natural philosophy which could not be derived from the Bible or otherwise be justified theologically. The astronomical knowledge of even the most learned of the church fathers was pitifully small. At least some of the Christian leaders flatly rejected the Greek conception of the world and supported a Biblical fundamentalism. 'What indeed has Athens to do with Jerusalem?' asked Tertullian. Not much, he thought: 'We want no curious disputation after possessing Christ Jesus, no inquisition after enjoying the gospel! With our faith, we desire no further belief.'[46]

The changed intellectual atmosphere in early Christianity is illustrated by the remarkable if short-lived return of a non-spherical Earth. According to Lactantius, a bishop who lived in the first half of the fourth century (and whose real name was Lucius Caecilius Firmianus), the sphericity of the Earth was a ridiculous as well as heretical belief. In his *Divinae institutiones*, he asked: 'Is there anyone as stupid as to believe that there are men whose footprints are higher than their heads? Or that things which lie straight out with us hang upside down there; that grains and trees grow downwards; that rain and snow and hail fall upwards upon the Earth?'[47]

Lactantius—'a poor mathematician' according to Copernicus—was not the only Christian who believed in a literal interpretation of Scripture. Some of the church leaders were flat-earthers, accepted the supracelestial waters, and denied the spherical shape of heaven.[48] They suggested that heaven was rather like a tent or the Tabernacle, a view they could easily find evidence for in the Holy Book, such as in Isaiah 40:22: 'It is he who sits above the circle of the Earth, and its inhabitants are like grasshoppers; who stretches out the heavens like a curtain, and spreads them like a tent to dwell in.' This was the opinion of Diodorus, a bishop of Tarsus in the fourth century. Most of the patristic writers were hostile to Hellenistic cosmology but did not attempt to replace it with a detailed cosmological system based on the Bible.

Such a system was what Cosmas Indicopleustes, a widely travelled Byzantine or Egyptian merchant of the sixth century, provided in his *Christian Topography*. Cosmas argued against



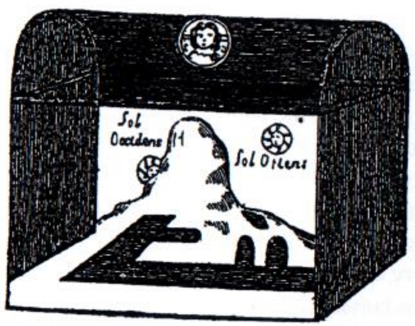


Fig. 1.8 Cosmas' universe. The left figure is a cross-section of the vaulted box containing the Earth or universe. The Sun moves round the large conical mountain. The figure to the right is Cosmas' diagram of the box with the mountain and four gulfs (from the left: Mediterranean, Red Sea, Persian Gulf, and Caspian Sea). From Cosmas 1897.

the spherical shape of the Earth, summarily rejected the epicyclic theory, and also declared it ridiculous to believe that the Earth was at the centre of the universe. Such views were 'absurdities contrary to nature, in opposition to scripture'. The Earth, an incredibly heavy body, must surely be at the bottom of the universe, he argued. It will come as no surprise that Cosmas believed that heaven was designed like the Tabernacle and that the only way to understand its construction was to pay close attention to the Mosaic writings.

Cosmas included in his Christian topography a figure of the civilized world, which he pictured as a vaulted box. Above was the vault of the sky, with the firmament between it and the ground. 'There is also the firmament which, in the middle, is bound together with the first heaven, and which, on its upper side, has the waters according to divine scripture itself.' The heavenly bodies did not revolve around the Earth, but were placed below the firmament and moved by angels. The Sun and the Moon disappeared each day behind a huge mountain, which to Cosmas explained the difference between night and day. The stars were not at immense distances, as the pagans held, but belonged to the aerial spaces together with the planets. For, 'How is it that many of the fixed stars are equal and like to the planet we call Mars, to which a lower sphere has been assigned, and how do we in like manner see not a few of them to be like the planet Jupiter?'[49]

It would be wrong, though, to believe that all early Christians were enemies of secular philosophy or fundamentalists of the same breed as Lactantius and Cosmas. In fact, the two were exceptions when it came to the non-spherical shape of the Earth. By far the most influential of the church fathers, St Augustine, was a learned man and much more moderate in his views. Augustine sometimes warned against natural philosophy, but in so far as it did not conflict with Scripture he was willing to take it seriously, if for no other reason because it might in some cases help in Biblical exegesis. As far as astronomy was concerned, he did not reject the spherical Earth, although he did not endorse it either. He had no doubt about the water above the firmament—after all, there was solid Scriptural evidence for it. As to the Aristotelian idea of an element particular to the heavens, the ether, he rejected it. That Augustine was not simply antiscientific may also be judged from Galileo's *Letter to Grand Duchess Christina*, where Galileo quoted Augustine extensively in support of the view concerning science and faith favoured by himself. One of the quotations reads:

> What is it to me [Augustine] whether heaven, like a sphere, surrounds the Earth on all sides as a mass balanced in the centre of the universe, or whether like a dish it merely covers and overcasts the Earth? . . . Hence, let it be said briefly, touching the form of the heaven, that our authors [of the Bible] knew the truth but the Holy Spirit did not desire that men should learn things that are useful to no one for salvation.[50]

It was only in the seventh century that a new scientific literature began to appear, and even then it relied heavily on earlier, mostly Roman authors. Writers such as Martianus Capella and Ambrosius Macrobius, who lived in the early fifth century, preserved the rudiments of Greek astronomy, such as the distinction between the planets and the fixed stars, and the spherical, Earth-centred universe. But this was about all that was left from the glorious past. As two historians of science have expressed it, 'Compared to the sophistication of the *Almagest*, knowledge of astronomy among the Latins in the second half of the first millennium was primitive in the extreme.'[51]

The ideas of John Philoponus, a philosopher from Alexandria who lived in the sixth century, were, however, far from primitive. A Christian strongly influenced by Neoplatonism, Philoponus criticized Aristotle's natural philosophy and sought to replace it with a system in harmony with monotheism. Thus he attacked the traditional doctrines of the eternity of the world and the essential difference between the terrestrial and heavenly parts of the world. According to Philoponus, heaven and Earth were made of the same elements, created by God but with no divine qualities. The light from the stars did not differ from light from terrestrial sources, a most un-Aristotelian view: 'There is much difference among the stars in magnitude, colour, and brightness; and I think the reason for this is to be found in nothing else than the composition of the matter of which the stars are constructed. . . . Terrestrial fires lit for human purposes also differ according to the fuel, be it oil or pitch, reed, papyrus, or different kinds of wood, either humid or in a dry state.'[52]

Since God had created the world out of nothing, it must have a finite age, contrary to what Aristotle had taught. Philoponus did not rest content with basing his conclusion on the authority of the Bible, but proved, to his own satisfaction, by means of *reductio ad absurdum* arguments, that an eternal universe would lead to absurdities. For example, the celestial bodies move with different periods, Saturn more slowly than Jupiter and much more slowly than the fixed stars. Now, if Saturn had revolved an infinity of times, Jupiter would have performed three times as many revolutions and the stars more than 10 000 times an infinite number of revolutions! This Philoponus thought was an impossible notion, and 'Thus necessarily the revolution of the heavenly bodies must have a beginning.'

Bishop Isidore of Seville, who lived around 600, was the author of a large encyclopedia in twenty books, *Libri etymologiarum*, which included many references to scientific subjects. Contrary to most other authors, he drew a sharp distinction between astronomy and astrology, rejecting prognostic astrology as superstition. In a smaller work, *De natura rerum*, Isidore compiled contemporary knowledge of the Earth and heaven. His Earth was a flat disc, and outside the firmament he assumed a watery heaven in accordance with Genesis. 'The sphere of heaven is a certain form, spherical in shape,' he wrote:

> Its center is the Earth and it is shut in equally on all sides. They say that the sphere has neither beginning nor end; since it is round like a circle its beginning and end cannot readily be seen. . . . Heaven has two gates, east and west, for the Sun issues from one and retires into the other. . . . The rising Sun follows a southerly path, and after it comes to the west and has dipped into the ocean it passes by unknown ways beneath the Earth and again returns to the east.[53]

The Venerable Bede, an English monk living a generation after Isidore, had an impressive mastery of conventional learning. He wrote a work on calendars which enjoyed a high reputation throughout the Middle Ages, and he was also the author of a cosmological treatise, again titled *De natura rerum*, which to a large degree relied on Pliny. Contrary to some of his predecessors, Bede had no problem with the spherical Earth, and he stated that the Sun was much larger than the Earth (he still stuck to the idea of water above the heaven). Bede was neither a scientist nor an innovative thinker, but he did provide some continuity through a difficult period. In a commentary on *De natura rerum* from the ninth century, the anonymous commentator made the interesting suggestion that whereas Mars, Jupiter, and Saturn revolved around the Earth, Venus and Mercury were satellites to the Sun. This kind of geo-heliocentric system was known in ancient Greece and was often ascribed to Heracleides of Pontus, a pupil of Plato. It bears some similarity to the world system devised by Tycho Brahe in the late sixteenth century.

By 900, astronomy and cosmology in the Christian West were still at a low ebb. The problem was not so much Scriptural fundamentalism, or the tension between Jerusalem or Athens, but rather that most of the products of Athens (and Alexandria) were unknown or only known in highly diluted versions from secondary sources. Only when the masterpieces of Greek philosophy and science became available in Latin versions could progress start anew.

1.3.2 *Aristotelianism revived*

The revival of learning in Western Europe relied crucially on translations of Greek scientific texts. As far as cosmology was concerned, Latin translations began to appear around 1150, and after a century or so almost the entire corpus of Greek astronomy and cosmology was available to European natural philosophers. Some of the works were translated directly from Greek to Latin, but most were based on Arabic books and commentaries. Spain, where Arabic and Islamic culture flourished, became the centre of the new translation movement. For example, this is where the best known of the translators, Gerard of Cremona, worked. The industrious Gerard produced translations from Arabic to Latin of Euclid's *Elements* and Aristotle's treatises on natural philosophy, including *De caelo*; but his greatest service to the revival of Greek science was probably his direct translation from the Greek of Ptolemy's *Almagest*, which he completed in 1175 (the first Arabic translation had appeared more than three hundred years earlier). Although the main texts of Greek astronomy and cosmology had been translated by the closing years of the twelfth century, it took another half-century until Aristotelian and Ptolemaic cosmology was generally known and made its impact on the teaching in the newly founded universities.

Even before the results of the translation movement became apparent, scholars produced texts of a cosmological orientation. These were influenced by Platonic and Neoplatonic thoughts, and of course also by Christian theology, whereas Aristotelian philosophy was of limited significance only. Scholars such as Thierry of Chartres, William of Conches, and Adelard of Bath, who all were active in the first part of the twelfth century, advocated a naturalistic approach to the study of nature. They conceived nature as an autonomous entity which proceeded in accordance with its own laws or inherent order. God had of course created the universe, but all of what happened after the creation was a result of natural causation. This view implied that it was the task of philosophers to find natural explanations and to have recourse to divine intervention only if such explanations should utterly fail. The message in William of Conches' *Philosophia mundi* was that the cosmos could be studied scientifically and that such a study of secondary causes would only affirm the glory of the undisputed primary cause, God.

Bernard Sylvester, who lived in the mid twelfth century, wrote a large treatise, *Cosmographia*, structured in two books, which included a good deal of natural philosophy. The first book (*Macrocosmus*) dealt with the creation of the world in a way that differed considerably from the account in Genesis. Bernard started 'before the beginning' with *Hyle*, a primeval and formless substance, the origin of which he did not explain and which he may have thought of as unoriginated. Out of the chaotic *Hyle*, the elements were shaped and order was introduced in the universe in a process closer to re-creation than to creation in the traditional Christian sense. In Bernard's poetic creation account, which shared some of the features of pre-Christian cosmogonies, matter was seen as an active power.

