1. ARISTOTLE'S COSMOLOGY

1.1. PLANTS AND ANIMALS VS. CELESTIAL OBJECTS

In *Cael*. B 5 Aristotle sets out to answer the surprising question why the direction of the diurnal rotation is from east to west, not the other way around.[1] Since he believes that, in contrast to what is the case with plants and animals, substances coming into being and passing away, nothing occurs randomly in the eternal realm of celestial objects, there cannot but be some reason why the diurnal rotation is from east to west (287b24–28). His brief explanation is prefaced by some words of caution, betokening understandable distress at his raising and trying to settle, albeit tentatively, the issue at hand.

To try to pronounce an opinion on intractable matters, such as the one Aristotle himself is looking into here, and the unwillingness to circumvent any subject might be considered a symptom of excessive eagerness to investigate or, worse, simple-mindedness. However, it is unfair, Aristotle continues, to chastise indiscriminately all those who dare tackle some very difficult problems without first taking into account their reason for so doing, and without considering whether the confidence, with which they put forward their proposed solutions, is commensurate with human cognitive limitations or not. He concludes by saying that, in explaining why the diurnal rotation is from east to west, he will say just what seems to him to be the case, and that we ought to be grateful to future thinkers who might be successful in coming up with adequate explanations of necessarily compelling nature (287b28–288a2).[2]

Similar sentiments are expressed in *Cael*. B 12. Aristotle opens this chapter with the remark that he must attempt to state what seems to him to be the case as regards two baffling problems, whose difficulty anyone would acknowledge, concerning the celestial objects and their motions.[3] His eagerness to attack such impenetrable questions is a sign of humility, not impetuousness, stemming from the willingness, due to a desire for knowledge, to be satisfied with making even very small steps towards an understanding of those things which we are most puzzled about (291b24–28). Before going on to put forward what by his lights is just a plausible solution to the problems at issue, Aristotle notes that it is good to try to expand our understanding of the celestial objects, though our starting points are necessarily scanty, for enormous distances separate us from the celestial phenomena (292a14–17).[4] But his deep conviction that the study of these phenomena is an intrinsically worthy enterprise motivates him to forge stubbornly ahead.

1 For the diurnal rotation, and the associated concept of the celestial sphere, see 1.3.3.

2 What Aristotle contrasts at the end of this passage are τὸ φαινόμενον and αἱ ἀκριβέστεραι ἀνάγκαι, however the latter might be understood.

3 Here, too, "what seems to be the case" translates τὸ φαινόμενον (cf. previous note).

4 Cf. *Cael*. B 3, 286a3–7.

Aristotle stresses how difficult it is to study the celestial objects also in the preface to *PA* (A 5), where he adds that the difficulty is more than adequately made up by how much excitement even a small progress in this area can generate. Contrasting the study of the eternal and divine celestial objects with the inquiry into transient plants and animals, he notes that the former is much worthier, for it deals with an eternal and divine, hence more valuable, subject-matter, but is unfortunately hampered by the fact that very few starting points are available to our senses, from which we can theorize about the celestial objects and those phenomena they exhibit that we desire most to understand. To obtain knowledge of perishable plants and animals is easier, because they live with us, here on Earth. As a consequence, we can learn much about each kind of plant and animal if we are willing to undertake sufficient efforts. If we manage to advance even a little our understanding of the heavens, however, this knowledge is so valuable that to possess it is more pleasurable than to have grasped all things that are close to us, just as to have been granted a mere glimpse of those we are in love with is more gratifying than the detailed inspection of many and much larger, or much more important, things (644b22–35).[5]

The beautiful *PA* passage might have influenced a section in Cicero's *Lucullus*, 127–128, where Cicero himself explains an Academic skeptic's cognitive attitude towards the study of celestial objects. In Cicero's view, the study of nature in general is a kind of natural food for thought. By inquiring into the highest reaches of the cosmos we are uplifted, and led to look down upon our totally insignificant affairs. He admits that these are matters as extremely inscrutable as they are supreme in importance, and adds that if we chance upon some ideas about the heavens that appear to have a likeness to what is true, our mind is filled with the kind of pleasure most appropriate to human beings. The Stoics, Cicero says, study the phenomena of the sky in order to affirm the truth of whatever conclusions they might be led to, but the Academic skeptics, wary of holding rash opinions, engage in the same branch of intellectual endeavor ready to be content with what seems to bear a likeness to the truth.

Aristotle does not think that the celestial objects are different from plants and animals only insofar as our epistemic access to them is concerned. It is generally agreed that, within the framework of his physics, at least after an initial phase of its evolution, for which we have very little, if any, evidence, the celestial objects are assumed to be made out of a kind of matter totally different in nature from those kinds of matter that are thought to make up all plants and animals.[6] The second

5 On the passages discussed so far see Falcon (2005) 85ff.

6 An initial phase in the evolution of Aristotle's physics, when he did not posit the existence of a special celestial matter, has been detected in the fragments of his early dialogue *On Philosophy*. See Solmsen (1960) 287, with n. 1, and Hahm (1982) 60, with n. 2. Hahm denies that in his lost work Aristotle introduced this novel kind of matter. Freudenthal (1995) 101–105 argues that is was introduced some time after the composition of the dialogue *On Philosophy*, as direct development of the physics Aristotle elaborated therein. Modern developmental accounts of Aristotle's physics usually focus on the evolution of his views about the ultimate sources of all motion and change in the cosmos. Surveys in Graham (1996) 171–172 and Graham (1999) xiii–xiv.

chapter of this study is an attempt at elucidating the stages at which Aristotle introduced this celestial matter.

1.2. THE FOUR TRADITIONAL SIMPLE BODIES

1.2.1. Fire, air, water and earth, and their qualities

Everything within the scope of our immediate experience is, according to Aristotle, ultimately made up of four kinds of elementary body, matter continuous in all three dimensions, or of four simple bodies.[7] These simple bodies are the "traditional" elements Empedocles of Acragas introduced into physics in the fifth century BC: fire, air, water and earth. Their simplicity lies in their unanalyzability into other bodies.[8] Aristotle thinks of them as combinations of qualities, which form two pairs of contraries. Earth is dry and cold, water is cold and wet, air is wet and hot, fire is hot and dry (*GC* B 3, 331a3–6);[9] as he explains in *Mete*. A 3, what is habitually called "fire" is the simple body of the same name when undergoing combustion (340b19–23). On what can be appropriately called "the cosmological scale" in this context, these four simple bodies are sorted out concentrically. The simple body earth is clumped around the center of the cosmos into a globe–the Earth; the simple body water is concentrated on the surface of this globe within a spherical shell of air, around which there is a spherical shell of fire.[10] All things in our close surroundings are ultimately constituted by all of these four simple bodies, bound together in insignificant amounts by comparison to how much of each exists in the cosmos (*GC* B 8, 334b30–335a9).[11]

This makes clear that, although the four traditional simple bodies are always neatly stratified on the cosmological scale, on much smaller scales they are not separated at any given time. They cannot be completely sorted out, Aristotle explains in *GC* B 10, 337a7–15, because, on scales much smaller than the cosmological scale, they constantly transform into one another, and, as a result, the concentration of each on the cosmological scale contains bits of all others, an exception, as Aristotle seems to suggest in *Mete*. A 3, being the outermost part of the

7 For the three-dimensional continuity of bodies see *Cael*. A 1, 268a1–10, an introductory characterization of what is studied in physics.

8 See the definition of "element" in *Cael*. Γ 3, 302a15–25.

9 The qualities constituting each and every portion of one of these four simple bodies can be paralleled to the so-called tropes, or abstract particulars, of modern metaphysics. Brief introductory account in Mellor & Oliver (1999) 17–20; fuller discussion in Williams (1999), Campbell (1999). Cf., though, Gill (1991a) 77–78.

10 Aristotle demonstrates in *Cael*. B 4 that the cosmos is stratified into spherical shells, with the Earth as the central sphere. Some of his arguments are discussed below, in 2.3.

11 Aristotle's explanation of why the constitution of any medium-sized object must include air and fire, too, is problematic. See Williams (1982) 178–179. Presupposed might conceivably be the assumption that all of the four traditional simple bodies are present near the surface of the Earth, where medium-sized objects exist, and the application of the principle that everything is made out of the body, or bodies, in which it is situated; see below, 1.3.1.

shell of fire (340b6–10; see Appendix 2), and perhaps the depths of the Earth (this seems to be implied by *GC* B 3, 330b33–331a1).[12] As we will see next, such impurities must exist in the first place if the four Empedoclean simple bodies are to be transmuted into one another.

