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THE MEDIEVAL COSMOS: ITS STRUCTURE AND OPERATION

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INTRODUCTION

Conceptions of the structure and operation of the physical cosmos during the Middle Ages, the period from about A.D. 500 to 1500, were dominated by the ideas of Plato and Aristotle. If we adopt the usual convention of an early and late Middle Ages, taking the late twelfth century as the approximate point of division, the former was dominated by Plato, the latter by Aristotle. Although Plato was dominant in the early period, Greek handbooks written in the Hellenistic period furnished additional cosmological material to a group of authors in late Antiquity and the early Middle Ages, whom modern scholars refer to collectively as the Latin Encyclopaedists. As the enthusiastic and sometimes credulous recipients of cosmological learning, Pliny and the later Latin encyclopaedists Macrobius, Chalcidius, Boethius, Martianus Capella, Cassiodorus, and Isidore of Seville, to name the most significant, were destined to serve first as staple fare during the early Middle Ages, and then as time-honoured authorities, though subordinate to Aristotle, in the late Middle Ages.

In the absence of the works of Aristotle and Ptolemy during the period 500 to 1100, the most significant influence in early medieval cosmology was Plato's *Timaeus*, in the incomplete Latin translation made by Chalcidius in the fourth century A.D. Plato's impact was even greater because of the indirect influence he had through Neoplatonism, as, for example, in the works of Macrobius.

As a whole, the cosmological fare of the early Middle Ages was meagre and unreliable. Despite these formidable obstacles, scholars in the twelfth-century, such as Bernard Silvester, Thierry of Chartres and William of Conches, began to study nature for its own sake. They interpreted natural phenomena, including cosmological ideas, with a surprisingly critical spirit. But they did so within the framework of the old cosmology. Their heroic efforts were doomed. Even as they worked, a new age of learning was dawning that would soon displace the incipient rational science that had been evolving within the context of the old learning.

Beginning in the second quarter of the twelfth century and continuing for more than a century, a vast treasure of Greek and Arabic science and philosophy was translated from Greek and Arabic into Latin. As more and more of it became available, medieval scholars came into possession of a complex cosmology and world view. The core of this new cosmology was formed by Aristotle's physical and

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metaphysical works, especially his *On the heavens* (*De caelo*), *Physics*, *Meteorology*, *On generation and corruption*, and *Metaphysics*. To Aristotle's works must be added those by Ptolemy (especially his *Almagest* and *Tetrabiblos*) and those by numerous Arab authors and commentators, notably Averroes (Ibn Rushd, 1126–98), Avicenna (Ibn Sina, 980–1037), Alhazen (Ibn al-Haytham, 965–*c*. 1039), al-Farabi (*c*. 870–950), Thabit ibn Qurrah (836–901), and the Jewish author, Maimonides (1135–1204). The source material for the new cosmology of the late Middle Ages was essentially a combination of Greco-Arabic works in Latin translation plus the traditional Latin literature of the early Middle Ages (which included commentaries on the six days of creation, known as hexaemeral treatises).

Basing themselves on the scientific works they inherited, medieval natural philosophers set about creating their own body of cosmological literature. The most important part of it derived from discussions on Aristotle's physical treatises, which took the form of commentaries on the texts, or sequences of questions that were drawn from those texts and answered in a highly stylized manner. From the thirteenth to the seventeenth century — some 350 to 400 years — the most significant discussions of medieval cosmology appear in the questions (*questiones*) posed in explication of Aristotle's physical treatises — especially *On the heavens*, *Physics*, *Meteorology*, and *Metaphysics*. In the fourteenth century, for example, John Buridan raised 59 questions in his explication of the four books of Aristotle's *On the heavens*, including the following:

> Whether the sky is heavy or light.
> Whether an infinite body is possible.
> If there were several worlds, whether the earth of one would be moved naturally to the middle of another.
> Whether it is possible that there are several worlds.
> Whether or not the sky [or heaven] is moved with any fatigue.
> Whether beyond the heavens that are moved, there should be assumed a heaven that is resting or unmoved.
> Whether the whole earth is movable.
> Whether the sky is always moved regularly.
> Whether all celestial spheres and all stars are mutually of the same ultimate species.
> Whether the stars are self-moved or moved by the motion of their spheres.
> Whether the earth is spherical.

Commentaries and questions were also written on other treatises relevant to cosmology, especially the *Treatise on the sphere* by John of Sacrobosco (died 1244 or 1256). Cosmological discussions were also included in medieval encyclopaedias, especially those by Vincent of Beauvais (*c*. 1190–*c*. 1264) and Bartholomew the Englishman (*fl*. 1220–50).

Christian Commentaries on Genesis

In the first chapter of Genesis, Christians had the outline of a creation account to which they had to subscribe as a matter of faith. God created the world in six days. On the first day, He created heaven and earth in chaotic and as yet unrecognizable form. To distinguish day from night, God also created light. On the second day, God created the firmament, which He also called "heaven" (*caelum*), in order to separate the waters above the firmament from those below. The earth was prepared for subsequent human habitation on the third day when God gathered the waters below the firmament into seas, thus exposing dry land, on which plants and trees were brought forth to generate their own kind. The firmament, or heaven, of the second day was brought to completion on the fourth day with the creation of the celestial bodies that would provide light for both night and day, a function not provided by the light of the first day. On the fifth day, God brought forth sea creatures and birds of the air and, on the sixth, and final day, climaxed His works with the creation of man and woman who were to rule over all living things.