Robert Grosseteste, the first chancellor of the University of Oxford and known in particular for his works on optics, wrote in the 1220s two cosmological treatises, *De luce* and *De motu corporali et luce*, in which he constructed a cosmology of light. The universe, he said, was originally created by God in the form of a point of light in a primeval, transparent, dimensionless form of matter; the light instantaneously propagated itself into an expanding sphere, thereby giving rise to spatial dimensions and eventually, by means of light emanating inwards from the expanding light sphere, to the celestial spheres of Aristotelian cosmology. Grosseteste described the essence of his cosmogony as follows:

> I hold that the first form of a body is . . . light (*lux*), which as it multiplies itself and expands without the body of matter moving with it, makes its passage instantaneously through the transparent medium and is not motion but a state of change. But, indeed, when light is expanding itself in different directions it is incorporated with matter, if the body of matter extends with it, and it makes a rarefaction or augmentation of matter . . . From this it is clear that corporeal motion is a multiplicative power of light, and this is a corporeal and natural appetite.[54]

Grosseteste's light-cosmogony was of course speculative, but it was a naturalistic explanation of the origin of the universe in so far as it did not rely on miracles or other divine intervention. And then the scenario has a curious, if of course superficial, similarity to modern accounts of the radiation-dominated expanding universe—inflation included!

During the first half of the thirteenth century, scholars became increasingly aware of the power of the Aristotelian thought system, with the result that Aristotle gradually replaced Plato as the authority in natural philosophy. The consequence was a world picture which was basically Aristotelian, but which included elements of the Ptolemaic system in the form of eccentrics, deferents, and epicycles.[55]

Everybody agreed that the spherical Earth was at the centre of the universe and that it was surrounded by seven planetary spheres in perfect contact. Outside the sphere of Saturn was the *primum mobile*, with the stars. However, to these eight spheres two or three more were usually added, mostly for theological reasons. The Bible speaks of the waters above the firmament, which had to be taken seriously; the general interpretation was that it referred to a 'crystalline' sphere above the stars consisting of water in either fluid or hard form. This ninth sphere—but it could also be two spheres, a ninth and a tenth—was starless and perfectly transparent. Some scholars added yet another sphere, an immobile 'empyrean heaven', the ultimate container of the universe and the abode of the angels. There was some discussion of whether the celestial spheres were fluid or solid, but from around 1300 a solid or crystalline theory was commonly adopted. As to the celestial spheres and the bodies revolving along with them, it was generally assumed that they were made of some incorruptible, perfect, unalterable substance, which in most cases was identified with Aristotle's ether or quintessential element. The stars and planets, assumed to be spherical like the Earth, did not differ physically from the orbs, as they were thought to consist of the same ethereal element, only in a much denser form. Most scholars believed that the stars and planets received their light from the Sun, but a few argued that they were self-luminous bodies.

Whatever the opinions on these questions, it was agreed that the celestial spheres were three-dimensional. They were endowed with thickness and arranged in such a way that the convex surface of one sphere was equal to the concave surface of the sphere following it. In this way, gaps in the heavens and problems with celestial voids were avoided. The model also made it possible to calculate the dimensions of the cosmos, very much along the lines that Ptolemy had used in his *Planetary Hypotheses*. Campanus of Novara, who flourished around 1260, may not have known about Ptolemy's work but his calculations nonetheless led to a universe strikingly similar to that of the Alexandrian mathematician (Table 1.3). According to Campanus' *Theorica planetarum*, the inner surface of the Moon's sphere was about 108 thousand miles, and the outer surface about 209 thousand miles. At the farthest end of the universe, Saturn was located between 52 and 73 million miles away from the centre of the Earth. Since the sphere of the fixed stars was assigned no thickness, Campanus' universe was a huge sphere of radius 73 million miles, of the same magnitude as Ptolemy's. Also like Ptolemy, Campanus believed he could calculate the sizes of the planets.

The picture of the medieval universe as outlined here, was basically qualitative and of more interest to the philosophers than to the astronomers. Astronomy was predominantly a mathematical science aimed at calculating the positions of planets and stars, and for this purpose cosmological problems such as the nature of the celestial substance were not of great relevance. The attitude of many medieval astronomers, if by no means all, was instrumentalistic. Was astronomy to provide a true representation of celestial phenomena or merely mathematical models that saved the phenomena? There was no unified position on this point during the Middle Ages. Moses Maimonides, the Jewish–Spanish philosopher of the late twelfth century, was in favour of an instrumentalist position. Concerning astronomy, he wrote:

> The object of that science is to suppose as a hypothesis an arrangement that renders it possible for the motion of the star [planet] to be uniform and circular . . . and to have the inferences necessarily following from the assumption of that motion agree with what is observed. At the same time the astronomer seeks, as much as possible, to diminish motions and the number of spheres.[56]

According to Maimonides, it was only God who knew the true reality of the heavens. Man could not possibly know this truth, and could only devise models that accounted as well as

Table 1.3 Cosmic dimensions according to Campanus of Novara. All figures are in miles.

	Least distance	Greatest distance	Thickness of sphere	Diameter of planet
Moon	107 936	209 198	101 261	1 896
Mercury	209 198	579 321	370 122	230
Venus	579 321	3 892 867	3 313 546	2 885
Sun	3 892 867	4 268 629	375 762	35 700
Mars	4 268 629	32 352 075	28 083 446	7 573
Jupiter	32 352 075	52 544 702	20 192 626	29 642
Saturn	52 544 702	73 387 747	20 843 044	29 209

possible for observed phenomena. Maimonides' position was not generally accepted, though, and most medieval natural philosophers denied that astronomy was merely model-making. In spite of different attitudes, astronomers realized that they were dealing with the same universe as the cosmologists and natural philosophers. As David Lindberg, a leading scholar of medieval science, has expressed it, 'astronomy and cosmology were not glaring at each other across a methodological chasm, but rubbing shoulders along a methodological continuum'.[57]

Islamic astronomers saw Ptolemy's *Almagest* in a different and more critical light than did their European colleagues. Ibn al-Haytam, who in Christian Europe was known as Alhazen, criticized the Ptolemaic system in about 1000 for being abstract geometry with no physical reality behind it. As Copernicus would do 500 years later, he objected to Ptolemy's use of the equant. The influential philosopher Averroes, or Muhammad ibn Rushd, later argued that although the deferent–epicycle theory might save the phenomena it was unsatisfactory. He, too, wanted a world system that made physical and not only mathematical sense. In a commentary on Aristotle, he wrote: 'The astronomer must, therefore, construct an astronomical system such that the celestial motions are yielded by it and that nothing that is from the standpoint of physics impossible is implied. . . . Ptolemy was unable to see astronomy on its true foundations. . . . The epicycle and the eccentric are impossible.'[58]

From the middle of the thirteenth century there appeared several books, usually with the title *Theoria planetarum*, which focused on planetary theory in the Ptolemaic tradition. They were mathematical in orientation and aimed at producing astronomical tables and calculating positions of the planets. *Tractatus de sphaera*, written by Johannes de Sacrobosco (John of Holywood), was an elementary and highly successful textbook which outlined the Aristotelian world picture but included only the most rudimentary planetary theory. As to the nature of the heavens, Sacrobosco wrote:

> Around the elementary region there is the ethereal, which is lucid and immune from all variation in its unchanging essence, and which turns in a circular sense with a continuous motion. It is called the 'fifth essence' by philosophers. Of this there are nine spheres . . . namely of the Moon, Mercury, Venus, the Sun, Mars, Jupiter, Saturn, the fixed stars, and the final heaven. Each of these spheres encloses the one below spherically.[59]

Sacrobosco's *De sphaera* was used as a textbook for nearly three hundred years.

We meet a different kind of cosmology in some of the literary masterpieces of the medieval world, such as Dante Alighieri's *Divina commedia* and Geoffrey Chaucer's *Canterbury Tales*.[60] In Dante's *Divina commedia*, written between 1306 and 1321, the reader is presented with a simplified Aristotelian cosmos consisting of the seven planetary spheres, an immense sphere of the fixed stars (the *stellatum*), and a starless *primum mobile*. When Dante and his beloved Beatrice enter this outermost sphere he notes with surprise that it is so uniform that he cannot say where he entered it. Dante believed in the actual existence of the crystalline spheres made up of 'rounded ether', but he had ten spheres rather than Aristotle's nine. The tenth was, however, non-physical, endowed with neither dimensions nor extension. It was the empyrean heaven, the mind of God himself and a kind of paradise where the souls of the blessed were found. Dante described the speed of revolution of the *primum mobile* as incomprehensible, a result of the desire of each part of this

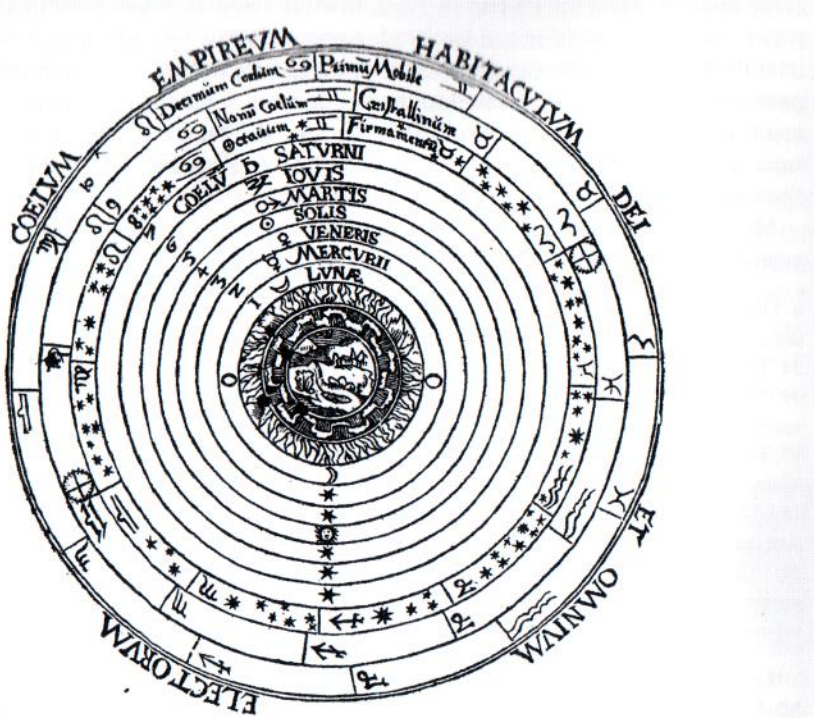


Fig. 1.9 The medieval Christian universe in a folk version, with the empyreum surrounding ten heavenly spheres. Illustration from Petrus Apianus's *Cosmographicum liber* of 1533.

sphere to conjoin with the divine empyreum. This 'heaven of pure light' had no limits and was not located in space. In the later *Il convivio*, he described the empyreum as 'the sovereign edifice of the world, in which all the world is enclosed, and beyond which is naught; and it exists not in space, but received form only in the Primal Mind, which the Greeks call Protonoe'.[61]

1.3.3 *Scholastic controversies*

Many theologians welcomed Aristotelianism if only it could be presented in a decent, Christianized version; but they were also aware of its dangers and the incompatibility of Aristotelian philosophy and certain Christian doctrines such as God's creation of the world. Around 1270, the faculty of arts in Paris housed a group of radical thinkers who were willing to carry Aristotle's rationalism and naturalism as far as possible, even to the point where it conflicted with religious dogma. Siger of Brabant and Boethius of Dacia were the most prominent of the group. Inspired by Averroes, they argued that it is the task of the philosopher to investigate every question that can be disputed on rational grounds; the arguments should be followed to their logical conclusion, without regard for the true faith. From the church's point of view, this was a deeply troubling position that had to be opposed. Action came in 1270, when the Bishop of Paris, Etienne Tempier, issued a list of 13 propositions which were declared false and heretical. Apparently this was not enough, for seven years later the list was greatly expanded, now covering 219 articles. To defend any of these propositions, many of which related to the opinions of Siger and other radical Aristotelians, could lead to excommunication.[62] The views of the radical Aristotelians (or Averroists) were condemned not only in Paris, but also in England, where the Archbishop of Canterbury issued condemnations in 1284 and again in 1286.

More than 20 of the propositions condemned by Tempier referred to cosmology; for example, it was an error to claim the following:

6. That when all celestial bodies have returned to the same point—which will happen in 36,000 years—the same effects now in operation will be repeated.
34. That the first cause [God] could not make several worlds.
49. That God could not move the heavens [the world] with rectilinear motion; and the reason is that a vacuum would remain.
87. That the world is eternal as to all species contained in it; and that time is eternal, as are motion, matter, agent, and recipient . . .
185. That it is not true that something could be made from nothing, and also not true that it was made in the first creation.
201. That He who generates the whole world assumes a vacuum because place necessarily precedes what is generated in that place; therefore, before the generation of the world there was a located place which is a vacuum.