1.2.2. The change of one simple body into another

We will leave aside for the time being what powers this change and how, to discuss how the analysis of the four traditional simple bodies into qualities allows them to turn into one another within the framework of Aristotelian physics. Aristotle describes three transmuting processes in *GC* B 4. By the first of them, fire transforms into air, air into water, water into earth, and earth into fire; this cyclical change can occur in the other direction. By the second process, fire turns into water, air into earth, water into fire, and earth into air. By the third process, fire and water change jointly into earth or air, air and earth into fire or water.[13]

The three processes that transmute one or two traditional simple bodies into another involve physical contact and interaction between two simple bodies.[14] But the real agents are the contraries. Two traditional simple bodies act on each other in virtue of their contraries. The cold e.g. is potentially the hot, and the hot is potentially the cold, just as the dry is potentially the wet, and the wet is potentially the dry. If the simple bodies they characterize come into contact, each quality acts on its contrary. The cold tries to assimilate to itself the hot, and its action is being met by an opposite reaction: if one of the contraries is "overpowered", it assimilates itself to the other, which also suffers a reciprocal change, as result of the interaction (*GC* B 7, 334b20–29).[15] But if the cold of e.g. earth assimilates itself to

12 For fire inside the Earth see *Mete*. B 4, 360a5–6, B 8, 365b24–27. Probably the best explanation of its presence is the mixture of all four traditional simple bodies in the surface layers of the Earth. When Aristotle speaks in *GC* B 3, 330b33–331a1, of the two simple bodies earth and fire as the purest of the traditional simple bodies, for they are "extremes", whereas the other two are "intermediates", it is quite unlikely that he tacitly denies the existence of impurities in the surface layers of the Earth and in the lowest layers of the spherical layer of fire. On terrestrial fire see also Freudenthal (1995) 70–73.

13 For the three transmuting processes see the helpful account in Gill (1991a) 67–77.

14 For the requirement that there must be physical contact between an agent and what is being acted upon by the agent see Aristotle's description in *Ph*. Γ 2, 202a3–12, of how a change is brought about by an agent; cf. *GC* A 6, 322b22–25.

15 On Aristotle's "law of action and opposite reaction" see *GA* Δ 3, 768b15–25, and cf. Kouremenos (2002) 114–115. That something which is hot or cold in actuality is cold or hot in potentiality, and can thus, under the right conditions, become actually cold or hot is stated by Aristotle in *GC* B 7, 334b20–22; for the principle at work here see *GC* A 7, 323b18–324a9. The transformation of one, or two, of the four traditional bodies into another occurs, as explicitly said in *GC* B 7, 334b20–29, if two interacting contraries, each of which is in potentiality the other, are not equal, or, as Aristotle puts it in *GC* A 10, 328a23–31, when the quantity of one of the two interacting simple bodies does not match the amount of the other in power; what is called "power" here is the capacity of each mass to assimilate the other to itself, by acting on the antagonist in virtue of its having in actuality the quality the antagonist has only in potentiality. For how Aristotle supposes this power to be quantifiable in theory–nothing hints that he

the hot of fire, earth turns into fire, the dry being common to both. A simple body has turned into another by the first of the three processes explained in *GC* B 4. In the second process, not just one but both qualities of a simple body turn into their contraries. Finally, in the third process, only one quality of each simple body turns into its contrary: e.g. the dry of fire assimilates to itself the wet of water, the cold of water assimilates to itself the hot of fire, and the result of the interaction is dry and cold earth.

A mass of e.g. earth outside its "natural place", where most of this simple body is collected at any given time, tends naturally to accrete to the clump. It moves there spontaneously, provided that no impediment stops it.

This "natural motion" of the four traditional simple bodies is conceived of as following radii of the spherical cosmos. Two of these four simple bodies, earth and water, move towards the center of the cosmos, and are heavy insofar as they possess the potentiality to do so. The remaining two, air and fire, shoot up away from the center of the cosmos towards the periphery, and are thus light insofar as they have the potentiality to do so.[16]

1.2.3. The formation of compound bodies

What happens if the contraries are equal in their powers?[17] If one can judge safely from *GC* B 7, neither agent turns into the other or suffers any change–the two simple bodies are left intact (334b20–23). However, if the contraries are equal in power only approximately, they cancel each other out, and in their place somehow emerge the dispositional properties of a compound, in whose formation the interaction of the simple bodies resulted (334b23–29).[18] The simple bodies cannot possibly be identified in a compound, but their potentiality is preserved in it, and so they will exist in actuality once again, when the compound will eventually decom-

ever had to deal with the practical problem of really measuring it, or that he even simply felt the need for such measurements–see the discussion in Kouremenos (2002) 104–106 (its conclusions are applied next to the formation of composites from the four traditional simple bodies, on which see also the following section here, and to the transformation of one, or two, of the four traditional simple bodies into another, processes intimately related, as will be explained in a moment).

16 All quantities of a traditional simple body have an equal tendency to approach the center of the cosmos, or move away from it; cf. *Cael.* B 14, 297a8–30. For the rectilinear natural motion of the four traditional simple bodies see *Cael.* A 2, where, though, Aristotle does not consider it necessary to explicitly identify with radii of the spherical cosmos the paths followed by the naturally moving masses of the four traditional simple bodies; he simply characterizes the direction of motion along the paths at issue as "downward" and "upward", or as being towards an unspecified middle-point, which is actually the center of the cosmos, and away from it. For weight and lightness see *Cael.* A 3, 269b20–29.

17 For Aristotle, comparable in power are not two contrary qualities themselves, but the quantities of two Empedoclean simple bodies, each of which interacts with the other in virtue of its being constituted by one of the two contrary qualities at issue. See above, n. 15, and the final paragraph of this section.

18 *GC* B 7, 334b20–29, is discussed in Kouremenos (2002) 108–109.

pose (*GC* A 10, 327b20–31).[19] Clearly, the transformation of the four traditional simple bodies into one another and the formation of compounds from all four of them are flipsides of the same coin.

Which dispositional properties emerge, and thus which compound body is generated, seems to be determined by how close to equality in power the contraries are (*GC* B 7, 334b23–29). Aristotle assumes that this closeness is continuously variable for each pair of contraries, which can easily allow for many kinds of compound bodies in the cosmos.

Whether the contraries are approximately equal in power is determined by the amounts of the Empedoclean simple bodies entering into combination; for the nature of compound bodies depends on the relations in which these quantities happen to stand to one another (*GC* A 10, 328a23–31, *de An*. A 4, 408a14–15). It thus follows that whether the contraries are exactly equal in power, or unequal enough for the one to assimilate the other into itself, cannot but also depend on the relation between the amounts of the simple bodies that interact (this is also clear from the discussion in *GC* B 6, 333a16–34, of the senses in which the four traditional simple bodies can be thought of as being comparable).[20]

1.2.4. The mass-ratio of two traditional simple bodies on the cosmological scale

As it turns out, the total amounts of the simple bodies fire and air existing in the cosmos at any given moment must have such a ratio to each other that their contraries, the dry and the wet respectively, are exactly equal in power; as with fire and air, so with air and water, water and earth, air and earth. The simple bodies in a pair are adjacent on the cosmological scale, so each acts on the other, and those in the first three pairs can turn into each other by the first of the three mechanisms for elemental change explained in *GC* B 4; the transmutation of the fourth pair into each other involves the second mechanism, whereby both qualities of a simple body change into their contraries. However, the possibility that one of the two simple bodies in a pair assimilates the other to itself on the cosmological scale must obviously be precluded, and so must be the possibility of a pair's uniting into a compound body on that scale.

That two of the Empedoclean simple bodies adjacent on the cosmological scale have always a certain mass-ratio on that scale is an assumption playing a crucial role in an argument Aristotle sets out in *Mete*. A 3 to drive home the unavoidable need for his belief that a fifth simple body exists besides fire, air, water and earth (340a1–13).

This simple body is the aforementioned kind of matter which, as is generally agreed among scholars, the celestial objects are assumed to consist of within the framework of Aristotle's physics, at least after a very poorly known early phase in

19 On the potential persistence of the four traditional simple bodies in a compound see most recently Scaltsas (2009) 242–258.

20 For a discussion of this passage see Kouremenos (2002) 104–108.

the evolution of his cosmology, which can very well be a figment of scholarly imagination.[21]

On much smaller scales, of course, the four Empedoclean simple bodies always both transform into one another and unite into compound bodies. As a consequence, local mass-gains and mass-losses of each of these simple bodies must be assumed to balance out precisely, in order for the mass-ratio of a pair of adjacent simple bodies on the cosmological scale to be always the same. The ratio between a quantity of a traditional simple body and that of the cosmically adjacent such body into which it can turn is assumed in *Mete*. A 3 to be equal to the mass ratio of the simple bodies in question obtaining on the cosmological scale (340a11–13).

1.2.5. The Sun and the change of the traditional simple bodies into one another

In *GC* B 10, Aristotle names "the double motion" of the Sun as the cause of the constant generation of the four traditional simple bodies from, and of their decay into, one another, as well as of the incessant formation of compound bodies from all of these four simple bodies, and of their decay: the apparent diurnal motion of the Sun, and its apparent annual motion in the ecliptic.[22] He lays particular emphasis on the annual motion, though, perhaps because it relates to the life-cycles of plants and animals, compounds of the four traditional simple bodies in which Aristotle has keen interest (337a7–15; cf. 336a15–b24).[23] This causal account is also hinted at in *Cael*. B 3, where Aristotle promises to be clearer later on, perhaps a reference to *GC* B 10. There, too, he is quite short on details, however. The apparent diurnal motion of the Sun mirrors the rotation of the Earth itself, and accounts for daily variations in the heating of the Earth by the Sun. The Sun's apparent annual motion reflects the Earth's orbiting the Sun, and thus brings about seasonal variations in the solar heating of the Earth. It must be this heating that causes the four traditional simple bodies to change into, and interact with, one another on scales much smaller than the cosmological scale. In *Cael*. B 3 Aristotle hints at a possible role of the planets and the Moon as causes of the perpetual transformation of the four Empedoclean simple bodies into one another, as well as of the generation of various compound bodies, and thus of complex medium-sized objects, out of them (286b6–9).