On this brief account, many Christians would exercise their exegetical skills, as numerous commentaries on Genesis bear witness. Did God create the world in six successive natural days, as the text explicitly declares, or were the six days intended to signify six periods of indeterminate length? Or, did God really create the world and all its creatures simultaneously, as indicated by Ecclesiasticus 18, 1 ("He that liveth forever created all things together")? During the Middle Ages, most scholars followed Saint Augustine and assumed that the world was created simultaneously, rather than in six natural days. Many assumed that God followed the order in Genesis, but so rapidly did He create that "before" and "after" were indistinguishable. Disagreements on meanings were easily multiplied. Each statement in the description of the first six days evoked a variety of interpretations. The relationships between God's activities on the different days was also problematic. In view of the great significance attached to the creation account, and the inviolate nature of scriptural truth, it seems surprising, at first glance, that so many conflicting opinions were tolerated. Why did the ecclesiastical authorities not insist on a uniform and strict literal interpretation? Because, as Saint Augustine wisely realized, it would be dangerous to the faith to uphold any particular literal interpretation so rigidly that the Church would be loath to abandon it even if subsequent scientific arguments clearly demonstrated its falsity. During the Middle Ages, and up to the time of Galileo in the seventeenth century, Augustine's admonition was taken seriously. Thomas Aquinas, for example, upheld Augustine's approach, so that, in his own commentary on the six days, he regularly included a variety of opinions to explain the different days, usually avoiding a firm commitment to any one of them. To be acceptable, an explanation had only to be compatible with Scripture. Although traditional commentaries on Genesis were still produced in the late Middle Ages, theological aspects of cosmology were usually incorporated into commentaries and questions on the *Sentences* (*Sententiae*) of Peter Lombard (died *c.* 1160), a theological treatise written around 1150, which served as the basic textbook in schools of theology for approximately five centuries. In the second of its four books, devoted respectively to God, creation, the incarnation, and the sacraments, Peter included a discussion of the six days of creation. As the standard text on which all theological students had to lecture and comment, there was ample opportunity for theologians to reflect on the origin and operation of the physical world.

Not only did theology affect medieval cosmology by reason of the creation account in Genesis, but, as guardians of orthodoxy, theologians made decisions that had an impact on cosmology. In 1277, the bishop of Paris, Etienne Tempier, condemned 219 articles that were not to be advocated in public or private under penalty of excommunication. A number of articles were relevant to cosmology. Twenty-three articles condemned the eternity of the world. Others involved celestial movers, such as intelligences and angels. A major objective of the condemnation was to undermine the certitude of Aristotelian natural philosophy where it clashed with traditional Christian interpretations concerning God's absolute power and freedom to do as He pleased. Thus the bishop of Paris condemned Aristotle's ideas that God could not make more than one world if He pleased, or that He could not move the world with a rectilinear motion because it would leave behind a vacuum, which was impossible in Aristotle's world. Thus did theology and dogma play a role in the formation of medieval cosmology.

Cosmology and Astronomy

In the ancient and medieval periods, cosmology was a subject studied primarily by natural philosophers, or theologians who were also natural philosophers, not technical astronomers. Few natural philosophers were knowledgeable about technical astronomy. Following a well-established Greek tradition, the roles of astronomer and physicist were sharply distinguished. The astronomer sought to 'save' the astronomical phenomena by appropriate, though not necessarily true, hypotheses from which one could readily predict planetary positions, as well as eclipses, conjunctions, and oppositions. By contrast, the task of the natural philosopher was to determine the essential nature and structure of the heavens: what they were made of; how they moved; how they were arranged and why; the influences they might exert on earth; and so on. Although Ptolemaic mathematical astronomy played a role, medieval cosmology was primarily the product of Aristotelian natural philosophy. Indeed, during the Middle Ages, natural philosophy, or physics, was deemed superior to traditional astronomy, since the former concerned itself with the real operations and structure of the world, while the latter need not, and often did not. Not until Copernicus insisted on the truth of his revolutionary astronomical hypotheses did physics become subordinate to the needs and requirements of astronomy.

The natural philosophers who produced medieval cosmology did not present it in the form of a grand, interrelated synthesis, akin to a Cartesian or Newtonian *Principia*. Medieval scholars utilized forms of scientific literature that did not lend themselves to syntheses. They organized knowledge primarily in the form of commentaries and questions on authoritative texts, especially the texts of Aristotle, or resorted to encyclopaedias. In general, medieval cosmology appears more like a collection of unrelated, or tenuously related, problems and topics, than an integrated whole. Nevertheless, there was general agreement on the broad overall structural framework of the world. What was lacking was widespread agreement on the details of cosmic operation.

THE MACROSTRUCTURE OF THE MEDIEVAL COSMOS

Most medieval natural philosophers would have agreed about the basic structure of the skeletal frame of the world. They assumed that the world was a unique, finite sphere filled everywhere with matter. From the circumference of the cosmic sphere to its geometric centre, the world was usually viewed as a vast hierarchy of decreasing sublimity and perfection. In the simile of the golden chain of Homer, as transmitted to the Middle Ages by Macrobius, "the close observer will find that from the Supreme God even to the bottommost dregs of the universe there is one tie, binding at every link and never broken".[1] The continuous descent of perfection, however, suffered a radical break at the point where the concave surface of the lunar sphere surrounded the convex surface of the sphere of fire. For it was at this juncture that Aristotle divided the world into two radically different parts, one celestial, the other terrestrial. The former was composed of an incorruptible, celestial ether that was shaped into a series of nested, celestial orbs within which the fixed stars and planets were carried around with uniform circular motion. The celestial region, where change was unknown, was incomparably more perfect than its terrestrial counterpart, where bodies composed of varying proportions of the four elements — fire, air, water, and earth — moved with naturally terminating rectilinear motions and suffered change incessantly. These broad and vital features of the macrostructure were accepted by virtually all natural philosophers. But there were numerous questions about the world and its operations that were inherently problematic. In these areas of cosmology and cosmogony, unanimity was far more difficult to arrive at and was not often achieved.

THE OPERATIONAL DETAILS OF THE MEDIEVAL COSMOS

Creation and Eternity

Among the problems, none was more difficult than that of creation. Was the world eternal, without beginning or end, as Aristotle and some Greeks claimed; or, did it have a beginning and would it have an end? During the early Middle Ages, support for a creation came from pagan sources, from Plato's *Timaeus* and Macrobius's *Commentary on the Dream of Scipio*. The doctrine of creation went largely unchallenged. With the introduction of Aristotle's works in the twelfth and thirteenth centuries, powerful arguments for the eternity of the world became available. Fearful that it might undermine belief in a supernatural creation from nothing, the bishop of Paris condemned the idea of an eternal world in 1270, and then more extensively in 1277. During the thirteenth century, and all through the Middle Ages, the faithful had to accept the creation of the world. Within this context, three opinions found varying degrees of support: (1) some insisted that the eternity of the world was rationally demonstrable; (2) others, like Saint Bonaventure, insisted, with equal fervour, that the creation of the world was capable of rational proof; and in the middle was (3) Thomas Aquinas, who argued that no rational proof was possible for either side, and further insisted that God could have willed the existence of the world without also causing it to have a temporal beginning. Thomas believed that God could, if He wished, produce a world that was both created and eternal. This opinion, which sought to reconcile the Aristotelian view that the world is eternal, without beginning or end, with the Christian belief that the world was created, and therefore had a beginning, was the most popular of the three.