Let us now consider some of the cosmological questions that were discussed in the Middle Ages, irrespective of whether they were mentioned specifically in the condemnations. First, it was generally agreed that the world was spatially finite. The possibility of an infinite world was sometimes discussed, but only to reject it as absurd and incompatible with Aristotelian physics. For example, Jean Buridan, an important Parisian scholar of the middle of the fourteenth century, argued that an infinite body cannot possibly move with a circular motion; for to do so there must be a centre, and an infinite body cannot have a centre. In spite of consensus on this point, there remained the possibility of an infinite, non-material universe, a possibility that was often discussed (see below).

Much more difficult was the question of temporal finitude, where Aristotle's insistence on an eternal world clashed head-on with the fundamental dogma of a world created in time. No wonder that article 87 specifically condemned the eternity of time, motion, and matter. Siger of Brabant was convinced of the truth of Aristotle's arguments and was consequently led to conclude that the world was not created. This was of course a decidedly heretical conclusion, and Siger was careful to point out that it rested wholly on reason; since it conflicted with faith, in this case reason could not be relied on. Other great medieval scholars, such as Buridan and Nicole Oresme, expressed a similar opinion. Logically and naturally, heaven could not have come into being, nor could it be annihilated. Nonetheless, it *was* created a finite time ago, and only in a supernatural act, by the will of God.

In his *De aeternitatis mundi* from about 1270, Thomas Aquinas discussed whether something that had always existed could be made; only if this was logically impossible would he concede that God could not have created an eternal universe. He argued that creation, in its theological meaning, differs from the generation of change or processes such as that studied by the natural philosophers. *Creatio non est mutatio.* Creation is to give existence to things, to cause them. God does not take 'nothing' and transform it into something, he causes things to exist continually in the sense that 'if the created thing is left to itself, it would not exist, because it only has a being from the causality of the higher cause'.[63]

Thomas distinguished between a temporal beginning of the universe and its creation, where the latter concept refers to the existence of the universe as such. Even if the universe had always existed, it would still depend on God for its very being; it would be created. As a Christian, Thomas believed that Aristotle was wrong and that the universe was of finite age; as a philosopher, he was willing to concede that the universe was eternal. At any rate, the question could not be answered on the basis of reason alone. What mattered was that God had caused the universe to exist, and this involved no contradiction with either reason or faith. Another line of reasoning, adopted by Thomas and his contemporaries, was that Aristotle's argument for the eternity of the world was not a formal proof and was therefore not in need of formal rejection; it could be dismissed on the sole ground that it was contrary to faith.

The possibility of other worlds was eagerly discussed during the Middle Ages.[64] Aristotle had emphatically rejected the possibility, but almost all medieval philosophers agreed that God could have created other worlds, had he so wished. Yet they also agreed that in fact God had chosen to create only one world. Article 34 of the condemnation of 1277 demanded that the faithful had to concede that God could create other worlds, but not that such worlds actually existed. Nicole Oresme, a Parisian philosopher and mathematician, was one of several scholars who examined the question and tried to find weaknesses in Aristotle's conclusion that only one world was possible. Oresme, who had translated Aristotle's *De caelo* into French, distinguished between three different ways in which the plurality of worlds could be conceived:

One way is that one world would follow another in succession of time, as certain ancient thinkers held . . . Another speculation can be offered which I should like to toy with as a mental exercise. This is the assumption that at one and the same time one world is inside another so that inside and beneath the circumference of this world there was another world similar but smaller. . . . The third manner of speculating about the possibility of several worlds is that one world could be entirely outside the other in an imagined space, as Anaxagoras held.[65]

After a lengthy analysis of the three possibilities, Oresme concluded that God in his omnipotence could make more worlds. 'But, of course, there has never been nor will there be more than one corporeal world.'

Related to both the question of the finitude of the universe and the question of other worlds, there was the question of whether or not the corporeal world was surrounded by an infinite void space, an idea with roots in ancient Greece (see Section 1.2). By and large, the favoured answer was—once again—that God could have created such a space, but that there was no reason to believe that he did. Buridan's conclusion represented the majority view: 'An infinite space existing supernaturally beyond the heavens or outside this world ought not to be assumed . . . Nevertheless, it must be conceded that beyond this world God could create a corporeal space and any whatever corporeal substances it pleases Him to create. But we ought not to assume that this is so [just] because of this.'[66]

The extracosmic void considered by the schoolmen was very different from the vacuum or non-being proposed by the Greek atomists. It was often conceived to be a spiritual heaven, God's abode, and therefore something which could not be confined to a finite world. Among God's many attributes were that he was omnipotent, transcendent, and infinite (in some non-spatial sense). It was sometimes suggested that an infinite world—or a finite material universe and an infinite void space—would be more consonant with God's power than a finite world. The eminent Oxford mathematician and natural philosopher Thomas Bradwardine identified infinite void space with God's immensity. Although his void space had neither extension nor dimensions, he nonetheless argued that it was real. Bradwardine followed Aristotle's arguments against a void a long way, but did not find them irrefutable. God could make a void anywhere he wished, within this world or outside it. 'Truly, even now, there is in fact an imaginary void place outside of the world, which I say is void of any body and of everything other than God.'[67] Oresme held a similar view.

It should be clear from this brief review that most of the cosmological problems discussed by medieval philosophers had very little to do with the business of the astronomers. The scholastic disputes about cosmology and cosmogony took place in a framework based on Christian theology and Aristotelian philosophy. What mattered was the delicate balance between these two pillars of insight, and in this context astronomical observations and calculations were of little or no relevance.

1.3.4 *New perspectives: Buridan to Cusanus*

The condemnations of 1277 helped create an intellectual climate where Aristotle's writings could be discussed more freely and critically. 'The philosopher' continued to be held in great esteem, but his system of natural philosophy was far from beyond criticism. We have an important example of this in the discussion of the Earth's immobility in the thirteenth century. Although no one drew the conclusion that the Earth actually moved, the arguments for a potentially moving Earth were impressive and demonstrated the willingness of some philosophers to depart from Aristotelian tradition.

Jean Buridan discussed the possibility of a daily rotation of the Earth around 1350. He pointed out that it was a problem of relative motion and that the motion of the stars could equally well be explained on this basis as on the traditional assumption that the stellar sphere revolved around the immobile Earth. In support of the hypothesis of a rotating Earth, he applied arguments based on the simplicity and economy of nature. 'Just as it is better to save the appearances through fewer causes than through many, if this is possible, so it is better to save [them] by an easier way than by one more difficult.'[68] Wasn't it more reasonable to assume that the relatively small Earth rotated with a fairly low speed than that the vast celestial spheres rotated with what must be an incredible speed? In addition to this argument, he added that rest was nobler than motion. As the noblest bodies, the stars therefore ought to be at rest, while the Earth, corruptible and ignoble as it was, ought to be in motion.

However, having presented his arguments in favour of a daily rotation of the Earth, Buridan started, in the spirit of dialectical thinking, to criticize them. He arrived at the conclusion that the Earth does not rotate after all. One of his counterarguments related to the strong wind that we would feel if the Earth rotated at high speed. He realized that supporters of the rotating Earth might 'respond that the Earth, the water, and the air in the lower region are moved simultaneously with diurnal motion,' but did not accept this explanation. At any rate, he adopted the conventional attitude that 'For astronomers, it is enough to assume a way of saving the phenomena, whether it is really so or not.' In the end, he kept to the orthodox Aristotelian view.

Buridan's discussion was further developed by his younger contemporary, Nicole Oresme, in *Le livre du ciel*, one of the classics of fourteenth-century natural philosophy. Here Oresme made the daring suggestion that the laws of terrestrial nature might be valid also for the celestial regions, a first step towards a dissolution of Aristotle's old distinction between the physics of the sublunar sphere and that of the spheres above the Moon. Also in opposition to Aristotle, but less controversially, he denied that the heavens were moved by intelligences (or angels). God had initially placed motive powers into the celestial bodies in such a way that no further application of power, whether animate or inanimate, was needed. Oresme may have been the first to use the metaphor of a clockwork that was later so famous when he wrote that 'the situation is much like that of a man making a clock and letting it run and continue its own motion by itself'.[69]

As far as the Earth's diurnal motion was concerned, Oresme basically discussed the same topics as Buridan, but in more detail and with greater sympathy for the hypothesis. He dismissed the problem of the wind that should constantly blow from the east by noting that the air would rotate along with the surface of the Earth. No experience, he emphasized, was able to dismiss the hypothesis of an axially moved Earth. Like Buridan, he considered the idea of a rotating Earth to be supported by reasons of simplicity as it avoided celestial speeds 'far beyond belief and estimation'. As another bonus, he mentioned that the hypothesis would do away with the generally assumed ninth sphere, which moved only with the diurnal motion:

> If we assume that the Earth moves as stated above, then the eighth heaven moves with a single slow motion and it is consequently unnecessary to imagine a ninth natural sphere invisible and starless; for God and nature would have made this ninth sphere for naught since by another method, i.e., assuming the Earth to move, everything can remain exactly as it is.[70]

Oresme referred to the passage in the Bible (Joshua 10:12–14) where God lengthened the day by commanding the Sun to stand still, and noted that the same dramatic effect could have been achieved much more easily by a temporary cessation of the Earth's rotation. Since God always acted in the most economic way, perhaps this was how he performed the miracle.

Yet Oresme decided that there were convincing theological reasons not to accept the rotating Earth. It was an interesting hypothesis, but not the way nature actually worked. In view of his impressive arguments in favour of a rotating Earth, Oresme's conclusion in *Le livre du ciel* was an anticlimax:

> However, everyone maintains, and I think myself, that the heavens do move and and not the Earth: For God hath established the world which shall not be moved, in spite of contrary reasons because they are clearly not conclusive persuassions. . . . What I have said by way of diversion of intellectual exercise can in this manner serve as a valuable means of refuting and checking those who would like to impugn our faith by argument.

It was one thing to go against Aristotle, quite another to question the authority of the Bible.

Nicholas of Cusa, also known as Cusanus, was a German cardinal and philosopher who wrote widely on a variety of subjects, including theology, mathematics, and natural philosophy.

He was fascinated by the concept of infinity, and in *De docta ignorantia* of 1440 he developed a metaphysical system (the doctrine of 'the coincidence of opposites') which he applied to cosmology, among other areas. The result was a number of bold claims that departed most radically from Aristotelian cosmology. However, it should be pointed out that the Renaissance philosopher Cusanus was essentially a Neoplatonist and Christian mystic, and that none of his arguments referred to empirical observations or were otherwise scientifically based. He stated that the cosmos had no fixed centre and no circumference as it was not bounded by any celestial sphere. His universe was 'relatively infinite' and homogeneous in the sense that any observer anywhere in the universe would observe essentially the same universe. There was no privileged place.

It is impossible for the world machine to have this sensible earth, air, fire, or anything else for a fixed and immovable centre. . . . And although the earth is not infinite, it cannot be conceived of as finite, since it lacks boundaries within which it is enclosed. . . . Therefore, just as the Earth is not the centre of the world, so the sphere of fixed stars is not its circumference. . . . Since it always appears to every observer, whether on the earth, the Sun, or another star, that one is, as if, at an immovable centre of things and that all else is being moved, one will always select different poles in relation to oneself, whether one is on the Sun, the Earth, the Moon, Mars, and so forth. Therefore, the world machine will have, one might say, its centre everywhere and its circumference nowhere, for its circumference and centre is God, who is everywhere and nowhere.[71]

And this was not all, for Cusanus also argued that the Earth was actually in motion. Moreover, he considered gravitation to be a local phenomenon such that each star or planet was a centre of its own gravitational attraction. Going even further than Oresme, he denied that there was any difference at all between celestial and sublunar matter; all celestial bodies, however noble, consisted of the same four elements as found on the Earth. Since there was life on the Earth, and the Earth was but a star, he assumed that there was life all over the universe. He even conjectured that the extraterrestrial beings differed in rank according to their location and that some of them, such as the 'bright and enlightened denizens' of the Sun, were superior to earthlings.

Cusanus' grand and bold cosmological vision anticipated some of the later developments in cosmology, in particular the cosmological principle, which is the claim that the universe is uniform on a large scale. But it should be kept in mind that Cusanus was no scientist and that his aim was not to devise a theory that could account for observable phenomena.