The Sun, Aristotle says in *Cael*. B 7, generates heat and light indirectly. Moving rapidly around the Earth, it acts on the mass of air which at any given moment the bulk of the Earth does not prevent from being so acted upon; this air-mass produces heat and light. The action of the Sun on the air is frictional, like the action of a rough surface on the inflammable material of a match against which it is scratched. It is apparently in virtue of its being already hot that air can be further

21 I have discussed the *Mete*. A 3 argument in Kouremenos (2002) 120–125. More detailed discussion of some of its aspects below, in 2.8.

22 The annual motion of the Sun in the ecliptic is discussed below, in 1.3.5. Its diurnal motion is due to its sharing in the diurnal rotation, for which see below, 1.3.3.

23 See Appendix 1.

heated by friction. Aristotle does not attempt to explain precisely how. But he adduces as empirical evidence for this mechanism the fact that projectiles moving through the air can heat it to such an extent that they are themselves set on fire, and even melt (289a19–35)!

Now, if the Sun, like all celestial objects, is assumed to be made out of a kind of matter which is different from the four Empedoclean simple bodies, since Aristotle says in *Cael*. B 7, with specific reference to the celestial objects, that everything consists of the simple body, or bodies, in which it is, or through which it moves (289a18–19), but places the simple body making up the celestial objects above both air (289a28–32) and fire (*Mete*. A 3, 340b6–10), how can there be friction between the air and the Sun if the Sun moves above the air?

It is very difficult to come up with a satisfactory answer. No direct clue as to a possible way around this problem is to be found in Aristotle's surviving works.[24]

The motion of the Sun might be assumed to cause waves in the surrounding medium, which are transmitted first to the fire right below the Sun and, via fire, to the air around the Earth. These waves cause the fire and the air to light up, and heat them up, too, by producing "internal" friction in them; the source of sunlight is primarily the overlying fire, as well as the fire in the air, and secondarily the air itself, being by nature hot, as fire is.[25]

No matter how it is transmitted to the air via fire, the mysterious frictional action of the fast-moving Sun on fire does not seem to cause this simple body (let alone air) to combust, not even in its outermost reaches, where it is purest and could be assumed to ignite directly underneath the Sun, thereby accounting for the intense brightness of this celestial object. Aristotle differentiates the appearance of the simple body fire undergoing combustion from that of the Sun, in *Mete*. A 3: he believes that the Sun looks white-hot, not fiery (341a35–36).[26]

In *Mete*. A 4 Aristotle explains that, when heated by the Sun, the Earth generates fire and water-vapor (341b6–22). The source of water-vapor is obvious, the simple body water within and upon the Earth. For Aristotle, ice is water with an excess of the cold (*GC* B 3, 330b25–29), so he may well assume, by a simple analogy, that water with a deficiency of the cold is water-vapor, which is buoyant

24 See Appendix 2.

25 See Appendix 3. Cf. also ch. 2, n. 3 and 65.

26 It should be noted that, although in *Cael*. B 7 Aristotle sets out to explain how light and heat are generated by the celestial objects (289a19–21), at the end of the chapter he seems to suggest that his aim was to account solely for the heat generated by the Sun (289a32–33), thus leading Alexander of Aphrodisias, *apud* Simp., *in Cael*. 442.4–12 (Heiberg), to the–by no means implausible–assumption that Aristotle's explanation of why all celestial objects are bright is in fact offered by the definition of light in *de An*. B 7, 418b3–17: light is the actualization of the potential "transparent", which is common to air, water, many solids and the celestial matter, by the presence in it of fire or the celestial matter (the latter is, of course, implicitly assumed to actualize "the transparent" only where it forms celestial objects, not around them). If so, Aristotle believes that the Sun and all the other celestial objects generate light directly. The fact that in *Mete*. A 3, 341a12–30, he mentions the simple body air to explain only the production of heat by the Sun seems to support Alexander's view. Here, too, however, Aristotle speaks of the air as being "set on fire" by fast motion, like the Sun's, which might suggest that the Sun produces heat and light indirectly, too, without having a fiery color.

in itself, and that this defect results from the action of air heated by the motion of the Sun. This air-mass is in contact with part of the Earth, and is thus able to heat cold water upon or within it, not to such an extent that water turns into air but sufficiently for it to evaporate, becoming lighter than it is as a liquid. Fire, moreover, is generated from earth, the simple body after which the Earth itself is named.

Aristotle does not explain how solarly heated air causes the simple body earth to yield fire. Within his physics, only one possible explanation presents itself. At play here must be the last of the three processes that can turn one, or two, Empedoclean simple bodies into another: the hot in air assimilates to itself the cold in earth, and the dry in earth assimilates to itself the wet in air, the result of the interaction being dry and hot fire. Fire is naturally more buoyant than water-vapor and air, so it predominates at higher altitudes, and near the outer boundary of its cosmic stratum is at last free of all admixtures (see below, 2.7).

As it shoots up towards its natural place, solarly produced fire will turn into water or air here, but assimilate these simple bodies to itself there; elsewhere, its interaction with water will produce earth (the cold in water will assimilate the hot in fire to itself and the dry in fire will assimilate the wet in air to itself, the result of the interaction being dry and cold earth). The motion of the Sun, through the heating of the adjacent strata of fire and air it somehow induces, powers the constant transmutation of the four Empedoclean simple bodies into one another, on scales much smaller than the cosmological scale, by perpetually seeding the stratum of air with the other three traditional simple bodies, which makes it possible for all four of them to interact with one another in all possible ways.

The intensity of this process is not uniform. The Sun's daily motion brings it below the horizon for part of the day, causing a diurnal cycle of increase and decrease in the amount of solar heating. Because of the annual motion, the amount of time the Sun spends above the horizon each day is not constant but varies throughout the year, superimposing on the diurnal cycle a longer undulation. Further undulations, of varying amplitudes, might be superimposed by the Moon, perhaps by the planets, too.[27]

1.3. THE FIRST SIMPLE BODY

1.3.1. The upper body

Those who are of the opinion that fire makes up the celestial objects, Aristotle observes in *Cael*. B 7, hold this view because they identify "the upper body", the kind of matter filling up the heavens, the celestial part of the cosmos, with the simple body fire, and think it logical that each being is constituted by the body or bod-

27 As already said, in *Cael*. B 3 Aristotle alludes to a possible role of the planets and the Moon as causes of the constant transmutation of the four traditional simple bodies into one another. The question which celestial objects, in Aristotle's view, heat the Earth and the surrounding air is addressed in Appendix 4.

ies in which it is situated, a general principle whose validity Aristotle himself accepts (289a16–19). Plato was among those according to whom fire fills up the heavens (for the most part), and is thus the (main) constituent of the celestial objects (*Ti*. 40a2–b8). For Aristotle, that the celestial objects consist of the body or bodies in which they are, and thus through which they move, entails that they consist of a simple body whose natural motion is circular, unlike the natural motion of fire, and the existence of which he has shown above (289a13–16). It is this fifth simple body, not one of the traditional simple bodies–not even fire, though it rises on top of the three other Empedoclean simple bodies–that in Aristotle's view is the upper body, the sole constituent of the celestial objects (for a different meaning of the expression "upper body" see Appendix 2).

1.3.2. The heavens

The heavens, the outermost realm of the cosmos which the upper body is assumed to pervade, are correspondingly called "the region of the cosmos where upper motions take place"–the motions of the celestial objects–"the upper regions" and "the upper place of the cosmos (see *Mete*. A 3, 339b17–18, 339b23 and 339b37; for another meaning of the expression "upper place" see Appendix 2).[28]

By way of contrast, Aristotle calls the rest of the cosmos, where the four traditional simple bodies are arranged in concentric spherical layers, "the region of the cosmos around the Earth" (*Mete*. A 2, 339a19–20). The celestial object nearest to the Earth is the Moon, so the lower boundary of the heavens is a sphere with the orbit the Moon follows each month as a great circle.[29] If we assume that the Moon is constituted out of the body in which it is, and thus through which it moves, a body occupying the heavens which is not identified with one of the four Empedoclean simple bodies, it is improbable that the Moon partially sticks into the sublunary realm of the cosmos, i.e. into the cosmic stratum of the simple body fire be-

28 Cf. *Oxford English Dictionary* (2nd ed. on CD-ROM, version 1.02) under "heaven": "The expanse in which the sun, moon and stars, are seen, which has the appearance of a vast vault or canopy overarching the earth, on the 'face' or surface of which the clouds seem to lie or float; the sky, the firmament. Since 17th. c. chiefly poetical in the sing., the plural being the ordinary form in prose" (1a); "The plural is sometimes used for the realms or regions of space in which the heavenly bodies move" (3b); "In the language of earlier cosmography: Each of the 'spheres' or spherical shells, lying above or outside of each other, into which astronomers and cosmographers formerly divided the realms of space around the earth…" (4). In *Cael*. A 9 Aristotle assumes that the heavens comprise only two spherical shells. With the Greek noun *ouranos* (which from now on will be left untranslated into English) he refers to the matter, or body, filling up each shell (it is not necessarily the same). A third sense of the Greek word as used by Aristotle picks out each of these two types of matter–or a single type differentiated according to the spherical shell it occupies–and all matter inside the sphere within the inner heavenly shell. See 2.2.3.