On Other Possible Worlds and Extracosmic Space

If the creation account in Genesis strongly suggested a temporal beginning for the world, it also seemed to signify its uniqueness. Here, at least, it appeared that Aristotle and Christianity were in agreement: there is only one world. This apparent unanimity of opinion was, however, deceptive. Although Aristotle's conclusion might be applauded, his derivation of it was offensive because he had argued that the existence of another world was impossible. To argue that creation of other worlds was impossible, even for God, was viewed as a restriction on God's absolute power to do as He pleased. Such restrictions were generally condemned in 1277. Article 34, for example, declared it an excommunicable offence to hold "that the first cause [God] could not make several worlds". As a consequence, scholars in the fourteenth century were compelled to concede that God could create other worlds, although they were free to deny that He had actually done so.

The worlds that were envisaged were exact replications of our own. On the assumption that God could create other worlds identical to ours, scholars were encouraged to consider the physical consequences of simultaneously existing worlds. Some of the derived consequences were in conflict with basic Aristotelian principles. For example, although Aristotle had argued that vacua of any kind were impossible, the existence of void spaces between these hypothetical and discontinuous worlds seemed a plausible and even compelling inference. Nicole Oresme, for example, not only found this acceptable, but also concluded that if such worlds were like ours, they would obey the same physical laws. Each world would be spherical and have its own 'up' and 'down', 'centre' and 'circumference'. Since all such worlds are co-equal, it followed that no single centre or circumference is privileged, a conclusion that implied rejection of a unique centre and circumference on which Aristotle had founded much of his physics and cosmology.

Also challenged was Aristotle's fundamental idea that each of the four terrestrial elements — earth, water, air, and fire — had one absolutely determined natural place, a concept that was viable only if one world existed with a single centre and circumference. With a plurality of coexisting, identical worlds, the element air, for example, could have no single natural place, since it would have a natural place in each world. It would therefore have a multiplicity of natural places. What Aristotle had deemed impossible was thus shown to be possible and intelligible. Although no one during the Middle Ages actually accepted the existence of a plurality of worlds, the hypothetical investigation of the consequences of a plurality of worlds was subversive of Aristotelian natural philosophy, since it revealed that the possible existence of other worlds was compatible with ours because they would cause no effects within it.

But even if our world were unique, the possibility that something might lie beyond gained credibility, despite Aristotle's contention in *On the heavens* that neither body, place, void, nor time could exist beyond the spherical bounds of our world. In commenting on this passage, Simplicius, the sixth-century Greek commentator, transmitted the arguments of Archytas of Tarentum, Plato's contemporary in the fourth century B.C., and that of the later Stoics. If a hand is thrust beyond the outermost circumference of our world, it would eventually be plunged into an infinite three-dimensional void that everywhere surrounds our world. In the fourteenth century, Thomas Bradwardine, Nicole Oresme, and probably Jean de Ripa, argued that a real infinite void space existed beyond our world, which they identified with God's infinite immensity. Because God was not a corporeal entity, his immensity lacked corporeal dimensions and therefore so did the infinite space associated with that immensity. Thus where the Greek Stoics had assumed an infinite three-dimensional extracosmic void space, medieval scholastics assumed a non-dimensional infinite void space.

Infinite void space became the locale for some interesting thought experiments. John Buridan argued that a body lying beyond the world in such a void would be in a place equivalent to its own material dimensions. Nicole Oresme imagined the conditions under which an absolute motion might occur in an absolute space: if God moved the world with a rectilinear motion in that infinite void, a possibility that had to be conceded by article 49 of the Condemnation of 1277, the resultant motion would be absolute, since nothing existed outside our world to which its own motion could be related.

Scholastic ideas about God and space form an integral part of the history of spatial conceptions between the late sixteenth and the eighteenth century, the period of the Scientific Revolution. From the assumption that infinite space is God's immensity, medieval and early modern scholastics derived most of the same properties of space — except for tridimensionality — as would be conferred upon it by the likes of Henry More, Isaac Newton, Otto von Guericke, and Samuel Clarke.

The Order of the Planets

Although important, the region beyond the world was not a central concern of medieval cosmology. It was the organization and structure of the celestial region of the world that received the most attention. Within that part of the world, the planets, wandering against the background of the fixed stars, were of paramount importance. Medieval natural philosophers were agreed on the existence of seven planets and the fixed stars. During the late Middle Ages, the accepted order of the planets was that assigned by Ptolemy, rather than that proposed by Plato and Macrobius, which had been in vogue during the earlier Middle Ages. Since the planets moved against the background of the stars, the latter were assumed to be farthest from the earth and equidistant from it. In the absence of measurable parallax, the order of the celestial bodies was made on non-astronomical grounds. Descending from the outermost planet, Ptolemy ordered the superior planets by their sidereal periods, thus locating Saturn, Jupiter, and Mars in that order. Because the Sun, Mercury, and Venus seemed always to remain close together, their order was not readily determinable except by some arbitrary means. Ptolemy chose the order: Sun, Venus, and Mercury, followed by the Moon, the closest planet to the earth.

A sense of symmetry made this order appealing. In the fourteenth century, Albert of Saxony expressed a widely-held sentiment when he declared that "it seems more reasonable that three planets should be above the Sun and three below, with the Sun in the middle, as a king in his kingdom, to the end that it should influence and illuminate equally above and below".[2]

Many considered the Sun the most important planet, even though it was not the farthest from the ignoble earth. Not only was the Sun vital for life, by supplying the world with light and heat and causing the change of seasons by its annual motion through the ecliptic, but it was judged the most noble of all planets. Nicole Oresme characterized it as "the most noble body in the heavens", even "more perfect than Saturn or Jupiter or Mars, which are all higher up".[3] Centuries of praise and glorification of the Sun in its middle position among the planets and its equal rule above and below may have proved helpful in preparing the way for a new solar role in the Copernican heliocentric cosmology of the sixteenth century.