1.4 The Copernican revolution

And new Philosophy calls all in doubt,
The Element of fire is quite put out;
The Sun is lost, and th'earth, and no man's wit
Can well direct him where to looke for it.
And freely men confesse that this world's spent,
When in the Planets, and the Firmament
They seeke so many new; they see that this
Is crumbled out againe to his Atomies.
'Tis all in peeces, all cohaerence gone;
All just supply, and all Relation . . .[72]

This passage from John Donne's *An Anatomie of the World*, published in 1611, expresses a bewilderment and lack of orientation that many men of culture felt was the result of the doubts that natural philosophers raised against the traditional world picture. Foremost among these doubts was the controversial idea that the Earth, hitherto regarded as the immobile centre of the universe, was merely one planet among others, whirling around the Sun at great speed. With the disappearance of the immutable heavens, the comforting sense of order and unity had disappeared too. The revolution in astronomy seemed to confirm 'the frailty and the decay of this whole World'. Donne's better-known contemporary, William Shakespeare, related to the same theme in *Hamlet* II,2:

Doubt Thou the stars are fire
Doubt that the Sun doth move
Doubt truth to be a liar
But never doubt I love.

The controversial part of Copernicus' new world system, as many saw it, was not so much that it removed the Earth from its central position in the universe, for that was not necessarily a dignified position. After all, it was farthest away from the angels and God's eternal heaven. Indeed, it was sometimes argued that the natural place for the Earth, in both a physical and a moral sense, was 'the centre, which is the worst place, and at the greatest distance from those purer incorruptible bodies, the heavens'.[73] It was worse that the Earth had become reduced to a planet, which could be taken to imply that the other planets were inhabited by living and rational creatures as well. If so, the door was open for a host of theological problems.

1.4.1 *A heliocentric cosmology*

Nicolaus Copernicus, born in 1473 at Torun in the north of what is now Poland, received his elementary education at the Jagiellonian University of Cracow and subsequently went to Italy to study at Bologna and Padua. Although his primary field of study was canon law, he also took an interest in medicine and astronomy. In 1503 he returned to Poland, where he settled permanently in Frombork (or Frauenburg), a small town in an isolated corner of Varmia. There he engaged seriously in astronomical studies, the prime result of his studies being the daring hypothesis of a Sun-centred universe. It is unknown when he arrived at this idea, but around 1512 he wrote a brief sketch of the new astronomical system, known as the *Commentariolus*, which circulated in handwritten copies among a small number of scholars.[74] Copernicus had only a single disciple, Georg Rheticus, and it is in a work of his, the *Narratio prima* of 1540 (a second edition appeared in 1541), that we find the first published account of the Copernican system.

After many years of delay, Copernicus' masterpiece *De revolutionibus* was finally published in 1543, the very year of his death. Whatever the reason for the delay, it is most unlikely that it was caused by fear of how the Catholic church would react to the book. In fact, Cardinal Nicolaus von Schönberg had in 1536 urged Copernicus to publish his manuscript, although at the time to no avail. Copernicus knew that his theory might be considered to be theologically controversial, but in his preface to *De revolutionibus*, dedicated to Pope Paul III, he argued that it was not. Only 'by shamelessly distorting the sense of some passage in Holy Writ to suit their purpose' could certain people ignorant of mathematics

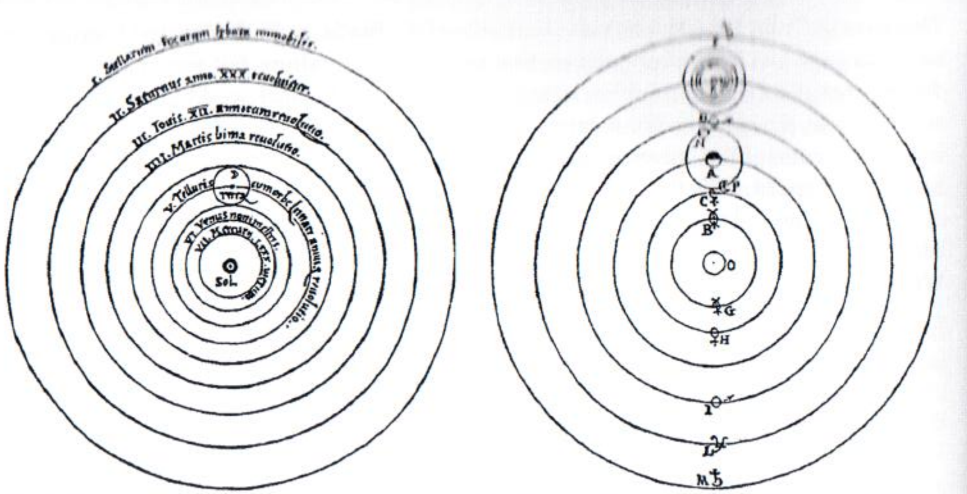


Fig. 1.10 Two historically important reproductions of the heliocentric world system. The picture on the left is from Copernicus' *De revolutionibus* (1543), with the sphere of the fixed stars completing the system. The version on the right is from Galileo's *Dialogo* (1632). The only difference between the two representations is that Galileo included the four moons he had observed moving round Jupiter.

find the work heretical.[75] Much like Ptolemy's *Almagest*, Copernicus' *De revolutionibus orbium coelestium libri sex* was thoroughly mathematical in nature and structure. Written in six books, it was a difficult and technical work, aimed at mathematically informed astronomers and at neither astrologers, philosophers, nor cosmologists. Indeed, Copernicus proudly emphasized that 'Mathematics is written for mathematicians' (*Mathemata mathematicis scribuntur*).

In the *Commentariolus*, Copernicus started by outlining in seven postulates the main features of his alternative to the traditional cosmology. The centre of the Earth was not the centre of the universe, a position which was instead occupied by the Sun. Whatever motion appeared in the firmament did not arise from it, but from the motion of the Earth, and the same was the case for the apparent motion of the Sun. Not only did the Earth rotate around its own axis, it also 'revolve[s] about the Sun like any other planet'. Copernicus further pointed out that his universe was of enormous dimensions: 'The ratio of the Earth's distance from the Sun to the height of the firmament is so much smaller than the ratio of the Earth's radius to its distance from the Sun that the distance from the Earth to the Sun is imperceptible in comparison with the height of the firmament.'[76] The reason for this postulate was the very same problem that Aristarchus had faced in his hypothesis of a heliocentric universe, namely the absence of an observed stellar parallax.

De revolutionibus started with a brief introductory section, in which it was stressed that the sole purpose of astronomy was to devise models that could save the phenomena. The message of this section, apparently written by Copernicus, was that the heliocentric theory was merely a computational model and not one that claimed to be true in a physical sense. It was not written by Copernicus, however, but by Andreas Osiander, a Lutheran theologian who was entrusted with the supervision of the printing of *De revolutionibus*. Copernicus certainly did not share Osiander's opinion, but for a while this was not generally known. Only in 1609 did Kepler reveal that the anonymous introduction was in fact written by Osiander. To believe that Copernicus subscribed to the instrumentalist position outlined in the introduction was 'most absurd', he wrote.

Why did Copernicus find it necessary to turn Ptolemy on his head and develop an astronomical theory that ran counter to tradition and common sense? It is often stated that the Ptolemaic system had grown increasingly complex and that epicycles had to be added to epicycles in order to match observations. This allegedly led to a crisis, which Copernicus responded to with his new world system. However, the contrast between the simplicity of the Copernican system and the complexity of Ptolemy's system of compounded circles is fictitious. There was no state of crisis at the time Copernicus started to develop his alternative.[77]

Copernicus was indeed dissatisfied with the Ptolemaic system, but not because of its number and arrangement of circles or because it failed observationally. His main objection was that the centres of its epicycles did not move with uniform speed on the deferents, but with respect to the fictitious equant. In the opening lines of the *Commentariolus*, Copernicus emphasized that such a system 'seemed neither sufficiently absolute nor sufficiently pleasing to the mind'. He found it to be a betrayal of the fundamental doctrine that uniform circular motion was the only allowed form for motion in the heavens and indicated that it was his desire to remedy this defect that led him to the new theory. Copernicus had also become annoyed that the astronomers had not been able to discover 'the form of the world and the certain commensurability of its parts', a reference to the order and distance of the planets, which had no theoretical justification withing the existing astronomy. As a third reason, he wanted to establish a world system which, methodologically and aesthetically, was simpler than the traditional one, a system which rested only on a few hypotheses. Geocentric astronomers were forced to make use of 'an almost infinite multitude of spheres', whereas Copernicus would rather 'follow the wisdom of nature, which, as it takes very great care not to have produced anything superfluous or useless, often prefers to endow one thing with many effects'.[78]

In addition to these arguments of a methodological nature, there were also arguments that reflected the revival in the Renaissance of Pythagorean and Neoplatonist thought. Thus, in a lyrical passage in *De revolutionibus*, Copernicus conceived the Sun—'this lamp of the very beautiful temple'—to be the most noble of the celestial bodies and for this reason the one which naturally should occupy a central position. And Rheticus stressed how wonderful it was that with Copernicus' innovation, the number of planets was reduced from seven to six. As he pointed out in *Narratio prima*, six was a sacred number: 'For the number six is honored beyond all others in the sacred prophecies of God and by the Pythagoreans and the other philosophers. What is more agreeable to God's handiwork than this first and most perfect work should be summed up in this first and most perfect number?'[79]

Copernicus' system was able to explain in a simple way the retrograde motions of the planets and, equally simply, the limited elongations of Mercury and Venus. These phenomena did not need any special hypotheses, but followed directly from the basic assumption of the Earth's annual revolution around the Sun. In several ways Copernicus' world system resembled that of Ptolemy, only with the Earth and the Sun being interchanged; the celestial spheres were still largely concentric, and Copernicus even had to introduce epicycles in the style of Ptolemy. But when we turn to the structure and dimensions of the Copernican universe we realize how different it was, after all, from the one traditionally accepted.

... to Copernicus, compared with the modern mean distances. All values in astronomical units.

	Least	Greatest	Mean	Modern mean
Mercury	0.26	0.45	0.38	0.39
Venus	0.70	0.74	0.72	0.72
Earth	0.97	1.03	1.00	1.00
Mars	1.37	1.67	1.52	1.60
Jupiter	4.98	5.46	5.22	5.20
Saturn	8.65	9.70	9.17	9.54

Contrary to the astronomers in the Ptolemaic tradition, Copernicus did not have to guess the order of the planets. He could calculate their distances in terms of the Earth's mean distance from the Sun, the astronomical unit (AU). For this unit distance, he found a value of 1142 Earth radii, which was much too small—the correct value is about 23 600—but Copernicus wisely decided to use the relative planetary distances, as given in Table 1.4.

We first note that Copernicus' planetary universe, as given by the distance to Saturn, is *smaller* by a factor of nearly two than what Ptolemy had found in his *Planetary Hypotheses*. Next, and more interestingly, the planetary spheres are much thinner and do not fill at all the space between the spheres. For example, Mars reaches out to 1.67 AU, far from the minimum distance of Jupiter, which is 4.98 AU. In other words, Copernicus' planetary model did not satisfy the principle of plenitude which was so dear to Ptolemaic astronomy. Even more shockingly, in order to accommodate the unobserved stellar parallax, the distance from Saturn to the sphere of the fixed stars had to be immense. 'The Earth is to the heavens as a point to a body and as a finite to an infinite magnitude', Copernicus wrote.[80] In a cosmological perspective, the Earth was merely an atom. 'It is not at all clear how far this immensity stretches out', he continued, but surely there must be an unoccupied space outside Saturn many times the planet's distance from the Sun. In terms of volume, the Copernican universe was at least 400 000 times as large as that of traditional cosmology! What was the nature and purpose of the space between the celestial spheres? Was it filled with some kind of ethereal substance? Was it a void? Nobody could tell.

When it came to the fixed stars, Copernicus had as little to say as Ptolemy. He seems to have placed all the stars, whatever their magnitude, on the same spherical surface at an immense distance from the Sun. At any rate, he did not indicate that the stellar sphere had any appreciable thickness. In Book I, Chapter 8, he briefly addressed the question of whether there might be something beyond the heavens, or 'If the heavens are infinite, . . . and finite at their inner concavity only'. Copernicus, the mathematical astronomer, did not come up with an answer, and preferred to leave the question to be discussed by the natural philosophers.