29 See *Mete*. A 3, 340b6–10, where the Moon is mentioned as separating the heavens from the region of the cosmos around the Earth. Hence the names "sublunary" and "superlunary" for the two main realms in Aristotle's cosmos. The orbit of the Moon around the Earth is assumed here to be very much like the apparent annual path of the Sun.

low, as it must do if its monthly circular orbit around the Earth marks off, in the above explained manner, the heavens from the sublunary part of the cosmos, and is traced by its center. The lower boundary of the heavens cannot be, strictly speaking, the sphere whose great circle is the orbit followed by the Moon each month. It is one inside it, with a smaller radius by at least a lunar radius.

The upper boundary of the heavens, now, is the sphere to which we are led to believe that the stars seen with the naked eye are fixed, an illusion forming the basis of Greek astronomy and still useful for the scientific treatment of many aspects of the sky. This illusion is due, first, to the Earth's diurnal rotation and, second, to the apparent immobility of the celestial objects at issue relative to one another for very long spans of time.

Generated naturally, the impression that the stars are luminous points of an enormous sphere, which is centered on the Earth and rotates once a day from east to west, the so-called celestial sphere, explains the customary description of these celestial objects as fixed.

1.3.3. Diurnal rotation and the concept of the celestial sphere

The Earth rotates on its axis from west to east. It does so against the backdrop of the very distant stars, and completes a rotation in a day. As a result, some stars are seen to rise in the east, move along parallel circles and finally set in the west. If the Earth had not been in the way, and the Sun had not swamped for part of the day the light of the stars, the latter would then be seen to describe complete circles in a day. An observer facing south in the Earth's northern hemisphere sees only a small part of the circles traced by the southernmost stars. The farther away a star is from the south, the greater the unseen arc of its circle. Northerly stars do not rise and set. Every day, they stay above the horizon for twenty-four hours, and the diameters of their parallel circles decrease progressively, the nearer the stars are to a point that does not share in the diurnal rotation. The straight line joining the centers of the parallel circles traced by all stars passes through this point, as can be easily determined with a very simple sighting instrument.[30]

For considerably long periods, a star is seen to always rise and set in the same places on the horizon, and to not change its position in the sky relative to other stars. This does change, of course, but very slowly, due to the motion of the stars in space. But such changes were unknown to the ancients, hence the traditional description of the stars as "fixed", and were first measured in 1718 by Edmund Halley.[31]

30 See Evans (1998) 33–34.

31 What Halley measured was not the actual motion of the stars Sirius, Aldebaran and Arcturus in space, but their so-called proper motion (a star's apparent angular motion across the sky relative to more distant stars, which is a projection onto the sky of the star's real motions in space relative to the Sun). The places on the horizon where a star is seen to rise and set change very slowly mainly due to a totally different phenomenon (the precession of the Earth's rotational axis about its orbital axis, on which see below n. 44).

Although the stars are not at equal distances from the Earth, they are so much removed from us that any sense of depth is lost. It seems to us that all stars, the most distant objects from us the naked eye can perceive, are equally distant from our planet.

Geocentricity is thus a naturally born notion, though we often tend to scoff at it when looking at ancient cosmologies with the anachronistic spectacles of the principle named after Copernicus that can be justly said to be one of the foundations of modern cosmology, and according to which there exists no privileged point in the universe, such as the one our senses inevitably endow our planet with occupying.[32] Anywhere in the universe, an observer will unavoidably get the impression of being located right in the middle of everything.

Now, relativity of motion allows us to explain easily the risings and settings of the stars, as well as the observed circularity of their parallel diurnal paths and all other related phenomena, even if we consider the Earth to be stationary, which is by no means an unreasonable point of view, given that we are unable to perceive directly our planet's diurnal rotation.[33]

We can very well assume that the stars are bright, point-like objects fixed to an enormous and transparent sphere, concentric with the comparatively insignificant globe of the Earth. If extended to infinity, the horizon of any Earth-based observer bisects it (the horizon is an imaginary plane to which the plumb line is perpendicular; the projection of the upper end of the plumb line marks a point on the celestial sphere called "zenith", whereas diametrically opposite to it is the point on the celestial sphere called "nadir"). This sphere is called "the celestial sphere", for obvious reasons.

A purely fictional object, the celestial sphere rotates once a day, opposite to the Earth's own rotation and about an axis which is nothing but a fictional extension of the Earth's own axis of rotation (that is, about the line on which the centers of the parallel circles described by the diurnal movement of the stars lie). The celestial sphere's counterparts to the Earth's equator and poles are thus appropriately conceived of as the celestial equator and poles respectively.

A great circle on the celestial sphere which passes through the celestial poles and the zenith of an observer at the Earth's midlatitudes cuts the horizon of the observer at the north and south points. The east and west points are found 90° measured clockwise from the north and south points respectively, at the intersections of the horizon and the celestial equator.[34] The altitude of the celestial pole visible from a place–its angular distance above the horizon–is equal to the latitude of this location.

32 For "the Copernican principle" see e.g. Rowan-Robinson (2004[4]) 63–64.

33 It was first demonstrated dynamically in 1851 by Léon Foucault, with the pendulum famously named after him. On Foucault's pendulum see e.g. Kaler (2002) 48–50.

34 For the markedly different appearance of the celestial sphere from different latitudes of the Earth see e.g. Evans (1998) 32–33, or the relevant sections in any introduction to spherical astronomy, such as Kaler (2002), a useful book designed with the needs of scholars in the humanities especially in mind.

This is how Claudius Ptolemy describes the genesis of the concept of the celestial sphere, when he introduces the elementary assumptions on which all of astronomy is founded (*Alm.* 10.4–11.13 [Heiberg]):[35]

> Τὰς μὲν οὖν πρώτας ἐννοίας περὶ τούτων ἀπὸ τοιαύτης τινὸς παρατηρήσεως τοῖς παλαιοῖς εὔλογον παραγεγονέναι· ἑώρων γὰρ τόν τε ἥλιον καὶ τὴν σελήνην καὶ τοὺς ἄλλους ἀστέρας φερομένους ἀπὸ ἀνατολῶν ἐπὶ δυσμὰς αἰεὶ κατὰ παραλλήλων κύκλων ἀλλήλοις καὶ ἀρχομένους μὲν ἀναφέρεσθαι κάτωθεν ἀπὸ τοῦ ταπεινοῦ καὶ ὥσπερ ἐξ αὐτῆς τῆς γῆς, μετεωριζομένους δὲ κατὰ μικρὸν εἰς ὕψος, ἔπειτα πάλιν κατὰ τὸ ἀνάλογον περιερχομένους τε καὶ ἐν ταπεινώσει γιγνομένους, ἕως ἂν τέλεον ὥσπερ ἐμπεσόντες εἰς τὴν γῆν ἀφανισθῶσιν, εἶτ' αὖ πάλιν χρόνον τινὰ μείναντας ἐν τῷ ἀφανισμῷ ὥσπερ ἀπ' ἄλλης ἀρχῆς ἀνατέλλοντάς τε καὶ δύνοντας, τοὺς δὲ χρόνους τούτους καὶ ἔτι τοὺς τῶν ἀνατολῶν καὶ δύσεων τόπους τεταγμένως τε καὶ ὁμοίως ὡς ἐπίπαν ἀνταποδιδομένους.
>
> μάλιστα δὲ αὐτοὺς ἦγεν εἰς τὴν σφαιρικὴν ἔννοιαν ἡ τῶν αἰεὶ φανερῶν ἀστέρων περιστροφὴ κυκλοτερὴς θεωρουμένη καὶ περὶ κέντρον ἓν καὶ τὸ αὐτὸ περιπολουμένη· πόλος γὰρ ἀναγκαίως ἐκεῖνο τὸ σημεῖον ἐγίνετο τῆς οὐρανίου σφαίρας τῶν μὲν μᾶλλον αὐτῷ πλησιαζόντων κατὰ μικροτέρων κύκλων ἑλισσομένων, τῶν δ' ἀπωτέρω πρὸς τὴν τῆς διαστάσεως ἀναλογίαν μείζονας κύκλους ἐν τῇ περιγραφῇ ποιούντων, ἕως ἂν ἡ ἀπόστασις καὶ μέχρι τῶν ἀφανιζομένων φθάσῃ, καὶ τούτων δὲ τὰ μὲν ἐγγὺς τῶν αἰεὶ φανερῶν ἄστρων ἑώρων ἐπ' ὀλίγον χρόνον ἐν τῷ ἀφανισμῷ μένοντα, τὰ δ' ἄπωθεν ἀναλόγως πάλιν ἐπὶ πλείονα· ὡς τὴν μὲν ἀρχὴν διὰ μόνα τὰ τοιαῦτα τὴν προειρημένην ἔννοιαν αὐτοὺς λαβεῖν, ἤδη δὲ κατὰ τὴν ἐφεξῆς θεωρίαν καὶ τὰ λοιπὰ τούτοις ἀκόλουθα κατανοῆσαι πάντων ἁπλῶς τῶν φαινομένων ταῖς ἑτεροδόξοις ἐννοίαις ἀντιμαρτυρούντων.