The Celestial Spheres

To the naked eye, the planets seem to be self-moved. Indeed, Plato assumed that it was the souls of celestial bodies that enabled them to be self-moved, like fish in water or birds in the air. Aristotle, however, denied self-movement and argued for the existence of transparent, invisible spheres to which the celestial bodies were attached, or in which they were enclosed. The natural rotary motion of these spheres, or orbs, produced the observable circular motion of every visible celestial body. Although the multitude of fixed stars was attached to a single sphere, each planet was carried around by its own sphere. Not only was each planet assigned its own orb, but each motion of the planet — daily motion, sidereal motion, motion in latitude, etc. — was also assigned its own orb. Ptolemy and Aristotle each employed a plurality of spheres to account for the resultant celestial position of each planet. All told, Ptolemy may have assigned as many as 41 orbs, while Aristotle assigned as many as 55. The orbs employed differed, however. Aristotle's were all concentric with respect to the earth, while Ptolemy's were eccentric. When both of these systems were introduced into western Europe during the late twelfth and thirteenth centuries, natural philosophers were faced with a dilemma.

The Problem about the Ptolemaic and Aristotelian Systems

The characteristic feature of Aristotelian cosmology, as reinforced by Averroes, the great Muslim commentator on the works of Aristotle, was that every celestial orb must rotate around a physical body located at its centre. In a system in which all physical orbs were concentric, the earth fulfilled this essential function. By contrast, Ptolemaic astronomy repudiated concentric astronomy and pure geocentricity, since it was obvious that concentric spheres could not account for the observed variations in the distances of the planets from the earth. The introduction of eccentric and epicyclic orbs was intended to remedy this fatal deficiency. In its simplest form, a planet's motion was representable by an eccentric circle with a centre other than that of the centre of the earth; or, if the earth's centre was retained, an epicycle, carrying the planet, might be added to the circumference; or, finally, some combination of eccentric and epicyclic circles might be employed. In the geometry of Ptolemy's system, not only was the earth removed from the centre of the universe when the astronomical data required it, but the distance of each planet from the earth could vary. Moreover, Ptolemy's system was not a mere geometric convenience that could be used to save the phenomena. In his *Hypotheses of the planets*, Ptolemy had devised a physical model of his eccentric system of the world that somehow became known in the Latin West even though the work itself was unavailable.

The Three-orb Compromise

To reconcile Ptolemy and Aristotle, medieval natural philosophers adopted a compromise, which had, in fact, already been made by Ptolemy in his *Hypotheses of the planets*. To use medieval terminology, they distinguished between a 'total orb' (*orbis totalis*) and a 'partial orb' (*orbis partialis*). The former is a concentric sphere whose geometric centre coincides with the centre of the world (which is of course identical with the centre of the earth); the latter is an eccentric orb whose geometric centre lies outside the centre of the world. The concave and convex surfaces of a concentric sphere contain between them at least three partial orbs, one of which, the eccentric deferent, carries an epicycle within which a planet is enclosed (for the configuration of the Moon's orbs, see Figure 1). With a few exceptions, this was the

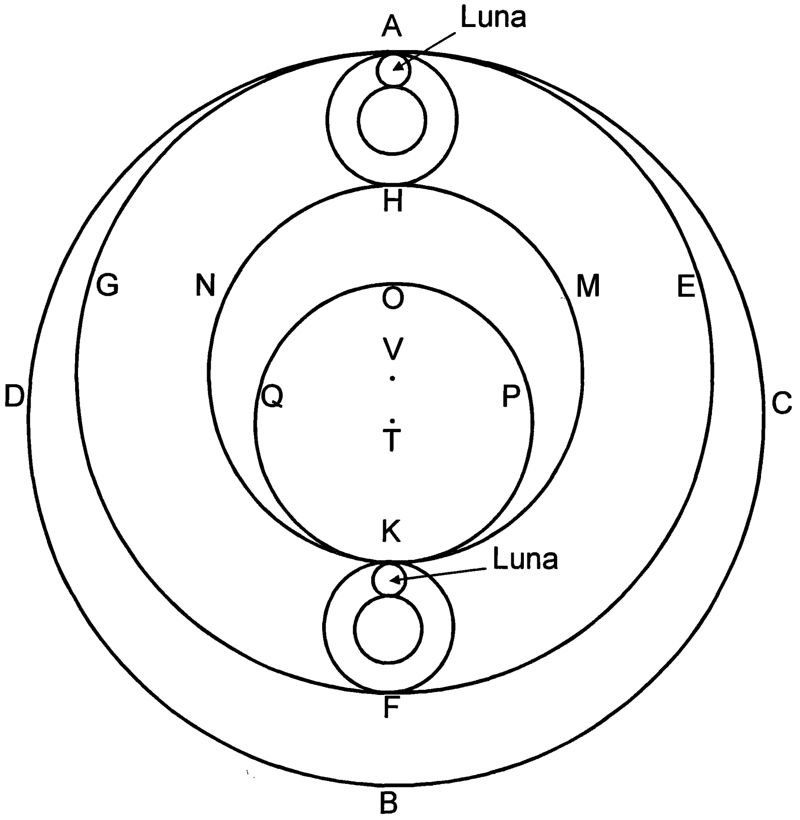

FIG. 1. The Moon's concentric, eccentric, and epicyclic orbs, based on Roger Bacon's description in his *Opus tertium*. The "total orb" is enclosed by the concave and convex surfaces, *OQKP* and *ADBC*, which have the earth, *T*, as their centre. This total orb is made up of three "partial orbs", namely the orbs enclosed by the circles *ADBC* and *AGFE*; *AGFE* and *HNKM*; and *HNKM* and *OQKP*. The eccentric deferent, which has the centre *V*, is the orb lying between *AGFE* and *HNKM*. Within the eccentric orb is an epicycle in which the planet — the moon in this example — is embedded.

system that was adopted during the Middle Ages. It was a compromise between Aristotle's cosmology and Ptolemy's astronomy.

Ptolemaic astronomy posed serious problems for Aristotelian cosmology. The inclusion of eccentric orbs within Aristotelian concentric spheres meant that Aristotelian cosmology had to accept some unpleasant 'realities'. Although the concentric orbs as a whole rotated around the physical earth as their centre, the eccentric orbs within each total orb did not have the earth as their centre, but rotated around a geometric point that was eccentric to the earth. Ordinarily, this would have been a repugnant idea and posed a serious dilemma. Either Aristotelians would have to abandon the centrality of the earth and therefore jeopardize the physics and cosmology that Aristotle had erected on the assumption of the earth's centrality; or, they would have to continue to accept a cosmology that was astronomically untenable.