1.4.2 *Tycho's alternative*

Copernicus' theory did not immediately attract much attention. It took a couple of decades until its significance and novelty were generally recognized and astronomers began to discuss its merits and defects. A few accepted the heliocentric system, but most of those who studied *De revolutionibus* held a more eclectic attitude: they used what they could use, especially the mathematics of the planetary theory, but without subscribing to the heliocentric theory as physically true. The influential Jesuit mathematician and astronomer Christoph Clavius wrote between 1570 and 1611 a long series of commentaries on Sacrobosco's *De sphaera* in which he critically reviewed alternatives to the traditional Ptolemaic system. He praised many aspects of Copernicus' work, but without accepting its heliocentric cosmology. On the contrary, he objected to Copernicanism with an array of physical, astronomical, and methodological arguments. Clavius' Ptolemaic universe, including the empyreum, consisted of 11 spheres. Although there were neither bodies nor motion in the empyrean heaven, this 'happy seat and home of the angels and the blessed' was no less real than the firmament and the planetary heavens. Clavius stated that beyond the empyreum there might be a kind of infinite space, where God could create other worlds.

Whereas Clavius defended the traditional world picture, the Danish nobleman Tycho Brahe suggested an alternative to both of the existing cosmologies.[81] In 1572, the 26-year-old Tycho observed what appeared to be a new star in the constellation of Cassiopeia, and in his book *De nova stella* of the following year he argued that it was indeed a new, if ephemeral, fixed star. This was of cosmological importance because the interpretation broke radically with the age-old belief that the heavens were perfect and unchanging. Clavius was among those who accepted Tycho's interpretation.

In 1574–75 Tycho gave a series of lectures at the University of Copenhagen in which he introduced the new world system of Copernicus—'the second Ptolemy', as he called him. He had much praise for the theory of the Polish astronomer and stated that he would deal in his lectures with the motion of the planets according to Copernicus and using his parameters; but, significantly, he would transfer them to an Earth at rest. Tycho had lost confidence in the Ptolemaic system, yet he was unable to accept that the Earth really moved around the Sun. After he (and others) had observed the great comet of 1577, he began thinking of an alternative that would accommodate the best of both systems, most likely inspired by 'proto-Tychonic' systems developed by the German mathematician Paul Wittich and others.[82] He realized that if the comet had passed through the spheres of Mercury and Venus, as his data indicated, the spheres could not be solid bodies; hence there was nothing to bar planetary orbits from intersecting, as in the case of Mars crossing the orbit of the Sun.

Tycho published his world system in 1588, as Chapter 8 of his treatise on the great comet, *De mundi aetherei*. According to Tycho, the universe was geocentric, with the Sun and the Moon circling around the immobile Earth; or, perhaps better, it was geo-heliocentric, for all the other planets revolved around the Sun (Fig. 1.11). This was clearly a compromise between the Ptolemaic and the Copernican system, physically closer to the former, whereas mathematically it was closer to the latter. Since the Tychonic system was geometrically equivalent to Copernicus' system, it could match all its predictions except the apparently non-existent stellar parallax. The dimensions of Tycho's world up to Saturn did not differ much from those of Copernicus'. He took the distance of the Sun from the Earth to be about 20 times the Moon's distance, for which he adopted the value 60 Earth radii. For the distance to the farthest planet, Saturn, he ended up with 11,000 Earth radii. In gross contrast to Copernicus, he put the sphere of the fixed stars immediately above Saturn's sphere, at an average distance of about 14 000 Earth radii.

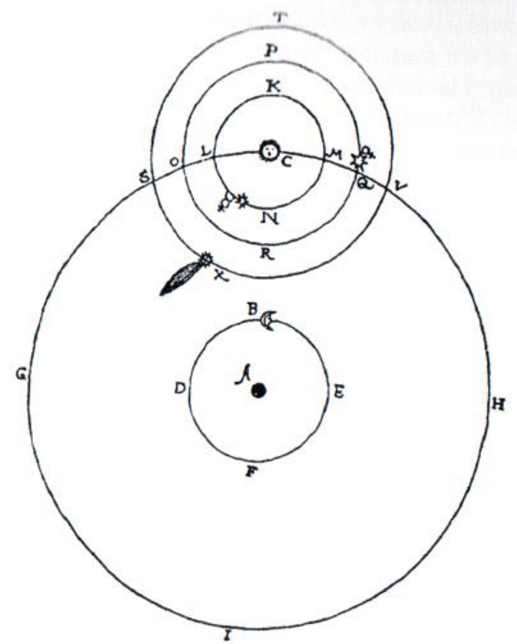


Fig. 1.11 The Tychonic world system, as reproduced in Tycho Brahe's *De mundi aetherei* of 1588. Whereas the Sun (C) revolves around the Earth (A), the other planets encircle the Sun. Only Mercury and Venus are shown in the figure. The object X is a comet, supposed to move in a circular orbit near that of Venus.

Why did Tycho, the self-appointed renovator of astronomy, refrain from going the whole way? Why did he not accept the heliocentric theory as representing the real universe? His reasons were diverse and not particularly original. In some cases they expressed a conservative attitude, as when he used the Bible as evidence against a moving Earth. The German astronomer Christopher Rothmann, with whom Tycho corresponded and who visited Uraniborg in 1590, denied that the Bible held any authority in scientific matters, but Tycho begged to disagree and maintained that the Scriptural evidence against Copernicus' theory must be taken seriously. What was undoubtedly of more importance, in matters of natural philosophy Tycho was at heart an Aristotelian. For this reason he accepted the dichotomy between the world beneath and above the Moon, and he used traditional Aristotelian arguments (already criticized by Buridan and Oresme) to prove the absurdity of a moving Earth.

The missing annual parallax for the fixed stars was another good reason to reject the Copernican theory. Tycho, armed with his excellent instruments, had looked for stellar parallaxes and found none. This he took to mean that the parallax, if there was one, was smaller than 1′ (minute of arc) or that, according to Copernicus' theory, the fixed stars were located at a distance at least 7 million Earth radii away. This enormous void space he simply was unable to accept; it was not only incredible, but also impossible. This uneasiness about the empty space between Saturn and the fixed stars was common at a time when it was generally assumed that the universe had a purpose, that it had been created for the benefit of man. In his *Dialogo* of 1632, Galileo lets Simplicio, the protagonist of the traditional world view, argue against Copernicus as follows:

How when we see this beautiful order among the planets, they being arranged around the earth at distances commensurate with their producing upon it their effects for our benefit, to what end would there then be interposed between the highest of their orbits (namely, Saturn's) and the stellar sphere, a vast space without anything in it, superfluous, and vain. For the use and convenience of whom?[83]

Later generations of scientists would smile at such teleological rhetoric, but at the time of Tycho and Galileo it was still part of the scientific discourse. Moreover, Tycho shared with other astronomers the belief that the stars had visible diameters, which he found to be between 1′ and 3′. This again implied that if the stars were located as far away as required by the Copernican system, they would have impossibly large diameters, several hundred times that of the Sun. Tycho found this to be plainly absurd, and hence a strong argument against Copernicus' mistake, but Copernicans such as Rothmann were not convinced. They typically found refuge in an old theological argument, namely that the vastness of Copernicus' universe reflected the vastness of God's creative power. In response to Tycho, Rothmann wrote:

Or what absurdity follows if a star of the third magnitude equals the entire annual orb? . . . The absurdity of things, which at first glance appear so to the multitude, cannot be so easily demonstrated. Indeed, divine Wisdom and Majesty is much greater, and whatever size you concede to the Vastness and Magnitude of the World, it will still have no measure compared to the infinite Creator.[84]

Although Tycho was mainly interested in devising a planetary system that agreed with observations, he also had an interest in the physics of the heavens. Like most other astronomers, he distinguished between the task of the astronomer (or mathematician) and that of the natural philosopher. As he wrote to Rothmann, cosmology belonged to the realm of philosophy, not astronomy:

The question of celestial matter is not properly a decision of astronomers. The astronomer labours to investigate from accurate observations, not what heaven is and from what cause its splendid bodies exist, but rather especially how all these bodies move. The question of celestial matter is left to the theologians and physicists among whom now there is still not a satisfactory explanation.[85]

On the other hand, the Renaissance holist Tycho was also convinced that astronomy had a non-mathematical, astrophysical, or cosmological side, and that this could not be separated from the studies of terrestrial matter and its changes. A devotee and practitioner of Paracelsian chemistry, he believed that, in a sense, astronomy was the chemistry of the heavens and chemistry a kind of terrestrial astronomy. By studying the heavens, the natural philosopher would get a superior knowledge of processes on the Earth, and he would likewise become a better astronomer if he was well versed in chemistry and alchemy (Fig. 1.12).

Although Tycho followed Aristotle in distinguishing between the sublunar and superlunar regions of the world, he did not admit the distinction to be absolute. He was more inclined to believe that the air gradually became thinner towards the Moon and was then connected to Aristotle's ethereal element (he did not admit fire among the atmospheric

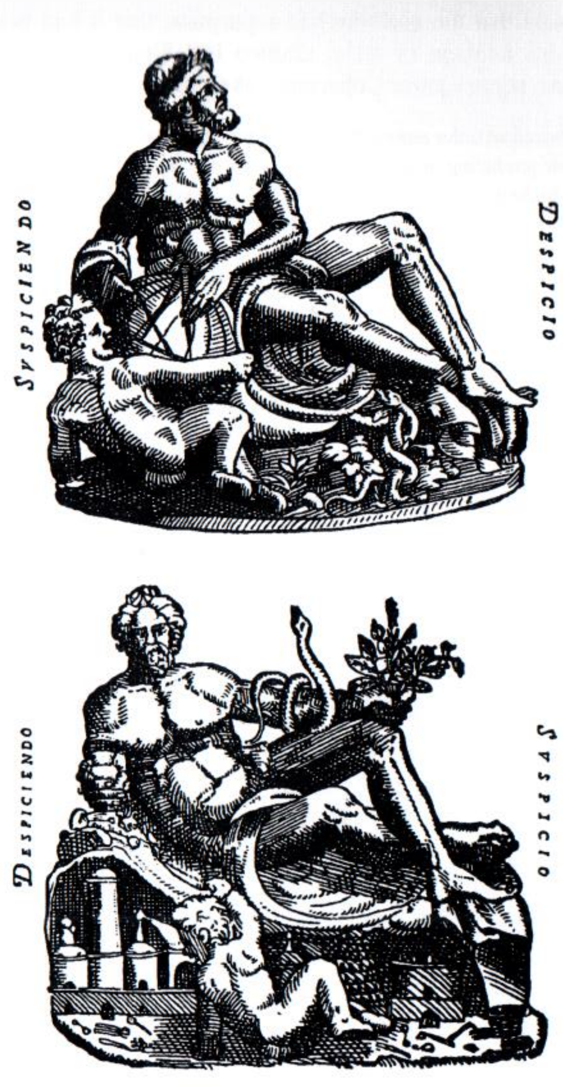


Fig. 1.12 At the two entrances of Uraniborg, Tycho Brahe placed relief sculptures which allegorically represented astronomy and chemistry. The two inscriptions related to the close connections between the two sciences ('By looking up, I see down', and 'By looking down, I see up'). From *Astronomiae instauratae mechanica* (1598).

elements).[86] The heavens were composed of ether, which appeared in a more dense form in the Milky Way and even more densely in the stars. In this way he suggested that the new star of 1572 could be explained as a temporary concentration of ether. Tycho's sketch of a physical cosmology was developed further by his pupil Cort Aslaksen, to whom the celestial ether was material in nature, nothing but air in a highly rarefied state. A representative of what was called Mosaic physics, he pictured the universe as consisting of three heavens, the atmosphere, the space containing the heavenly bodies, and God's eternal heaven. Contrary to Tycho, Aslaksen accepted that the Earth could perform a daily rotation.[87]

In the period from around 1620 to 1660, Tycho's hybrid cosmology received much attention and was to some extent also accepted, especially among Jesuits and other Catholic scholars, who, for theological reasons, could not openly endorse the Copernican theory. For example, the eminent French natural philosopher Pierre Gassendi was a Copernican at heart, but he was also a Catholic priest and, publicly, he defended Tycho's system (and he wrote a biography of Tycho Brahe, the first full biography of a scientist ever). Whereas Gassendi used the Tychonian system to further the cause of Copernicanism, the Jesuit astronomer Giovanni Riccioli believed that Tycho's world model was superior to that of Copernicus (Fig. 1.13). Riccioli's favoured model differed in its details from Tycho's by having Jupiter and Saturn (together with the Sun) circling the Earth, the other three planets revolving around the Sun. During a large part of the seventeenth century, such 'semi-Tychonic' systems were popular and widely discussed.[88] In his important book of 1651, *Almagestum novum*, Riccioli dealt in penetrating detail with the question of the mobility of the Earth. Following the scholastic tradition, he presented arguments for and against, but of course concluded that the Earth was immobile. Characteristically, in this conclusion theological arguments counted as heavily as did arguments based on scientific evidence.