> It is a reasonable assumption that the ancients got their first notions on the matters under consideration from the following kind of observations. They saw that the Sun, the Moon and the other celestial objects were carried from east to west always along parallel circles, and that they began to rise up from below, as if from the Earth itself, gradually getting up high and then in a similar fashion turning and getting lower, until they were gone from sight as if they had fallen to the Earth, and that after they had stayed invisible for some time, they rose and set once again, these times, as well as the places of risings and settings, being fixed and, for the most part, the same.
>
> What chiefly led the ancients to the concept of the celestial sphere was the revolution of the ever visible stars, which was observed to be circular and to take place about a single center, the same [for all]. This point necessarily became [for the ancients] a pole of the celestial sphere. The stars that were closer to it revolved on smaller circles, while those farther away described ever larger circles in proportion to their distance, until the distance to the stars that became invisible was reached, of which those near the ever visible stars were observed by the ancients to stay invisible for a short time, while those farther away stayed invisible for longer, again proportionately [to their distance from the pole]. Originally, therefore, it was only this kind of observations that led the ancients to the aforementioned concept, but as their researches went on, they grasped that everything else was in accord with it, since all phenomena without exception contradict alternative notions.

The Sun, the Moon and the planets of our solar system, among which the Earth is obviously not counted here, participate in the diurnal rotation of the celestial

35 See also Gem., *Isag.* 12.1–4, and the introduction to Eucl., *Phaen.*, which is perhaps unauthentic. The work's attribution to Euclid has also been suspected. On its authenticity, as well as on that of its introduction, see Berggren & Thomas (2006) 8ff.

sphere, upon which their paths are projected. Unlike the stars, however, they do not move each along one single, perfect circle every day (see below, 1.3.5).

Ultimately responsible for Aristotle's belief in the sphericity of the cosmos is the relativity of motion manifested in the diurnal revolution of the stars, an apparent motion from which the concept of the celestial sphere ensues naturally.[36]

Compared with the size of the huge scales modern cosmology has accustomed us to ponder, Aristotle's cosmos is thus a decidedly puny affair, extending only up to those bright stars visible to the naked eye, all of which are in the same region of the Milky Way galaxy as our Sun.[37] A geometrically perfect sphere, whose center is coincident with the spherical Earth's, it hangs not in void, or emptiness, but in nothingness.[38]

1.3.4. Enter the first simple body

As is clear from *Mete*. A 6, 343b28–32, Aristotle knew that stars can be occulted by planets, just as the Sun can be eclipsed by the Moon, from whence it clearly follows that the Sun must be farther away from the Earth than the Moon. Moreover, since in *Cael*. B 12, 292a3–9, he mentions lunar occultations of planets, and knew that at least Mars, Jupiter and Saturn are for sure beyond the Sun (as follows from *Cael*. B 10), he had strong grounds for believing that the stars are the most distant contents of the cosmos from the Earth, whose center he took to be coincident with that of the cosmos, for, as said above, an observer located anywhere in the universe forms unavoidably the impression of being in the middle of it (for the relative distances of the celestial objects see 2.8.4).

Since in *Cael*. B 8 Aristotle argues that the stars do not trace their diurnal circles moving independently of the enveloping mass of the upper body, a spherical shell (see *Cael*. B 4), but as fixed parts of this diurnally rotating object, he considers the celestial sphere a physical surface, the boundary-surface of the cosmos, not a merely useful, albeit naturally generated, illusion.[39]

36 Arguing in *Cael*. B 4 from a physical basis for the sphericity of the *ouranos* in the last of the three senses of the term we saw above, in n. 28, Aristotle strongly emphasizes that the rotation of the universe, whence its sphericity follows, is both an observed fact and a fundamental hypothesis, and that its sphericity can also be proven (287a11–14). Questions such as the shape of the cosmos, as he explains in *Ph*. B 2, 193b22–32, can be tackled in two ways, either astronomically–this approach is adopted by Ptolemy, in the above translated passage from the *Almagest*–or physically, as Aristotle himself approaches the question of the shape of the universe in *Cael*. B 4. Some of the arguments Aristotle sets out in *Cael*. B 4 for the sphericity of the universe will be discussed below, in 2.3.

37 See e.g. Rowan-Robinson (2004^4) 1–3 and Kaler (2001) 3. Kaler's book is a very informative and readable introduction to the stars for the general reader.

38 Aristotle states his conclusion that there is nothing outside our cosmos, not even void, at the end of *Cael*. A 9, as a corollary of his extended argument demonstrating the impossibility of a plurality of worlds (279a11–18). For the spherical cosmos as embodying true geometric perfection see the passage translated at the end of ch. 3, and cf. Kouremenos (2003b) 472–476.

39 On whether *Cael*. B 8 concerns the stars only see Appendix 7.

Like all celestial objects, the stars are spherical (for the sphericity of the celestial objects see *Cael.* B 8, 290a7–9, and B 11). Whether they are distributed at exactly, or approximately, equal distances from the center of the cosmos Aristotle does not explain. No part of them can stick outside the cosmos.

The existence of the fifth simple body, which in *Cael.* B 7 is considered to be the filler of the heavens and the sole constituent of the celestial objects, is demonstrated in *Cael.* A 2. Its properties are derived in *Cael.* A 3. Aristotle calls it "the first simple body" (*Cael.* A 3, 270b2–3), for its circular natural motion is prior to the rectilinear natural motion of any Empedoclean simple body. The circle is prior to the straight line because the former is complete, whereas the latter is incomplete, and what is complete is naturally prior to what is incomplete: a straight line can be infinite–lacking beginning or end or both–or finite, in which case either of its "limiting points" can be produced, parts it hitherto lacked being thereby added to it (*Cael.* A 2, 269a18–23).[40]

Since in *Cael.* A 2 Aristotle contrasts the circular natural motion of the first simple body with the rectilinear natural motions of the four traditional simple bodies, he suggests to the careful reader that the point round which the first simple body performs its circular natural motion is tacitly, and neatly, assumed to be the same as that towards, or away from, which water and earth, or air and fire respectively, move naturally: the center of the cosmos, which is identical with the center of the Earth (268b17–269a9).

40 The straight lines Aristotle speaks of in *Cael.* A 2, 269a18–23, are undoubtedly geometric, not physical. He believes that the cosmos, being a rotating sphere, is finite, so in it there cannot be infinitely large objects, whose straight edges would have lacked beginning and end. Nor, consequently, can any of the finitely large, straight-edged objects existing in it at any given time keep on growing indefinitely, in which case an object's edges would have been indefinitely extendable. That the universe could not have been a rotating sphere had it been infinite is demonstrated in *Cael.* A 5, 271b26–272a7; further arguments to the same effect are adduced below, in 272b17–273a6. In "Euclidean" geometry, the only one Aristotle knew, straight lines are arbitrarily extendable, however. As finally crystallized at some time around the end of the fourth century BC, moreover, this geometry does admit infinite straight lines (see Euc., *Elementa* 1.12). Aristotle's justly famous discussion of infinity in *Ph.* Γ concerns physics, not mathematics, as he himself observes (see 5, 204a34–b4), nevertheless his characterization of infinity (6, 206a9–29) can be safely assumed to allow the arbitrary extendibility of geometric magnitudes, banishing from geometry only infinitely large magnitudes. Nothing in *Ph.* Γ is incompatible with the unqualified claim in *Cael.* A 2, 269a18–23 that geometric lines can be indefinitely extended (cf. *Cael.* B 4, 286b20, and *Ph.* Γ 4, 203b22–25). In *Ph.* Γ Aristotle emphasizes that continued addition cannot exceed any assigned limit, unless physical objects are infinitely large (6, 206b20–27). But he speaks having in mind only the partial sums of an infinite series of decreasing terms in constant ratio–imagined as parts of a material thing–and their convergence to a limit: that no such partial sum can be arbitrarily large but all are less than the limit–in a counterintuitive contrast to the continually diminishing terms of the corresponding infinite sequence, which can exceed any assigned limit–does by no means entail that geometric straight lines cannot be arbitrarily extended. Aristotle simply denies that an infinite number of parts, into which a material thing is potentially divisible by his lights, cannot but make the thing itself infinitely large, as his pupil Eudemus of Rhodes seems to suggest in a fragment of his *Physics* Simplicius has preserved (*in Ph.* 459.23–26 [Diels] = Eudem., fr. 62 Wehrli). For this assumption see Sorabji (1983) 334–335 (cf. Epicur. *Ep. ad Hdt.* 56–57, Lucr. 1.615–622).