The solution lay in distinguishing between total concentric orbs and partial eccentric orbs, the latter enclosed within the former. This solution was already known to Roger Bacon and was widely accepted during the late Middle Ages.

The Number of Orbs in the Cosmos

Since there are at least three partial orbs for every planet and only one total orb, there are obviously many more partial than total orbs. Medieval natural philosophers were far more interested in total, concentric orbs, than in partial, eccentric orbs, as is immediately evident in one of the most popular questions in medieval cosmology: "On the number of spheres, whether there are eight or nine, or more or less." The expected response had to be in total orbs, usually anywhere between eight and eleven. Seven concentric orbs were assigned to the seven planets and one more for the daily motion of the sphere of the fixed stars, for a total of eight. But the fixed stars were rarely assigned only one motion. Often three were required: one for the daily motion; one for precession of the equinoxes, which was a west-to-east motion of the fixed stars that occurred at the rate of 1° in 100 years and thus produced a complete revolution of the starry sphere in 36,000 years; and one for trepidation, an alleged progressive and regressive motion of the stars assigned by Thabit ibn Qurra, a ninth-century Arab astronomer. On the principle that a single sphere was required for each distinct celestial motion, one additional sphere had to be assigned for precession and trepidation, for a total of ten orbs. If we add to these, an all-encompassing, immobile empyrean sphere, we obtain a total of eleven concentric spheres.

Scholastic natural philosophers disagreed on the number of total orbs in the universe because they disagreed on the number of motions to be assigned to the sphere of the fixed stars. Those who assigned the three motions mentioned above, would have added two orbs, one for each additional motion, and arrived at ten moving orbs. If they added the empyrean, they would have a total of eleven. For those who assigned only two motions, the total would have been nine moving orbs and the empyrean, for a total of ten. Those who assigned only the daily motion would have assumed eight moving orbs and, if they added the empyrean, would have obtained a total of nine concentric orbs.

Because they knew little about technical astronomy, medieval natural philosophers generally ignored the role played by the partial eccentric orbs that lay between the convex and concave surfaces of a concentric, or total, orb. Such concerns were better left to astronomers. What mattered was that the foundations of Aristotelian cosmology were preserved while honouring, albeit tenuously, the basic tenets of Ptolemaic astronomy. The glaring fact that partial, eccentric orbs did not have the earth as their physical centre was virtually ignored.

Although the celestial spheres of medieval cosmology were conceived as physically real and not mere geometrical constructions to save the astronomical phenomena, scholastic natural philosophers were under no illusions that they had arrived at the precise number and order of the heavenly orbs. If their own obvious lack of agreement failed to convince them, their considerable philosophical sophistication would have. They were not only aware that new data might require revisions in their conceptions, but they were sensitive to the fact that a variety of celestial arrangements were compatible with their current data.

The Theological Spheres

The sphere of the fixed stars and the concentric spheres beyond were intimately related to Christian theology. Commentaries on the second day of creation produced two major orbs that were essentially theological in character. The first was the firmament, which divided "the waters from the waters". Some interpreted the biblical firmament as a single heaven that embraced all the planets and fixed stars, while others, perhaps most, identified it solely with the eighth sphere of the fixed stars. Occasionally, as Thomas Aquinas reports, the firmament was equated with air, largely because clouds were seen as vapours above the air, or firmament, while the rain that fell was perceived as forming the waters below the firmament.

Although the waters above the firmament were deemed real, their precise nature was debatable. Early on, these waters came to be called "crystalline", a term that was applied to fluid, as well as to congealed waters, like ice or crystal. Supporters could be found on each side. For Saint Jerome (*c.* 347–419?) and the Venerable Bede (672–735), the waters were hard and crystal-like, whereas for Saint Basil and for Saint Ambrose (*c.* 339–97), they were fluid and soft. Whether hard or soft, however, the crystalline sphere was usually located above the firmament and was identified with the ninth or tenth transparent, bodiless, celestial orb and sometimes with both.

All the orbs we have spoken of thus far in this section were assumed to be moving with uniform, circular motion. All had some astronomical function. The empyrean heaven or sphere is a notable exception. Not only was it immobile, but it had no astronomical purpose. Nor (unlike the firmament and the crystalline spheres) did it have a biblical sanction, although the heaven created on the first day was sometimes called the "empyrean". The empyrean heaven was a product, not of science nor of faith based on scripture, but of faith alone. It emerged as a separate heavenly sphere only in the twelfth century, when theologians such as Anselm of Laon, Peter Lombard, and Hugh of Saint Victor described it as a place of dazzling luminosity, which it received directly from God. It was soon viewed as the dwelling place of God and the angels, as well as the abode of the blessed. Despite its perpetually radiant state, the empyrean heaven transmitted none of the light that filled it. As a sphere, it was transparent, invisible, and incorruptible. Nothing existed beyond its convex surface. As Campanus of Novara put it in the thirteenth century, "It is the common and most general 'place' for all things which have position, in that it contains everything and is itself contained by nothing".[4]

Are the Orbs Hard or Soft?

We saw earlier that opinions varied about the state of the crystalline sphere, as to whether it was hard like crystal, or fluid like water. We may extend that uncertainty to all the celestial orbs. Medieval natural philosophers never formally inquired about the hardness or softness of the celestial orbs. Only by occasional remarks do some of them imply an opinion.

Prior to the thirteenth century, if celestial orbs were characterized at all, they were likely to have been thought of as fluid rather than hard. A gradual shift began in the thirteenth century. At first, a few scholars, one of whom was Giles of Rome (b. before 1247, d. 1316), invoked a combination of hard and soft orbs, usually treating the convex and concave surfaces of the concentric spheres as hard, while assuming that the eccentric orbs within were soft. In the fourteenth century, a few scholars indicated their belief in hard orbs. For example, Themon Judaeus (*c.* 1330 – d. after 1371) declared that "a heaven [i.e., orb] is a hard (*durum*) body without capacity for flowing". Few were as explicit as Themon, but it is likely that if pressed directly, most by then would have agreed with him. Not until Tycho Brahe and Galileo Galilei reformed astronomy with their observational achievements did the concept of a fluid heavens emerge as a more plausible alternative to hard orbs. Tycho showed that the comet of 1577, which he carefully observed, had a path that would have produced collisions with hard orbs, if the latter existed. The satellites of Jupiter, which could occupy any positions around Jupiter, also made it difficult to justify hard orbs. Although some defenders remained, many scholastic Aristotelians, especially those who shifted their allegiance to Tycho Brahe's geoheliocentric system, also abandoned hard orbs.