For more than half a century, the Catholic church had no problems with the Copernican system, but in 1616 it was formally banned and after the infamous process against Galileo in 1633 it was impossible for scientists in Catholic Europe to support it. Copernicanism was controversial in the Protestant world as well, if not to the same extent or with the same consequences. Martin Luther allegedly branded Copernicus as a fool who would turn the entire science of astronomy upside down, but the historical basis for this often-quoted judgement is next to worthless. Although Luther was not a pro-Copernican, neither was he an anti-Copernican. For all we know, he may have been indifferent to or perhaps even ignorant about the revolution in astronomy (Luther died in 1546, three years after the publication of *De revolutionibus*).[89]

1.4.3 *Towards infinity*

Copernicus' universe was spherical and no less finite than Ptolemy's and Tycho's. Yet it was immensely larger, and for this reason alone invited a renewal of speculations concerning cosmic infinitude. The possibility of an infinite and infinitely populated universe, as discussed by a few early Copernicans, should be distinguished from the discussion of an infinite void space beyond the cosmos. This latter debate had roots in medieval philosophy and theology, and it continued to be an issue in the sixteenth and seventeenth centuries, largely unaffected by Copernicus' new astronomy. The imaginary, infinite void space was usually conceived to be divine and dimensionless, and hence physically unreal. However, to Otto von Guericke, the famous Magdeburg mayor and pioneer of vacuum technology, the infinite space beyond the material cosmos was real and three-dimensional. In his celebrated treatise of 1672 on the Magdeburg experiments, *Experimenta nova*, he described the infinite nothingness as an active and powerful entity, as what has been called an 'ode to nothing'.[90]

Fig. 1.13 The Italian Jesuit astronomer Giovanni Riccioli published in 1651 a great work with the ambitious title *Almagestum novum*. As is apparent from its frontispiece, he found that a Tychonian system (not quite the same as Tycho Brahe's) should be rated higher than the heliocentric system of Copernicus. The Ptolemaic system is placed on the ground, indicating that it is not considered a worthy competitor. 'I am raised that I may be corrected', Ptolemy utters.

The discussion in the seventeenth century of an infinite universe was indebted to the revival of the ancient atomic theory of matter by natural philosophers such as Francis Bacon in England and Pierre Gassendi in France. The renewed interest in the atomism of Democritus and his followers was primarily of relevance to chemistry, but also included cosmological aspects. In a book of 1675, the Englishman Edward Sherburne summarized what he took to be the essence of atomistic cosmology (see Fig. 1.4): 'The Ancient Philosophers, especially those of *Democritus* and his School, and most of the Mathematicians of those Times, asserted the *Universe* to be *Infinite*, and to be divided into two chief Portions; whereof the One they held to be the World, or rather Worlds, finite as to Bulk and Dimension, but infinite as to Number. The other Part or Portion, they extended beyond the Worlds, which they fancied to be a *Congeries* of infinite Atoms. Out of which not only the Worlds already made received their Sustenance, but new Ones also were produced.'[91]

Apart from the extra-cosmic, more or less theological void, was the world also infinite with respect to celestial bodies? Thomas Digges, an English mathematician and contemporary of Tycho, was among those who observed the new star of 1572. An early adherent of Copernicanism, he tried to prove the new theory by measuring the annual parallax of the fixed stars, but of course he failed. In 1576 Digges added to a book on meteorology written by his father a chapter on cosmology, which included a free translation of the cosmological part (Book I) of Copernicus' *De revolutionibus*. The novelty of 'A Perfit Description of the Coelestiall Orbes' was that Digges did not collect the stars in a sphere, as Copernicus had done, but distributed them throughout an infinite universe (Fig. 1.14) Still, he wrote of the stars as being located in a fixed sphere or orb, albeit one 'reachinge vp in *Sphaericall altitudes* without ende'. Moreover, his infinite starry heaven was 'the gloriouse court of ye great god' and 'the habitable of the elect, and of the coelestiall angelles'. Digges's universe was infinite in this theological sense, but it is more uncertain whether it was also the first infinite Copernican universe in a physical and astronomical sense.[92] Shakespeare may have been acquainted with Digges's works and it has been argued that his world picture enters allegorically in several of the Bard's plays.[93]

The Italian maverick philosopher Giordano Bruno (or Filippo Bruno of Nola, as his name of birth was) was burned at the stake on 17 February 1600 because of his heretical religious views. He was a martyr of intellectual freedom, but not of science—if for no other reason because he was not a scientist. At any rate, his unorthodox and partial support of Copernicanism had little to do with his trial and cruel death.[94] Talented, undisciplined, and influenced in particular by Cusanus and related mystical thought, Bruno dealt with cosmological topics in *The Ash Wednesday Supper* of 1584, in *On the Infinite Universe and Worlds*, also of 1584, and in the Latin poem *De immenso* of 1591.

It is a matter of some dispute whether Bruno was truly a Copernican. Certainly, his understanding of the Copernican system was poor and at least on one occasion he seriously misunderstood it.[95] He had neither an interest in nor suffient knowledge of mathematics to appreciate *De revolutionibus* and frankly stated that 'I care little for Copernicus.' The planetary system that he proposed in *De immenso* had little to do with Copernicus', as he put Venus and Mercury on the same epicycle, which, opposite to it, also carried the epicycle carrying the Earth and the Moon. The proposal lacked any observational evidence, a fact that did not bother Bruno the least. He had only disdain for the astronomers' concern with the number and order of the planets, questions which he

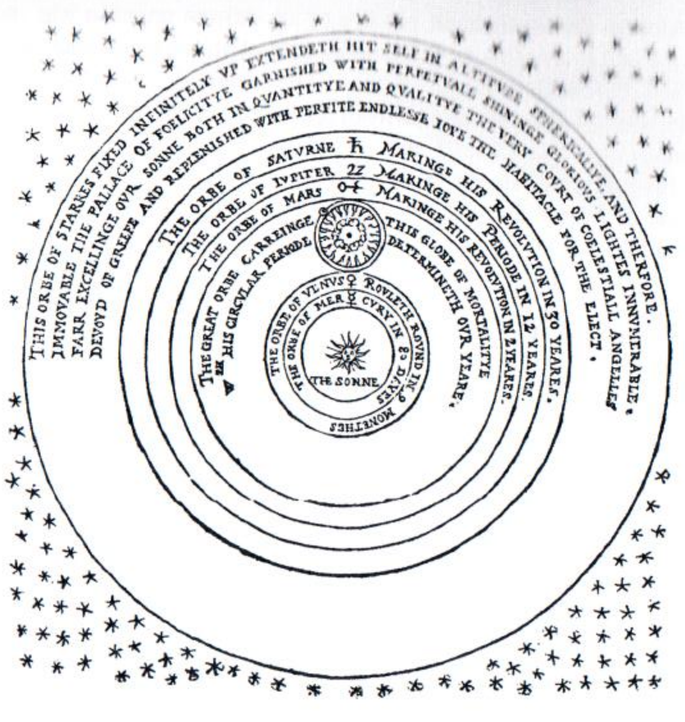


Fig. 1.14 Thomas Digges's Copernican system of 1576.

considered to be unimportant. They were even meaningless, for Bruno was convinced that comets were planets, which implied that the number of planets encircling the Sun could not be known. Given that Bruno's main affinity with Copernicanism was his conviction that the Earth and planets revolved around the Sun, it is doubtful whether he can reasonably be called a Copernican.

At any rate, Bruno saw himself as a reformer of the Copernican system, which in his version was given a different and more grandiose perspective. For one thing, he denied that the orbits of the planets were necessarily circular or reducible to circular motions. For another, he rejected the Aristotelian notion of a fifth element peculiar to the heavens and declared that the celestial bodies were made of the very same elements as those constituting terrestrial matter. As to Copernicus' preservation of the sphere of the fixed stars, he dismissed it as a 'fantasy'. Even more importantly, he emphasized again and again that the universe—the real, physical universe—was infinite in size and in a continual state of change. The Earth was not at the centre of the world; and neither was the Sun, for there was no centre of the universe, only an infinity of local centres. In *On the Infinite Universe and Worlds*, he wrote: 'There are then innumerable suns, and an infinite number of earths revolve around those suns, just as the seven we can observe revolve around the Sun which is close to us.'[96] Each of the infinite number of earths was inhabited. Without going into details, Bruno's

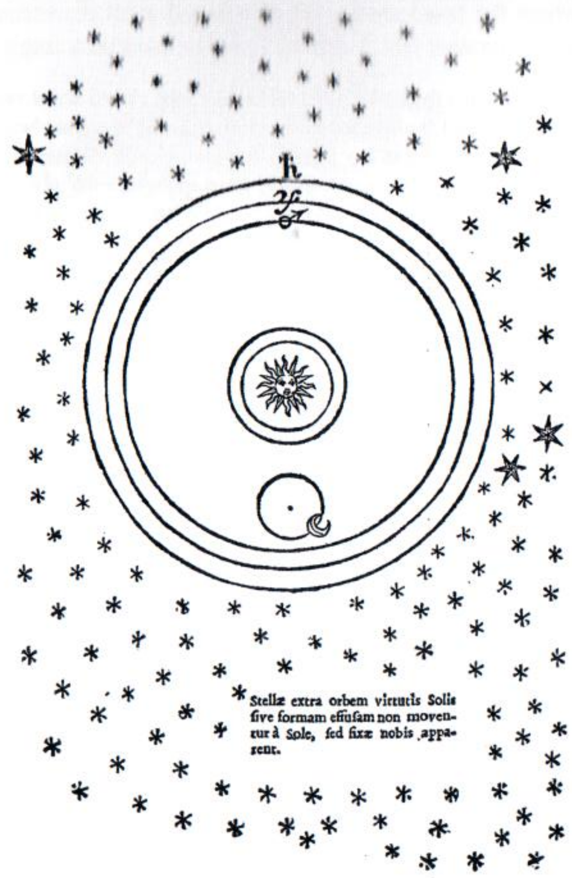


Fig. 1.15 William Gilbert's representation of the universe in his *De mundo sublunari*, published posthumously in 1651.

cosmic vision included many bold proposals of a kind Copernicus would not have admitted. There is no doubt that he went much beyond Copernicus, but then he—contrary to Copernicus and Tycho—could afford the luxury of ignoring observations. The speculative and non-astronomical features in Bruno's poetic vision are further illustrated by his suggestion that there might be other earths revolving around our Sun.

In the years around 1600, elements of Copernicanism appeared in many places outside astronomy. One example was provided by William Gilbert, the English physician who is best known for his pioneering work on lodestones and magnetism, *De magnete* of 1600. Influenced by Bruno and being a Copernican of a sort, Gilbert accepted the diurnal rotation of the Earth, whereas he ignored the more important annual revolution. However, there are reasons to believe that he accepted the system of Copernicus ('a man most deserving of literary honour') at the time he wrote his book on magnetism. He seems to have believed in an infinite world where the fixed stars were distributed at all distances from the Earth. Rhetorically, he asked if the stars had ever been found to reside in a single sphere:

> No man hath shown this ever; nor is there any doubt that even as the planets are at various distances from Earth, so, too, are those mighty and multitudinous luminaries ranged at varous heights and at distances most remote from earth: they are not set in any sphæric framework or firmament (as is supposed), nor in any vaulted structure. . . . What then, is the inconceivably great space between us and these remotest fixed stars? and what is the vast immeasurable amplitude and height of the imaginary sphere in which they are supposed to be set? How far away from Earth are those remotest of the stars: they are beyond the reach of eye, or man's devices, or man's thought.[97]

Indeed, the new philosophy called all into doubt. One understands John Donne's worries. Gilbert operated with two cosmic forces, electricity and magnetism, and he suggested that the former was responsible for the aggregation of matter, and hence somehow related to gravitation. His account of gravity was by no means clear, but it did imply that gravity was not a property restricted to the Earth; the other celestial bodies had their gravities, too, a view that contradicted the Aristotelian distinction between the sublunary and superlunary regions of the world.