Whether the circular motion at issue is the rotation of a disc, or of a number of concentric rings, of a spherical shell, or of many concentric spherical shells about axes passing through their center, which is the same as the Earth's, Aristotle does not bother to make clear. Near the end of *Cael.* A 2, he unmistakably hints that the simple body introduced here makes up celestial objects–"things that move circularly", in his own words, as well as continuously and everlastingly–whose motion he assumes to be the circular natural motion of their matter (269b2–13; translated in 2.2.1). Within the framework of the geocentric worldview, celestial objects are the only things that spring to one's mind as those that always execute circular motion round the center of the cosmos.

The Moon orbits the Earth, and appears to do so in a circle. The Sun appears to move circularly round the Earth, completing a trip in a year, whereas the Moon needs only about a month. In one day, the Sun is seen to describe another circle round the Earth, as is the Moon, a result of the Earth's diurnal rotation. For the same reason, in a day the stars appear to trace out parallel circles, whose centers lie on the same line–the axis of the enormous celestial sphere, whose bright points are the stars, and which spins diurnally from east to west, i.e. opposite to the direction of the Earth's actual rotation, whereas the Earth lays immobile at its center. As far as their apparent diurnal motion in a single day is concerned, the Sun and the Moon–actually their centers–can be treated as points on the celestial sphere. This holds equally true of the planets, whose apparent diurnal motion round the Earth in a day is thus circular. They, too, have another apparent motion round the Earth.

In many respects, this motion is similar to the apparent, non-diurnal motion of the Sun, or to the real, non-diurnal motion of the Moon, round the Earth. It differs from either, in that it deviates from circularity (this, as it will turn out, is not an insignificant complication). Compared, however, to the number of the planets, the number of the stars is immense, so circular motion round the Earth rules in the sky of the geocentric cosmos.

1.3.5. The non-diurnal motion of the Sun, the Moon and the planets

The Greeks certainly knew very early on that the place on the horizon where the Sun rises gradually shifts from a southeastern point, where the Sun rises at winter solstice, to a northeastern one, were the Sun rises at summer solstice.

Over the same period, the place of the Sun's setting on the horizon is also displaced from a point in the southwest, where the Sun sets at winter solstice, to another in the northwest, where the Sun sets at summer solstice (the Sun rises and sets exactly in the east and west only at equinoxes, midway between the northernmost and southernmost limits to the motion of its rising and setting place). The direction of motion then reverses.

The Greek word for solstice, *tropē* (see e.g. Hes., *Op*. 479 and 564), literally means "turning", and denotes the reversals in the direction in which the Sun's rising and setting places on the horizon are observed to move, one occurring at summer solstice, the other at winter solstice.

The English term “solstice”, from the Latin *solstitium*, refers to the apparent standing still of the Sun at the extreme northern and southern limits to the motion of its rising and setting points along the horizon, before it reverses direction. This motion is easily observed with the gnomon.[41]

It follows that the circular path of the Sun in the sky, unlike that of a star, is not the same every day. At equinoxes, it almost coincides with the celestial equator, which is bisected by the observer’s horizon–this is why at equinoxes the hours of daylight and darkness are equal. At solstices, it almost coincides with two small circles of the celestial sphere which are parallel to, and equidistant from, the celestial equator, one to the north, with its largest part above the horizon, and the other to the south, with its largest part below the horizon. These are the tropics–of Cancer, where the Sun is at summer solstice, when the time of daylight is the longest during the year, and of Capricorn, where the Sun is at winter solstice, when the time of daylight is at its annual minimum.

Between a solstice and an equinox, the successive diurnal paths of the Sun coincide very closely with parallel, small circles of the celestial sphere sandwiched between a tropic and the celestial equator; over the course of a year, the Sun’s path is a spiral, which is traced out twice in this period. Spirals are described by the Moon and the planets, too, a coil corresponding to a diurnal revolution. What Plato calls in *Lg*. 7 “wanderings” of the Sun, the Moon and the five planets–their following, as he proceeds to explain, not always a single path but many–is chiefly their tracing out spirals (822a4–8).[42] In our extremely few sources for the early history of Greek astronomy, the spirals of the planets, the Sun and the Moon are first mentioned by Plato, in his *Timaeus*, alongside the correct explanation of the phenomenon (39a5–b2).[43]

The cause of these spirals is the fact that the angular distances of all celestial objects at issue here from the celestial equator (their “declinations”) are not constant. They change continuously. This is so because the Sun, the Moon and the planets do not just follow the celestial sphere in its diurnal rotation, as if they–or their centers–were fixed in it. Simultaneously, they each execute a slower, eastward motion across the field of stars in paths inclined to the celestial equator (a continuous, much slower change in the declinations of the stars was first detected by the astronomer Hipparchus of Nicaea, in the second century BC, and is due to the precession of the Earth’s rotational axis about its orbital axis).[44]

41 On the gnomon see Evans (1998) 27–30 and 53–54. It is a rudimentary, and probably the oldest, astronomical instrument–the simplest sundial.

42 Not the retrogradations of the planets, for which see below, since neither the Sun nor the Moon exhibits this phenomenon.

43 We should not, however, follow Dicks (1970) 129 and Vlastos (1975) 54–55 in attributing to Plato the discovery of either the phenomenon itself or its explanation.

44 On precession see e.g. Evans (1998) 245–246 and Kaler (2002) ch. 5. The Earth precesses pretty much like a spinning top, whose non-vertical rotational axis wobbles slowly about the vertical passing through the point of contact of the axis with the floor because the gravity of the Earth tugs on the top. The Earth’s rotational axis is at an angle to the plane of its orbit round the Sun. It wobbles slowly about the perpendicular to this plane because gravitational forces, due mainly to the Sun and Moon, are exerted upon its equatorial bulge.

In the case of the Sun, this motion marks out on the celestial sphere a great circle forming with the celestial equator an angle which is equal to the angular distance of each tropic from the celestial equator. This angle is actually the angle between the axis about which the Earth rotates and the perpendicular to "the ecliptic plane", in which the Earth orbits the Sun in an eastward direction. Of course, to us it appears that it is the Sun that orbits the Earth from west to east along the ecliptic–which, regarded geocentrically, is just another great circle on the celestial sphere–completing a circuit in a year.[45]

By observing at regular intervals which stars appear in the west soon after sunset near the place on the horizon where the Sun has set, we are able to follow the path of the Sun over the course of a year among the stars of "the zodiacal constellations"; these constellations define on the celestial sphere a belt or band, which is called "the zodiac".

The ecliptic bisects the zodiac, and we can locate it quite accurately with the help of lunar eclipses. They occur when the Sun and the Moon are exactly on opposite sides of the ecliptic with the Earth in between, hence the name of this great circle on the celestial sphere.

The other planets of our solar system also orbit the Sun in an eastward direction. With the exception of Pluto–which at any rate from August 2006 is not officially categorized as a planet–they do so in planes inclined a few degrees to the ecliptic and passing through the broad belt of the zodiac, within whose boundaries the planets are always to be found. The Moon, too, orbits the Earth in a plane slightly inclined to the ecliptic, and in an eastward direction.[46]

Thus, to the Earth-based observer, the Moon and the five planets visible to the naked eye appear to move against the backdrop of the distant stars from west to east, traveling near the ecliptic. Each of these celestial objects needs a characteristically different time to complete a circuit with the exception of Venus and Mercury– like the Sun, they each need a year– and traces out a spiral wound about the celestial sphere, as its motion from west to east, in a path inclined to the celestial equator, combines with the much faster diurnal rotation, in which it participates.[47]

Clearly, the planets are naturally grouped together with the Sun and Moon by their traveling eastwards on, or very close to, the ecliptic–in general, within the zodiac. These seven celestial objects are thus characteristically distinguished from the stars in that they are seen to constantly shift positions, relative to both the stars and each other, because of their easterly motions. This is why the Greeks called them "wandering celestial objects", in contrast to the fixed ones, the stars, or simply "wanderers"–*planētes asteres*, or just *planētes*, from whence is derived the modern term "planet".

45 Since the Sun is much closer to the Earth than the celestial sphere, the geocentric ecliptic is actually a great circle on the celestial sphere which is coplanar with the circle of the Sun's apparent, annual motion round the Earth.

46 The facts that the orbits of all planets are almost coplanar and that all planets orbit the Sun in the same direction are signatures of our solar system's origin.

47 It follows that regular observations of the motion of the Moon and of the planets can also help define the position of the zodiac among the stars.

The planets, moreover, appear from the Earth to wander also in a manner totally peculiar to them. At regular intervals, their eastward motion is seen to be interrupted. A planet appears to be stationary in the sky, a phenomenon called “first station”, then begins to move again, though in the opposite direction, but after a while stops for a second time (“second station”), and, finally, when its motion resumes, the direction is once again to the east.