On the Causes of Celestial Motion

Medieval natural philosophers formulated many questions about celestial motions. Some were about motion in space and time or about the kinematics of celestial motion. In this category, the questions were about uniformity and regularity of motion, and whether celestial bodies could have two simultaneous, contrary motions. A few scholastics — especially Nicole Oresme — were concerned about whether celestial motions were commensurable or incommensurable.

The dynamics of celestial motion, however, overshadowed the kinematic aspects. Numerous questions were posed about the causes that produced the uniform, perpetual, circular motions of celestial bodies. Because medieval natural philosophers were virtually unanimous in their belief that the planets were not self-moved, but were carried around by the orbs in which they were embedded, the problem they had to resolve was what, or who, caused each and every invisible celestial orb to move incessantly around the sky with uniform, circular motion. Medieval scholars could find in the writings of Aristotle two basic motive causes, one internal, the other external. The celestial ether that filled the heavens was the substance from which all the orbs and planets were composed. Aristotle (writing in *On the heavens*) held that by its very nature the ether moved with circular motion. But he also argued (in the *Physics* and *Metaphysics*) that each orb had its own external, immaterial, spiritual mover, or intelligence, which was separate and distinct from the orb with which it was associated. Aristotle characterized each of these intelligences as an "unmoved mover" because it could cause its orb to move without being in motion itself. The first of these unmoved movers was accorded special status because it was associated with the outermost moving sphere, or the sphere of the fixed stars, which enclosed the world in Aristotle's system. Indeed, Aristotle identified the first unmoved mover with God.

But how does an "unmoved mover" cause something else to move and yet remain motionless itself? "It produces motion by being loved", was Aristotle's reply. The nature of this extraordinary love relationship is left unclear. Is it the celestial orb that loves its own intelligence? Or does the intelligence of each orb love the first unmoved mover and, by virtue of that love, seek unremittingly to unite with its object of love. As it vainly seeks union with its beloved, does it cause its own orb to move with an incessant circular motion?

Aristotle located the first unmoved mover (or 'prime mover', as it was more commonly known) at the circumference of the universe, where it served an essential function in his cosmic system. According to Aristotle, everything that is moved is moved by something other than itself. Now, a cause of motion must be something that is either in motion itself, or is at rest. If a cause of motion is itself in motion, then we must ask what caused it to be in motion, and so on. But if everything that is moved is moved by another, there would be an infinite sequence of motive causes. To break this potentially disastrous infinite regress, Aristotle argues that the sequence of movers terminates with the prime mover, which causes other things to be in motion because it is the object of their love, but is itself motionless.

Aristotle thus bequeathed two causal explanations for the motion of celestial orbs, one internal, the other external. A third interpretation was also attributed to Aristotle. According to an opinion derived from Neoplatonic sources and transmitted to the Latin West by Avicenna, and subsequently reported by Thomas Aquinas, Aristotle was said to have distinguished two immaterial substances that were associated with each orb: a soul and an external intelligence. The soul is an integral part of its orb, whereas the intelligence is distinct from its orb, though associated with it in some sense. It follows that as each orb moves around with uniform circular motion, its soul moves with it. But the soul is not the direct cause of the orb's motion. Motion arises because of the soul's love of, and desire for, the separate intelligence that is associated with the same orb. The direct cause of motion is therefore the separate intelligence, which causes the soul to love and desire it, thus enabling the soul to move its orb around and around. In this explanation, the soul functions as an internal mover and the intelligence as an external mover.

External Movers

Although God, the Prime Mover, could directly move the celestial orbs as an efficient cause, He chose rather to assign this task to a secondary cause of His own creation, but gave no indication as to whether it was external or internal. During the Middle Ages, the most popular explanation of celestial motion assumed that God had opted for an external mover in the form of an intelligence, or angel (the terms were usually synonymous). God had chosen to associate an external, separate intelligence with each orb.

How did an intelligence move an orb? It was often assumed to do so by means of three things: intellect, will, and a third spiritual entity which carried out the command of the intellect and the will, namely a finite motive force (*virtus motiva finita*), or, as it was also called, an "executive power" (*potentia executiva*). This third force was required because the intellect could command the will, but neither the intellect nor the will could complete an act that it willed. To execute a command, an executive power, or third force, was invoked. An intelligence, or angel, was limited in power and could not will its commands from a distance. It had to be in direct contact with its orb. Because intellect and will were associated with voluntary acts, celestial motions were viewed as voluntary actions. It seemed plausible, therefore, to assume that each intelligence voluntarily commanded its orb to move with uniform, circular motion. Moreover, since each uniform and regular celestial motion was destined to continue into the indefinite future, each motive intelligence was assumed to possess an inexhaustible force (*vir infatigabilis*), which it derived from the Prime Mover, either all at once, when He created it, or in increments doled out as needed from His own inexhaustible reservoir.

Although intelligences were originally incorporeal, spiritual entities, they eventually assumed the status of impersonal forces. Intellect and will were de-emphasized while the finite, motive force, or "executive power", was viewed as the real mover. Intelligences continued to play a role as celestial movers well into the seventeenth century. Even after hard orbs were rejected, intelligences were simply transferred to the planets themselves.

Internal Movers

Although intelligences were the most popular causal explanation for the motion of celestial orbs, internal movers attracted a few significant adherents. Already in the thirteenth century, John Blund and Robert Kilwardby argued that each celestial orb possessed a natural, intrinsic capability for self-motion. By contrast with the vague, innate capacity postulated by Blund and Kilwardby, John Buridan applied his well-quantified impressed-force, or *impetus*, theory to explain celestial motions. Because the Bible made no mention of intelligences as celestial movers, Buridan dispensed with them and assumed that at the creation God impressed impetuses, or forces, into each orb. In the absence of external resistances and contrary tendencies, the impressed impetus of an orb would remain constant and move its orb with uniform, circular motion forever. Although the most popular causal explanation of celestial motion involved external movers in the form of intelligences, or angels, there were those who opted for internal forces as a better, and probably simpler, alternative.