Renaissance cosmology was a far broader subject than the kind of mathematical astronomy practised by Copernicus and the professional astronomers. Astrology was an integrated and most important part of the period's cosmology, although Copernicus was exceptional in his lack of interest in astral influences. So-called Paracelsianism, named after the Swiss physician Paracelsus (Philippus Aureolus Theophrastus Bombastus von Hohenheim), was an important intellectual force in the second half of the sixteenth century and a source of inspiration for Tycho Brahe, among others. The Paracelsians were primarily interested in chemistry and alchemy, which they used in understanding the cosmos. For example, they explained in detail the creation of the world, as recounted in Genesis, in terms of chemical transformations. Their universe was a living entity where all parts interacted through 'sympathies' and 'antipathies', and it was represented in the microcosmos by means of so-called correspondences. Paracelsus and his allies considered the universe as a vast chemical laboratory, but their interests were largely limited to the Earth and did not include mathematical models of the universe. While it makes sense to speak of Paracelsian cosmology, it was a cosmology of a very different kind from the one cultivated by the astronomers.

Although chemical philosophers of a Paracelsian inclination were strongly anti-Aristotelian, they did not support the Copernican system. One of them, the English physician and mystic Robert Fludd, recognized the primacy of the Sun but nonetheless rejected the views of Copernicus and Gilbert. Fludd's arguments were mainly traditional, including references to the Bible and the lack of an annual parallax. He was convinced that the Earth was the most massive body in the universe and therefore immobile. 'Certainly the reasons of Gilbert are ridiculous,' he wrote in 1617, 'it is impossible to believe that the heavens can be carried around in the space of twenty-four hours because of their boundless magnitude.'[98]

1.4.4 *Galileo and Kepler*

The Copernican revolution was largely completed during the first half of the seventeenth century, not least through the path-breaking works of Galileo Galilei and Johannes Kepler. As a young man, Galileo was in favour of traditional cosmology, but he soon came out in support

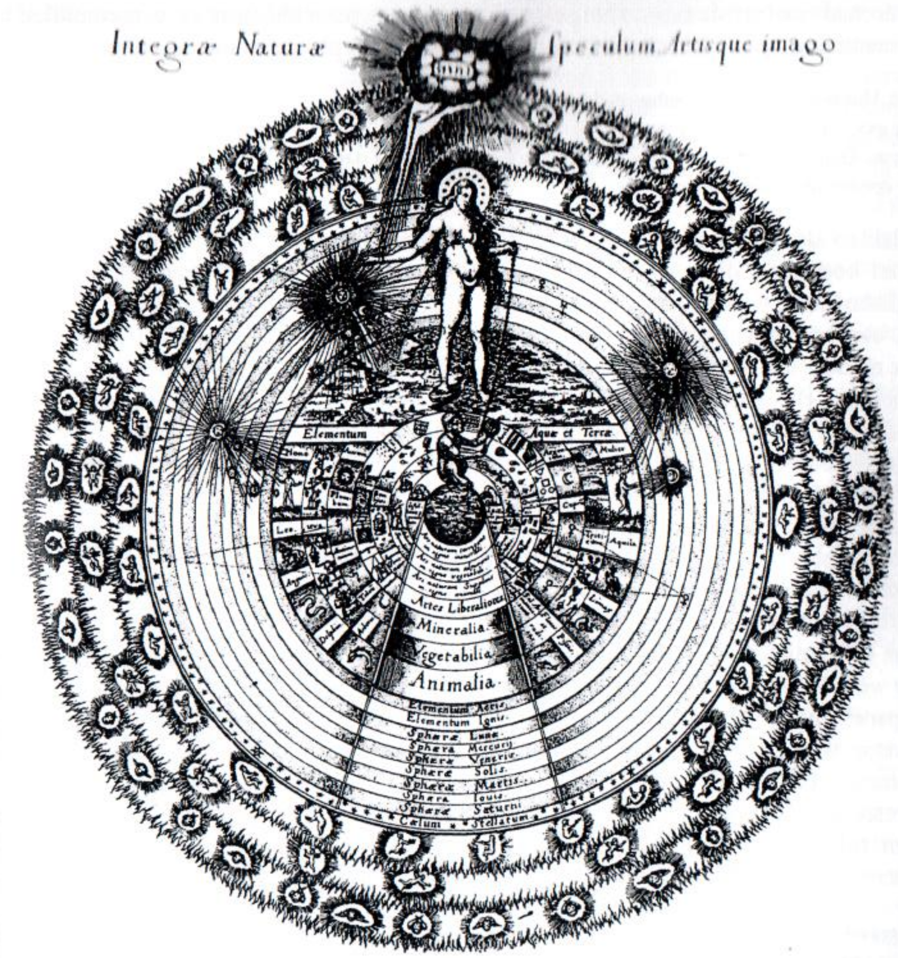


Fig. 1.16 The Paracelsian universe as magnificently depicted in Robert Fludd's *Utriusque cosmi* of 1617. The sublunary world of the four elements, governed by the alchemical goddess, is separated from the lower heavenly regions. Beyond the sphere of the fixed stars is the upper celestial world. The ape sitting on the central Earth symbolizes humans' poor reflection of divinity.

of the Copernican world picture, which he tirelessly defended throughout his life. His approach to celestial problems was decidedly physical and in this respect very different from the astronomical approach of Copernicus, Tycho, and Kepler and also different from the philosophical approach of Bruno. This may explain his limited interest in cosmology, a field he seems to have regarded with a mixture of scepticism and indifference. All the same, the sensational discoveries he made with the new optical tube in 1610 and reported in *Sidereus nuncius* did much to change the picture of the universe. When he turned his primitive telescope toward the Milky Way he instantly solved a riddle that had occupied astronomers and natural philosophers for two thousand years. The Milky May, he now realized, was 'nothing but a congeries of innumerable stars grouped together in clusters'. Galileo's discoveries caused great excitement, and the news was rapidly disseminated throughout learned Europe.

Intellectuals and artists excelled in praising the Italian master philosopher, as exemplified by a contemporary poem by Johann Faber, a German–Italian physician and botanist:

> Yield, Vespucci, and let Columbus yield. Each of these
> Attempts, it is true, a journey through the unknown sea. . . .
> But you, Galileo, alone gave to the human race the sequence of stars,
> New constellations of heaven.[99]

Galileo also discovered the spots on the Sun, traditionally believed to be a perfect and sacred body, and deduced that the Sun rotated with a period of about 28 days. (The Englishman Thomas Harriot had studied the Sun with a telescope and observed sunspots a little earlier, but without publishing his observations, and Chinese naked-eye observations were made much earlier.) Wherever Galileo directed his telescope, he found crowds of stars invisible to the naked eye, and he discovered that while his instrument could magnify the planets and make them look like discs, it could not do the same with the fixed stars. The stars consequently must be at enormous distances from the Earth, just as Copernicus had claimed. Another strong argument for Copernicanism, and against the Ptolemaic system, came from Galileo's discovery that Venus exhibited phases. The only way to explain the observed phases of Venus was to assume that the planet moved in an orbit round the Sun; the observed change in phases did not fit with the Ptolemaic system.

With regard to the number of stars and their spatial distribution, Galileo was not very clear. He denied that the stars were placed in the same sphere, but without asserting that they were found at all distances with no limit. In the famous *Dialogo*, he denied the infinity of space, and in other of his writings he indicated that it would never be known whether the universe was finite or infinite. During the last years of his life, Galileo, who since the infamous trial of 1633 had lived in forced isolation in his house in Arcetri outside Florence, corresponded with Fortunio Liceti, a professor of philosophy of Aristotelian inclination. From this correspondence, we learn about Galileo's agnostic attitude to cosmology. Concerning the question of the finitude or infinitude of the universe, he wrote:

> The reasons on both sides are very clever, but to my mind neither one is necessarily conclusive, so that it always remains ambiguous which assertion is true. Yet one argument alone of mine inclines me more to the infinite [universe] than the finite, this being that I cannot imagine it either as bounded *or* as unbounded and infinite; and since the infinite, by its very nature, cannot be comprehended by our finite intellect, which is not the case for the finite, circumscribed by bounds, I should refer my incomprehension to the incomprehensible infinite [rather] than to the finite, in which there is no necessary reason of incomprehensibility.[100]

In another letter to Liceti, of 1641, he described the question of the centre of the universe as 'among the least worthy of consideration in all astronomy' and went on to state that any search for a centre of space, or for the shape of space, was 'a superfluous and idle task'.[101]

If Galileo expressed reservations with respect to the grand questions of cosmology, his contemporary Kepler did not. On the contrary, the German mathematician was fascinated by such questions and wrote exuberantly about them.[102] His main concern was with the spatial dimensions of the universe but he also had an interest in the temporal dimension. On the basis of Biblical and astronomical evidence, he concluded that God had created the universe in 3992 BC and that Jesus Christ was born in 4 BC.

In his *De stella nova* of 1606, a work discussing a new star that had appeared in the skies two years earlier, Kepler took up the question of the extension of the sphere of the fixed stars. He was aware that Bruno and Gilbert had defended the infinity of the universe, a notion that filled him with a 'secret, hidden horror' and which he was eager to refute. He likewise denied Bruno's version of the cosmological principle, the claim that the world looks the same to every cosmic observer, whatever star is chosen as the vantage point. His arguments in favour of a finite world in which the solar system occupies a privileged position were in part metaphysical, in part based on observations that he thought spoke against a world filled with an infinite number of stars. The Milky Way and the fixed stars limit our space, but is it not possible that beyond the limit there is an infinite space, either a void or a space thinly populated with stars? Kepler discussed the question systematically and his answer was a firm no.

Kepler's early rejection of infinity relied on philosophical reasoning and naked-eye astronomy. The picture of the starry heaven changed with Galileo's telescopic discoveries, yet the change only confirmed Kepler in his conviction of a finite world. This he made clear in *Dissertatio cum nuncio sidereo* of 1610, a hastily composed comment on and summary account of Galileo's *Sidereus nuncius*. In the course of his argument against infinitism, he examined Bruno's idea of an infinite number of worlds, each of them differing from ours. He claimed that in these other worlds the five regular polyhedra—the geometrical basis of his world model described in *Mysterium cosmographicum* of 1596—would not exist in the same form as we know them. To Kepler, this was reason enough to conclude that 'this world of ours is the most excellént of them all, if there should be a plurality of worlds'.[103]

Kepler returned to the question in later works, in particular in the *Epitome astronomiae Copernicanae* published in three instalments between 1618 and 1621. As Galileo had shown, there are numerous stars that cannot be seen with the naked eye. This might be because they were too far away from the Earth, or because they were too small to be seen. Kepler unhesitatingly endorsed the second option, concluding that 'the visible sky is . . . everywhere raised above us by nearly the same distance. There is therefore an immense cavity in the midst of the region of the fixed stars, a visible conglomeration of fixed stars around it, in which enclosure we are.' He believed that an infinite number of stars could be ruled out logically, as the very notion was contradictory—'all number of things is actually finite for the very reason that it is a number'.[104] As to the possibility of a finite world immersed in an infinite space, he rejected it on conceptual grounds, using the Aristotelian argument that there cannot be space without bodies located in it.

In *Epitome*, Kepler not only reconfirmed the finitude of the universe, he also calculated its size.[105] The radius of the sphere of the fixed stars he took to be 60 million Earth radii or 4 million solar radii. From this it follows that the volume of space up to the stars was 64×10^{18} as great as the volume of the Sun. Kepler argued that the volume of the entire stellar sphere was merely 8×10^9 times the volume of the Sun, thus ending up with a cosmos in which the stellar region was of negligible size. The sphere of the fixed stars was curiously thin: its thickness was 6000 times smaller than the radius of the Sun, not more than nine English miles! This implied that the stars were incredibly small bodies, an assertion Kepler thought was supported by telescopic observations (which revealed stars as points, not as round discs). He found this surprising picture of the stellar world to be satisfactory for at least two reasons. For one thing, it refuted Tycho's main objection to the Copernican system; for another, it showed how radically different the Sun was from the fixed stars and how much more impressive the central body was. Kepler was no less a sun-worshipper than Copernicus. 'Of all the bodies in the universe the most excellent is the Sun, whose whole essence is nothing else than the purest light', he wrote. He continued:

It is a fountain of light, rich in fruitful heat, most fair, limpid, and pure to the sight, the source of vision,. . . called king of the planets for his motion, heart of the world for his power, its eye for his beauty, and which alone we should judge worthy of the Most High God, should he be pleased with a material domicile and choose a place in which to dwell with the blessed angels.[106]

Kepler's universe was indeed heliocentric.