As result of this reversal in the direction of its zodiacal motion called “retrogradation”, the planet is seen to trace out a looping or zigzag path;[48] the shape of a retrograde path is not the same from one retrogradation to the next, a striking deviation from circularity in the path of the planet’s mainly eastward motion against the stellar backdrop.

Retrogradations are as spectacular as they are puzzling within a geocentric world model. The phenomenon is explained easily from a heliocentric point of view, however, given the differently sized orbits of the planets around the Sun, and their unequal orbital speeds.[49]

So far we have dealt with departures from circularity, which characterizes the apparent motion of the stars, in the apparent motions of the planets. These celestial objects, however, along with the Sun and Moon, differ from the stars in another prominent respect, too.

The stars trace out their apparent, diurnal paths in a regular manner, never slowing down or speeding up, for the rotation of the celestial sphere reflects the rotation of the Earth on its axis, which is uniform, whereas the zodiacal motions of the planets, the Sun and the Moon against the backdrop of the celestial sphere have variable speeds.

Since the Earth orbits the Sun not in a circle but in an ellipse, it moves along its orbit at a variable rate, and thus the Sun is seen by an Earth-based observer to move along the ecliptic at an inconstant rate. As a consequence, the lengths of the four seasons of the year are unequal.[50] The variable speed at which the Moon orbits the Earth, and at which it is observed from the Earth to move through the zodiacal constellations in a circle inclined to the ecliptic, is more pronounced, for the eccentricity of the Moon’s elliptical orbit is larger than the Earth’s, which also re-

48 Illustrations in Gregory (2000) 133, fig. 23, Yavetz (1998) 265–267, fig. 36, 38, 40.

49 See Kaler (2002) 304–306.

50 The seasons are the Sun’s traversing the four quadrants into which the ecliptic is divided by four points. Two of them are the diametrically opposite points at which the circles of the ecliptic and the celestial equator intersect. They are called “equinoxes”, just like the moments of the year at which the Sun is found there. The other two points, called “solstices”, are the positions of the Sun at the similarly named moments of the year, and are also diametrically opposite: they are the midpoints of the two semicircles into which the ecliptic is divided by the equinoxes. The equinoxes and solstices, conceived of as points, are thus placed symmetrically round the ecliptic, at 90° intervals. The seasons are the Sun’s moving along the ecliptic from spring equinox to summer solstice (spring), from summer solstice to autumnal equinox (summer), from autumnal equinox to winter solstice (autumn) and from winter solstice back to spring equinox (winter). The lengths of the seasons are the times it takes the Sun to move over each quadrant of the ecliptic. For the inequality of the lengths of the seasons, or simply the inequality of the seasons, see Evans (1998) 210–211.

sults in a considerable enlargement of the lunar angular diameter at perigee (the point on the orbit of the Moon closest to the Earth).[51]

Variable are also the speeds at which the five planets appear from the Earth to move eastwards across the sky, again the consequence of orbital eccentricities, due to which are also variations in the brightness of the planets, especially prominent for Mars (in the case of Venus, as in Mercury's, such variations result partly from the planet's phases), as well as the non-uniform distribution of retrogradations around the zodiac.[52]

1.3.6. The first simple body and the four traditional simple bodies

Nothing in *Cael.* A 2 suggests that the first simple body not only is the constituent matter of celestial objects but also fills the heavens. Perhaps Aristotle expects his readers to infer this from the principle that all beings are made up of the same kind(s) of body in which they are, and through which they move.

At the end of *Cael.* A 2 he says that the first simple body is separated from all simple bodies around us here near the center of the cosmos (269b13–15), thereby making it clear that no trace of the first simple body is found where the four traditional simple bodies are. He also adds that the nature of the first simple body is higher than the nature of any Empedoclean simple body, in proportion as the first simple body is farther away from the center of the cosmos than any of the traditional simple bodies (269b15–17).

This remark might be meant to explain why the first simple body does not mix with the four other simple bodies–they are thus always confined below it.

Given the priority of the first simple body's natural motion over the natural motions of the four Empedoclean simple bodies, whence it follows that the nature of the first simple body is higher than that of any traditional simple body, one is justified in thinking of the first simple body as being both spatially and axiologically separated from the other simple bodies existing in the cosmos (see also Appendix 2).[53]

Another reason why the first simple body is not present in the realm of the cosmos where the four traditional simple bodies are always confined is that its presence there would have been otiose, for it does not decay into any of the four Empedoclean simple bodies, nor is it generated from any of them. One easily infers that this is so because the first simple body, unlike each traditional simple body, does not arise from a member of one of the two pairs of basic contrary quali-

51 For a striking photographic illustration of the large variation in the Moon's apparent diameter at perigee and at apogee see Kaler (2002) 246.

52 For the variations in the brightness of the planets due to their orbital eccentricities and phases see Kaler (2002) 306–308. For the non-uniform distribution of planetary retrogradations around the zodiac see Evans (1998) 340, *Zodiacal Inequality*, with fig. 7.24; the epicyclic model of planetary motion (which is post-Aristotelian) is presupposed.

53 Against the view that the first simple body originally served as celestial matter and substance of man's rational soul see Moraux (1963) 1213–1226, Hahm (1982) 66–67. The presence of the first simple body in compound bodies is assumed by Reeve (2002) 47–48.

ties, cold-hot and wet-dry, being combined with a member of the other pair.[54] If the first simple body cannot turn into any other simple body and vice versa, however, it cannot also react with the other simple bodies to form compound bodies, so what could possibly be the purpose of its presence below the heavens? As Aristotle remarks in *Cael.* A 4, divine nature makes nothing purposeless (271a33).

In *Cael.* A 3 he argues that no process in nature can yield the first simple body out of another simple body, or, conversely, another simple body out of the first simple body. The first simple body is, in other words, exempt from substantial change. If so, the first simple body, unlike the four traditional simple bodies, neither increases nor decreases locally at any given time; it does not suffer local mass-losses that would have been counterbalanced by local mass-gains occurring elsewhere in the part of the cosmos it fills up, in order for the total amount of it existing in the cosmos to be always the same (see above, 1.2.4).

Whence it follows that the first simple body cannot but also be free of all change in the degrees in which it possesses whatever other properties it might have beside mass, given that, all the time, the other four simple bodies turn locally into one another, and also suffer, again locally, variations in the degrees in which they each possess their properties other than mass, just as all of their living compounds do, which invariably undergo growth and diminution.[55]

The first step in this argument rests on the assumption that any two of the four traditional simple bodies can turn into each other, for they have contrary qualities as their constituents, each of which is in potentiality, and thus can become in actuality, the other.[56] By Aristotle's lights, this qualitative contrariety is reflected in the rectilinear natural motions of the two simple bodies, for they have contrary directions.[57] The natural motion of the first simple body is circular, however, and is not paired with a motion whose direction is contrary.

Nature has, therefore, exempted the first simple body from qualitative contrariety with the four Empedoclean simple bodies, thus from substantial change as well. Reasoning as explained above, Aristotle then concludes that the first simple body does not suffer local gain and loss in mass, too, and is also free of all variation in the degrees in which it possesses whatever other properties might belong to it (*Cael.* A 3, 270a12–35).

54 It is thus unclear how the first simple body can be perceptible; see Appendix 5.

55 The text does not mention "change in degree" but only "change of properties". In the case of the four traditional simple bodies, however, a change of properties results in substantial change, so it seems that, as regards the simple bodies, when Aristotle talks about their suffering "changes of properties" in this context, after he has shown that the first simple body does not participate in substantial change, unlike the four traditional simple bodies, he actually means "changes in the degrees in which properties are possessed". That the hot and cold come in degrees is stated in *GC* B 7, 334b7 (the same must also apply to the other two tangible qualities, the wet and the dry); cf. B 3, 330b25–28. Which properties the first simple body can have beside corporeality, on which see Appendix 5, is totally unclear. It is remarkable that Aristotle does not argue against the alterability of the first simple body from the already established fact that that this simple body lacks tangible qualities; cf. Wildberg (1988) 87.

56 The contrary qualities are not explicitly mentioned; see Appendix 6.

57 Cf. *GC* B 3, 330b30–331a3, B 4, 331a14–20; see, moreover, *Cael.* Δ 4, 311a16–29, for earth and water, air and fire (the objection in Wildberg [1988] 86 carries no force).

The crucial thesis that no motion is contrary to circular motion is established in *Cael.* A 4.[58] That the first simple body is ungenerated, indestructible and absolutely unchangeable helps Aristotle establish that its circular natural motion does not speed up and slow down–it is totally uniform (see *Cael.* B 6, 288a27–b7).

1.3.7. The eternity of the first simple body's natural motion

As already said (1.3.4), in *Cael.* A 2 Aristotle implicitly assumes that the perpetual circular motions in the heavens are due to the natural motion of the first simple body, which is circular. Nowhere in this chapter, however, does he argue for the eternity of the first simple body's natural motion. He assumes it to be easily derivable from the basic fact that the natural motion of the first simple body is circular.