The Properties of Celestial Bodies

By "the properties of celestial bodies", we chiefly mean the properties of the celestial ether, since the planets, stars, and orbs were assumed to be composed of this extraordinary substance. The most striking property that Aristotle assigned to the celestial ether, or fifth element, was incorruptibility. On the basis of his conviction that ancient peoples had recorded no alterations in the heavens and that none had been observed there, Aristotle concluded that the ether suffered no change (other than change of position, which was evident by virtue of the motions of the planets and stars).

Because of its incorruptibility, Aristotle and his medieval followers assumed that contrary, or opposite, qualities, such as rarity–density, hotness–coldness, heaviness–lightness, and so on, were absent from the celestial ether. Since contrary qualities were associated with generation and corruption, or change, in the terrestrial region, it was appropriate that they should be absent from the celestial region, where change was supposedly non-existent. But if the heavenly ether lacked contrary qualities, why did natural philosophers and astrologers describe Saturn as cold and dry, Mars as hot and dry, the Moon as cold and wet, and so on for the other planets? If these qualities did not really subsist in the heavenly bodies, why did astrologers and natural philosophers speak as if they did?

The standard medieval reply to such a question would have been that the celestial ether possessed these qualities only virtually (*virtualiter*), not formally (*formaliter*) or actually. That is, celestial bodies could be said to "possess" hotness and coldness only in the sense that they could somehow cause changes in hotness and coldness in bodies below the Moon, even though the celestial bodies did not actually possess the qualities they could produce in terrestrial bodies. To say, for example, that Saturn was cold was not to say that the quality 'coldness' actually inhered in Saturn's etherial matter, but rather that Saturn had the capability to produce the effect of coldness in the terrestrial region. Again, the Sun was not actually hot, but had the capability of causing hotness in objects in the terrestrial region.

Celestial bodies were not confined to the production of a few contrary qualities in the terrestrial region. During the Middle Ages, many assumed that celestial bodies governed all activities of sublunar bodies. In the fourteenth century, Themon Judaeus spoke for his time when he declared that "every natural power of this inferior sensible world is governed by the heavens". Such a sweeping claim was based not only on Aristotle, but on the obvious role of Sun and Moon, where the former was essential for life itself and the latter was associated with tidal action and the balance of bodily fluids. Since the celestial region was assumed to be more noble and perfect than the terrestrial region, natural philosophers were virtually unanimous in their conviction that celestial influences were unidirectional, flowing down from the celestial to the terrestrial regions. But how did such influences descend to the earth? How were they transmitted from one celestial sphere to another and then on through the concave surface of the lunar sphere and on down to the earth itself?

Celestial bodies were thought to affect the terrestrial region by three different instrumentalities: motion (*motus*), light (*lumen*), and influence (*influentia*). In the Aristotelian-Ptolemaic system of orbs in the Middle Ages, scholars sometimes implied that influences were radiated down from orb to successive orb by virtue of the planetary motions. Because the orbs were nested one within another and in contact at all points, some natural philosophers implied that influences were somehow transmitted mechanically from rotating orb to rotating orb and ultimately from the concave surface of the lunar sphere down to the terrestrial region. Unidirectional transmission of effects may have been considered plausible because of the belief that any celestial sphere could drag its immediate inferior neighbour with it and therefore transmit effects to it. But such a mode of transmission would have been implausible in the Aristotelian system of spheres because the orbs were assumed to move without friction, so that the orbs would presumably slide by each other without transmitting anything. More important than this, however, was Aristotle's introduction of "unrolling spheres", which were intended to seal off each set of planetary orbs from its immediate neighbours above and below. Thus, effects from the orbs of Jupiter, for example, could not be transmitted to the planetary orbs of Mars. Moreover, each orb had its own motive intelligence and was independent of all other orbs. There was no reason to believe that any individual orb could receive effects and then transmit them to the next orb below. Although some authors may have believed in mechanical transmission of effects by means of the motions of orbs, they did not, and could not, devise an effective mode of transmission within Aristotelian cosmology.

If mechanical transmission of celestial effects proved unsatisfactory, the transmission of light from the Sun to the earth through transparent and invisible orbs was easy to imagine. Because they were thought to receive their light from the Sun, all the other planets could also transmit light to the earth. Roger Bacon described the light (*lumen*) of the Sun as essential for the production of all generative effects on earth. The transparent orbs offered no resistance to the light rays that passed through and were unaffected by their passage.

For the numerous terrestrial effects that could not be accounted for by light, the existence of an all-purpose "influence" (*influentia*) was assumed. Themon Judaeus described it as "a certain quality, or virtue, diffused throughout the whole world, just as the species of heat or light is multiplied".[5] Celestial influences were invoked to explain the action of magnetism and the tides. Because influences could pass through opaque objects, they were also invoked to explain the generation of metals in the bowels of the earth.

In addition to the specific influences just described, a "universal nature" was also invoked to explain how the order of the world as a whole was preserved. The universal nature, also called "celestial force", or "universal agent", originated in the celestial region from whence it was diffused throughout the sublunar domain. The universal nature was contrasted with the particular natures of terrestrial bodies. By virtue of its particular nature a body moved to its natural place, a heavy body down and a light body up. Ordinarily, the behaviour of terrestrial bodies was governed by their particular natures. The fundamental purpose of the universal nature was to preserve the continuity of the universal material plenum, that is, to prevent formation of vacua within the world. To achieve this objective, the omnipresent universal nature would, if necessary, cause bodies to act contrary to their particular natures: heavy bodies would be made to rise and light bodies fall. Indeed, if fire were suddenly to descend from its natural place below the concave surface of the lunar sphere, some were prepared to believe that the heavens would immediately descend in a straight line to prevent formation of the dreaded vacuum. Only the human will and intellect were exempt from celestial influences.

The planets, stars, and orbs were all composed of the same transparent ether. Stars and planets were visible only because each celestial body was a region of highly concentrated ether that was capable of receiving light and becoming self-luminous, or, for those who considered the celestial bodies to be opaque, of reflecting light from the Sun. The prevailing medieval opinion was that the stars and planets received their light from the Sun, with some further assuming that the planets were also weakly self-luminous.