Notes

1. One indication of the strong interest in archaeoastronomy as a research field is the foundation in 1977 of the journal *Archaeoastronomy Bulletin* and in 1979 of *Archaeoastronomy*, published as a supplement to *Journal for the History of Astronomy*. Among the many scholarly works on Stonehenge as an astronomical observatory, North 1996 deserves to be singled out as a most detailed and erudite book on the subject.
2. See Plumley 1975, which I largely follow. See also Frankfort 1959, pp. 51–70.
3. Cited in Plumley 1975, p. 34.
4. Cited here from Jacobsen 1957, pp. 18–19. Other accounts of Mesopotamian cosmology are given in Lambert 1975 and Rochberg-Halton 1993.
5. English translation in Schiaparelli 1905.
6. Gombrich 1975 provides a summary account of ancient Indian cosmologies.
7. Gombrich 1975, p. 115.
8. Needham and Ronan 1993, p. 66.
9. For details and historical evidence, see May 1994. May's assertion that creation out of nothing is not to be found in the Bible has not remained uncontested. Copan and Craig 2004 argue forcefully that the idea is indeed in the Old Testament, if not explicitly stated.
10. Quotations from McKirahan 1994, pp. 11 and 9. Online version: http://sunsite.berkeley.edu/OMACL/Hesiod/theogony.html.
11. Quoted in Whitrow 1998, p. 47. On the idea of the cyclical universe in a cultural and historical perspective, see, e.g., Eliade 1974 and Jaki 1974.
12. Quoted in McKirahan 1994, p. 23. The following quotations are from the same source.
13. A detailed analysis of Empedocles' cyclical cosmos can be found in O'Brien 1969.
14. On Pythagoras and the Pythagorean school, see Riedweg 2002.
15. McKirahan 1994, p. 104.
16. Ibid., p. 326. Much later, this cosmic scenario was taken up by cosmologists of a speculative orientation, including Kant, whose cosmological vision was much indebted to the atomists (see Section 2.2).
17. *De rerum natura* exists in many translations. The quotations are from Lucretius 1997, a reprint of a translation from 1904, pp. 45–46, 93, 96, and 205. An online version can be found on http://classics.mit.edu/Carus/nature_things.html.
18. Quoted in Sambursky 1963, p. 202. See also Jaki 1974, p. 114.
19. Aiton 1981, p. 79.
20. For Plato's possible influence on Eudoxus' world model, see Knorr 1990.
21. Eudoxus' system was reconstructed by Schiaparelli in 1874. However, it is possible that Schiaparelli's clever reconstruction was also to some extent a modernization and that it included features that did not appear in the authentic version.
22. Farrington 1953, p. 279.
23. Quoted in Heath 1959, p. 275.
24. Quoted in Wright 1995, p. 151.
25. For details on Plato's cosmology, see Cornford 1956.
26. *De caelo*, as quoted in Munitz 1957, p. 95.
27. Sambursky 1963, p. 203.
28. Quoted in Freudenthal 1991, p. 50.
29. See Webb 1999 for an overview.
30. Van Helden 1985 provides an excellent survey of distance determinations from ancient Greece to the late seventeenth century.
31. Aristarchus' work is translated in Heath 1959 (first edn 1913).
32. Heath 1959, p. 353.
33. Van Helden 1985, p. 6.
34. See Gingerich 1985.
35. *The Sandreckoner* is translated in Heath 1953 (first edn 1912). Quotations from pp. 221–221 and p. 232.
36. The similarity between Archimedes' and Eddington's numbers is discussed in Brown 1940, who argues that the number of particles in Archimedes' model universe may be interpreted to be of the same order of magnitude as Eddington's cosmical number.
37. Pliny 1958. Quotations from book II, pp. 171–173 and 177–179. A 'book' denoted a part or large chapter of a work, not a separate text.
38. Ptolemy 1984, pp. 45–46.
39. Ibid., p. 37.
40. Ibid., p. 38.
41. See Goldstein 1967. Accounts of Ptolemy's cosmology can be found in, e.g., Evans 1993 and Aaboe 2001, pp. 114–134.
42. Goldstein 1967, p. 8. Other quotations are from the same source.
43. Quoted in Cohen and Drabkin 1958, p. 118.
44. See Haber 1959 and Dean 1981.
45. The complex story is told in May 1994. But see also Copan and Craig 2004 for a different view.
46. Lindberg 2002, p. 48.
47. Lactantius 1964, III.24
48. Dreyer 1953, pp. 207–219.
49. Cosmas' cosmography was translated into English in 1897. Quotations from Cosmas 1897, pp. 11 and 129.
50. Galileo's *Letter* is reproduced in Drake 1957 (online version at www.fordham.edu/halsall/mod/galileo-tuscany.html). Quotation from p. 184.
51. Hoskin 1999, p. 72. The two historians are Michael Hoskin and Owen Gingerich.
52. Sambursky 1973, p. 135. See also Sambursky 1987, pp. 154–163.
53. Brehaut 1912, III, 32.1, 40.1, and 52.1.
54. Crombie 1953, p. 107. Grosseteste's light (*lux*) should not be understood as ordinary, visible light, but rather as the principle of light, of which ordinary light is only one manifestation.
55. Cosmology during the late Middle Ages is described in detail in Grant 1994.
56. Quoted in Crowe 1990, p. 74.
57. Lindberg 1992, p. 262.
58. Crowe 1990, p. 74.
59. See North 1975, p. 6.
60. On Chaucer's cosmology, see North 1990.
61. Orr 1956, p. 297, which offers a detailed account of Dante's universe.
62. A selection of the condemned articles is presented in Grant 1974, pp. 47–50.
63. From Thomas's *Writings on the Sentences of Peter Lombard*, as quoted in Carroll 1998, p. 88.
64. See the careful account in Dick 1982.
65. Grant 1974, pp. 548–550.
66. Grant 1994, p. 170.
67. Grant 1974, p. 560.
68. Ibid., p. 501.
69. Grant 1994, p. 478.
70. Grant 1974, p. 509.
71. Cusanus 1997, pp. 158–161. Jasper Hopkins' English translation of *De docta ignorantia* can be found online at www.cla.umn.edu/jhopkins/DI-Intro12–2000.pdf.
72. Quoted in Koyré 1968, p. 29. On the Copernican revolution, see also Kuhn 1957.
73. Lovejoy 1964, p. 102, who quotes John Wilkins, *Discourse Concerning a New Planet* (London, 1640). Wilkins, an English natural philosopher who played a leading role in the founding of the Royal Society, was in favour of Copernicanism.
74. *Commentariolus* was only rediscovered and published in the late nineteenth century. I use the English translation in Rosen 1959, which also includes a translation of Rheticus' *Narratio prima*. Rheticus' work can be seen at www.lindahall.org/services/digital/ebooks/rheticus.

75. Copernicus 1995, p. 7. To illustrate the foolishness of his potential enemies, he referred to Lactantius, who, as we have seen, used arguments from the Bible to deny the spherical shape of the Earth.
76. Rosen 1959, p. 58.
77. Gingerich 1975.
78. Copernicus 1995, p. 24. On the basis of the very same metaphysical doctrine of nature's economy, the Copernican system would soon be criticized for its vast gaps in the form of superfluous and useless voids.
79. Rosen 1959, p. 147.
80. Copernicus 1995, p. 14. The sentence is to be understood figuratively, not as a claim that the universe is infinite.
81. On Tycho and his cosmology, see Schofield 1981 and Thoren 1990, pp. 236–264.
82. Gingerich and Westman 1988.
83. Galilei 1967, p. 367.
84. Van Helden 1985, p. 52. Letter of 18 April 1590.
85. Howell 1998, p. 526. Letter of 17 August 1588.
86. Tycho outlined his view of the relationship between the heavens and the Earth in the preface to a book published by one of his assistants in 1591. See Christianson 1968.
87. Blair 2000. A part of Aslaksen's work, *De natura caeli triplicis* from 1597, was translated into English as *The Description of Heaven* (London, 1623).
88. Variants of the Tychonic system are discussed in Schofield 1981.
89. Hooykaas 1972, pp. 121–122.
90. Grant 1969, especially pp. 55–57. Von Guericke's description of the extra-cosmic void has a curious similarity to the quantum vacuum of modern physics.
91. Quoted in Heninger 1977, p. 193.
92. Koyré 1968, pp. 35–39.
93. See Usher 1999, where it is suggested that the true theme of *Hamlet* is the controversy between the three rival world systems, Ptolemy's, Tycho's, and Digges's. Usher argues that Shakespeare was probably a Copernican.
94. Singer 1950; Koyré 1968, pp. 39–54. It is commonly recognized that Bruno's crimes were theological and political, rather than related to his espousal of the Copernican system. See, e.g., Lerner and Gosselin 1973.
95. McMullin 1987.
96. Singer 1950, p. 304, which includes a translation of *On the Infinite Universe and Worlds*. Available online at www.positiveatheism.org/hist/bruno00.htm.
97. Gilbert 1958, pp. 319–320. On Gilbert's magnetic cosmology, see Freudenthal 1983.
98. Quoted in Debus 1977, p. 244. Fludd became involved in a bitter dispute with Kepler concerning the correct application of mathematics to natural phenomena; see pp. 256–260.
99. Quoted in Cohen 1985, p. 74. Amerigo Vespucci was the Italian seafarer who sailed to the Americas about 1500 and after whom America is named.
100. Quoted in Drake 1981, pp. 405–406. See also Koyré 1968, pp. 95–99.
101. Drake 1981, p. 411.
102. Koyré 1968, pp. 58–87.
103. Rosen 1965, p. 44, which includes a complete translation of Kepler's *Dissertatio*.
104. Koyré 1968, pp. 81 and 86.
105. Van Helden 1985, pp. 87–90.
106. Quoted in Burtt 1972, p. 48.

2

THE NEWTONIAN ERA

2.1 Newton's infinite universe

During the seventeenth century, the road to Copernicanism often went through Cartesianism. The famous French philosopher, mathematician, and physicist René Descartes developed an ambitious theory based on matter and motion that purportedly explained all natural phenomena, including those in the heavens. The proud motto of later Cartesian natural philosophers was 'Give me matter and motion, and I will construct the universe.' Cartesian astronomy and cosmology became hugely popular, but at the end of the seventeenth century Descartes's theory was challenged by Isaac Newton's very different system of natural philosophy. Although Newton's physics celebrated its greatest triumphs in celestial mechanics, it was also applied to cosmology and provided, for the first time, the field with a measure of scientific authority based on the universal law of gravity. The Newtonian universe, as it appeared in the early years of the eighteenth century, consisted of a multitude of stars spread out over infinite space. While the law of gravitation governed Newton's cosmos, the true governor was God, who was never absent from the mind of Newton and his contemporaries.

2.1.1 Celestial vortices

Starting in 1629, Descartes was preparing a comprehensive work on his mechanical cosmology when he learned about the condemnation of Galileo's *Dialogo*. In a state of shock, he decided to withhold from publication *Le monde*, a cosmological work firmly founded upon Copernican principles. 'I wouldn't want to publish a discourse which had a single word that the Church disapproved of', he piously confided to Marin Mersenne, his learned friend who was not only a chief scientific intelligencer but also had sympathy for Copernicanism.[1] Nonetheless, Descartes did publish the main part of his cosmology (if only anonymously) in his famous *Discours de la méthode* of 1637 and also in *Principia philosophiae*, published in 1644. *Le monde, ou traité de la lumière* appeared posthumously in 1664. He claimed that the relativity of motion made the Copernican theory acceptable from a formal point of view, whereas as a physically true theory it had to be rejected.

Descartes's physics was nothing but geometry and motion, and so was his cosmology. In *Principia philosophiae* he ambitiously sought to understand nature in purely mechanical terms. He argued that space (or extension) and matter were identical, a doctrine that had important consequences. First, if space itself is meaningless without matter, there can be no genuine vacuum. The world is necessarily a plenum. Second, since space cannot vary in density, neither can matter. Yet we do not experience a completely uniform world, but a world with differences between one part and another. The differences, as they appear as