The Terrestrial Region

The cosmology of the terrestrial region involved the study of the four elements and their incessant interactions. The natural generative and corruptive activities of the sublunar region derived from the continuous transformations of one element into another and from the fusion of the four elements, in varying proportions, into the myriad of compound bodies that formed the world of ordinary experience. Without this incessant activity, caused by the Sun's light and heat, the sublunar region would long ago have settled into four homogeneous, static, concentric rings of fire, air, water, and earth.

Despite the need to use eccentric orbs in technical astronomy, which required that the earth be removed from the centre of the universe, most natural philosophers wrote about the earth as if it lay immobile in the geometric centre of the world. A few, however, and John Buridan was one of them, attributed real, but minute, motions to the earth. Under the influence of geological changes caused ultimately by solar heat, Buridan assumed that the earth's density was perpetually altered, thus causing continuous shifts of the earth's centre of gravity. Since the earth always sought to rest in its natural place at the geometric centre of the universe, it shifted its position until its centre of gravity coincided with the geometric centre of the universe. When this coincidence was destroyed by the next shift of the earth's centre of gravity, the earth once again moved slightly to bring its centre of gravity into coincidence with the geometric centre of the world. In this manner, the earth was thought to oscillate perpetually around the geometric centre of the world.

But Buridan and, a few years later, Nicole Oresme contemplated a more daring concept of terrestrial motion when they considered whether the daily rotation of the heavens might not derive from a real daily axial rotation of the earth. After proposing cogent arguments for believing in axial rotation, both eventually rejected this alternative, for different reasons. They were agreed, however, that if the earth did actually undergo a daily rotation, while the heaven remained immobile, the astronomical phenomena would be 'saved' just as well as if the earth were immobile and the heavens moved with a daily rotation. Their arguments included appeals to the relativity of motion and economy of effort, with the earth requiring a much smaller velocity to complete a daily rotation than the huge heavens.

Dimensions of the Universe

Since the celestial spheres were thought to be nested one within another, it was routinely assumed that the radius of the convex surface of one planetary sphere, say Mars, was exactly equal to the radius of the concave surface of Jupiter, the next upper planetary sphere. In this manner, void spaces and extraneous matter between orbs were excluded. The dimensions and distances of the planets as they were usually cited in the Middle Ages are listed in Table 1, which is drawn from Campanus of Novara's widely used astronomical treatise, *Theory of the planets*.[6] Some of these measurements make the cosmos seem idiosyncratic rather than the beautifully crafted creation of an infinite creator. In particular, the thicknesses of the planetary spheres seem beyond comprehension. The sphere of Venus, for example, is approximately nine times thicker than that of the Sun and Moon, the planets immediately above and below; and with the spheres of the superior planets, we witness an enormous increase in thickness over the Sun and inferior planets. The diameters, and therefore the sizes, of the planets also seem to vary in strange ways.

From the centre of the earth to the convex surface of Saturn, Campanus calculated a distance of approximately 73 million miles. The eighth sphere of the fixed stars was the last visible component of the universe. On the basis of the nested-sphere pattern described above, the concave surface of the sphere of the fixed stars would be assumed contiguous with the convex surface of the sphere of Saturn, from which we may infer that Campanus took the concave surface of the sphere of fixed stars to be some 73 million miles from the earth's centre. But were all the visible stars arrayed on the concave surface? Or were they distributed at different distances, so that the eighth sphere was of considerable thickness, like the planetary spheres? On this arrangement, some stars might be much farther away than 73 million miles. However, if such questions arose, they were largely ignored.

Although many thought the stars were innumerable, most were agreed that only

TABLE 1. Data from Campanus of Novara's *Theory of the planets*, distances being given in miles with fractions ignored.* Column 1 = distance from earth of concave surface of planetary sphere; column 2 = distance from earth of convex surface of planetary sphere; column 3 = thickness of planetary sphere; column 4 = diameter of planet; column 5 = circumference of planet.

Planet	1	2	3	4	5
Moon	107,936	209,198	101,262	1,896	5,961
Mercury	209,198	579,320	370,122	230	725
Venus	579,320	3,892,866	3,313,546	2,884	9,095
Sun	3,892,866	4,268,629	375,762	35,700	112,200
Mars	4,268,629	35,352,075	28,083,446	7,572	23,800
Jupiter	32,352,075	52,544,702	20,192,627	29,641	93,160
Saturn	52,544,702	73,387,747	20,843,045	29,209	91,800

*By omitting the fractions, the value of each thickness is altered from Campanus's table by a fractional part of one. For example, Campanus gives 101,261 26/33 as the thickness of the Moon's sphere (instead of 101,262), 370,122 5/11 for Mercury, and so on.

1,022 were visible — a figure that came from Ptolemy's catalogue of stars in the *Almagest*. Each star was a dense accumulation of celestial ether capable of reflecting light, and therefore visible. These 1,022 stars were divided into six magnitudes of differing degrees of brightness, where brightness was usually equated with size: first magnitude stars, for example, were the brightest and largest.

Whether the cosmos was a sphere with a radius of approximately 73 million miles, or whether it was 100 million miles, or even much larger, is of little importance. By comparison to modern dimensions of our universe, the medieval cosmos was minuscule, although it did not appear so to those who lived in it. For them, it seemed very large indeed. "The really important difference", C. S. Lewis explains, "is that the medieval universe, while unimaginably large, was also unambiguously finite". It is this emphatic finitude that contrasts so starkly with our modern universe. This virtual incommensurability between the perceived sizes of the medieval and modern worlds prompted Lewis to declare that

> to look out on the night sky with modern eyes is like looking out over a sea that fades away into mist, or looking about one in a trackless forest — trees forever and no horizon. To look up at the towering medieval universe is much more like looking at a great building. The 'space' of modern astronomy may arouse terror, or bewilderment or vague reverie; the spheres of the old present us with an object in which the mind can rest, overwhelming in its greatness but satisfying in its harmony. That is the sense in which our universe is romantic, and theirs was classical.[7]

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6. Table 1 is slightly modified from tables in Benjamin and Toomer (eds), *op. cit.* (ref. 4).
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