Any amount of the first simple body moves spontaneously in a circle, just as a rock falls spontaneously. The path of a falling rock is a straight line-segment joining the center of the Earth, near which the rock will be at rest, and another point, at a finite distance, from which the rock started falling. Motion on such a path cannot be eternal. You can move in a circle forever without reaching any boundary, however, for in a circle there is no endpoint to serve as the terminus of your motion.[59]

The circular motion of the first simple body, being natural like the rectilinear motion of a falling rock, is completely effortless and tireless, unlike that of a living thing. It would stop only if a terminus intrinsic to the circle itself, which formed a physical barrier, were reached. However, given the absence of such a terminus on a circle, it is impossible for the natural motion of the first simple body to ever come to a stop, and since a circle also lacks a point, which is defined intrinsically on it and from which the natural motion of the first simple body might have started, this motion is eternal.[60]

1.3.8. The first simple body and the stars, the planets, the Sun and the Moon

Aristotle shows that the stars do not trace their parallel diurnal circles moving independently of the surrounding mass of the first simple body, which fills up their realm, but as parts of this mass, which forms a spherical shell centered on the Earth: this shell rotates uniformly once a day from east to west, about an axis perpendicular to an equator on the same plane as the Earth's which passes through the poles and center of the Earth (see above, 1.3.4). The diurnal rotation of this shell is the natural motion of the first simple body, and the stars are said to be fixed, or embedded, immovably in their "deferent" shell in the sense that their positions

58 See below, 3.5.

59 A circle can thus be conceived of as infinite: see *Ph.* Γ 6, 206b33–207a10.

60 Cf. *Ph.* Θ 9, 265a27–b8, and Graham (1999) 160–161 *ad loc*. The reason why the natural motion of the first simple body is eternal is hinted at in *Cael.* B 1: this motion is such, i.e. circular, that it has no end (284a3–6). It is explicitly stated in *Cael.* B 6, 288a22–25, in another argument for the uniformity of the first simple body's natural motion.

relative to the shell's other parts are fixed–they move naturally as much as any other part of the first simple body.[61]

The planets, however, cannot be assumed to be fixed in this shell, a physical analogue for the celestial sphere, nor can the Sun and the Moon, participation in the diurnal rotation being not their sole motion.

From the Earth the Sun appears to orbit it once every year, just as the Moon orbits the Earth once a month (see 1.3.5). The annual motion of the Sun takes place in a plane slanted to the celestial equator, and its direction is from west to east. The Moon's monthly orbit lies in a plane slightly inclined to the annual orbit of the Sun, and the direction of its motion in this orbit is also from west to east.

All planets appear from the Earth to execute round it a motion which is similar to the Sun's annual and the Moon's monthly motion in that it has an easterly direction but only in general, for often each planet, if we disregard its participating in the diurnal motion and consider only its second motion under discussion now, is seen to stand still, resume moving but in reverse, stand still for a second time, and then start moving again in its principal eastward direction.

The planets execute this interrupted motion keeping always quite close to the circular path of the Sun's annual motion, crossing it to pass above or below, just as the Moon also does in its monthly course round the Earth. Their own paths, however, deviate markedly from circularity (see above, 1.3.5), due to the episodes of directional reversal. Each planet appears to complete a trip round the Earth not in the same time, with two exceptions, Venus and Mercury (each needs a year). The interval between two successive directional reversals is different for each planet.

The non-diurnal motion of the planets, the Sun and the Moon does not have uniform speed. Because of the combination of the westward diurnal motion with a slower and–always or mainly–opposite motion in planes that are slanted to the equator of the celestial sphere, the planets, the Sun and the Moon are each seen to trace out in a day a circular loop of a spiral wound around this starry sphere, background against which the peculiar motions of the wanderers are projected.

1.4. EUDOXUS' THEORY OF HOMOCENTRIC SPHERES AND ARISTOTLE'S *METAPH.* Λ 8

1.4.1. A brief outline

In light of *Metaph.* Λ 8, scholars assume that, in order to handle the zodiacal motion, Aristotle considered the heavens not a single spherical shell of the first simple body but an onion-like structure made up of a number of concentric shells of this simple body, with no vacuum between two consecutive shells.[62]

61 It is not the case that the stars are carried round as if they were a dead weight. That they revolve diurnally as fixed parts of the rotating mass of the first simple body surrounding them is shown in *Cael.* B 8 (cf. Appendix 7). For this mass forming a spherical shell see the arguments Aristotle offers in *Cael.* B 4, some of which are discussed below, in 2.3.

62 See e.g. Bodnár & Pellegrin (2006) 271, Broadie (2009) 231; cf. Heglmeier (1996) 51.

This view of the heavens was based on an insight of Aristotle's older contemporary Eudoxus of Cnidus, a mathematician and astronomer.[63]

A point of the innermost of four homocentric spheres, all of which rotate about different axes simultaneously, can be made to revolve round the center of the system in a way broadly similar to that in which a planet is seen to move round the Earth: that is, with a fast motion, like the diurnal rotation, and with a slower, opposite motion charted against the backdrop of the system's outermost sphere, an abstract stand-in for the star-spangled celestial sphere, and at times reversing direction.

This results from the rotation of each sphere being superadded to that of the next lower sphere in the system. To achieve the trick, parameters such as rotational axes, directions and periods must be chosen appropriately.

What matters here is that Aristotle is thought to have turned seven Eudoxean systems of homocentric spheres, five for the planets, one for the Sun and one for the Moon, each of which needed not four but three homocentric spheres, into as many systems of homocentric spherical shells of the first simple body, plugged into one another in the order he deemed correct. The celestial object itself is assumed to be immovably embedded within the mass of the innermost shell in its system, its motion being due to the rotation of this shell as modified by the rotations of the outer component parts of the system.[64]

Aristotle is credited with the addition of a number of extra spherical shells between two successive systems, also made up of the first simple body, in order to allow the outermost shell in the lower system to spin uninfluenced by the innermost shell in the upper system, and to follow the diurnal rotation of the outermost shell in the Saturnian system, Saturn being the planet which is farthest out from the Earth (see Appendix 8). This shell shares its rotational period and direction with its counterparts in the six inner systems of shells, producing each the motions of Jupiter, Mars etc. None of its six inferior counterparts, however, need be assumed to carry "copies" of the stars.

According to Simplicius, Theophrastus called *anastrous*, "lacking celestial objects", all spheres except the centermost in a Eudoxean deferent system of a wanderer (*in Cael.* 493.11–20 [Heiberg] = Thphr., fr. 165B FHSG).

63 On the dates of Eudoxus see Zhmud (1998) 227–228.

64 Aristotle does not tell us how Eudoxus ordered the Moon, the Sun and the five planets. He remarks only that Callippus of Cyzicus, who "succeeded" Eudoxus and introduced a few modifications to the original theory of homocentric spheres in an attempt to make it "yield the phenomena", adopted the same ordering of the spheres as his predecessor–that is, he adopted the Eudoxean ordering of the seven wanderers (*Metaph.* Λ 8, 1073b32–33). Aristotle's comment might be understood as a hint that the Eudoxean ordering had not been universally accepted. We can assume that he followed the order adopted by Plato in *R.* 10, 616e4–617b5; it is also attested in the brief work *de Mundo* (2, 392a23–29) that has come down to us as part of the *Corpus Aristotelicum*. If so, the system of homocentric spheres for the Moon is inserted inside the system for the Sun. The system for the Sun is next inserted inside the system for Venus, which is plugged into the system for Mercury. The system for Mercury is plugged into the Martian system, that into the Jovian and the Jovian into the Saturnian. Later arrangements place the Sun after Venus and Mercury, and also exchange the places of these two planets.

1.4.2. A closer view

The theory of homocentric spheres seems to have aimed at geometrically reproducing certain aspects of lunar, solar and planetary motion. (On the origins of the theory see below, 3.1.) Eudoxus assumed that the Moon, the Sun and the planets are each immovably affixed to its own sphere–in other words, that these seven celestial objects are just points of seven spheres, each of these seven spheres being the innermost one of a system of nested spheres. He posited four spheres for each of the five planets, three for the Sun and also three for the Moon. All spheres in a system are centered on the same point standing for the Earth, and are also assumed to simultaneously rotate uniformly on different axes, though not necessarily all in the same direction and with the same period.

As already said, each sphere transmits its motion to the next one, so only the outermost sphere in a system rotates without being influenced by the rotation of any of the rest; also, in all seven systems, the outermost sphere has the same direction and period of rotation. The stars are assumed to be affixed to it.

Since there can be only one sphere of the fixed stars, one cannot avoid forming the impression that Eudoxus treated of seven highly idealized models of the cosmos, each being just the celestial sphere with the Earth at the center and with only one non-stellar celestial object inside (we have no evidence to assume that Eudoxus was interested in turning his theory of homocentric spheres into a physical system); from the Earth, this object appears to perform not a simple revolution but a complicated motion under the influence of the combined rotations of all encasing spheres.

A sphere is denoted by S_i in the following outline of the theory. The index shows the order of the sphere in the system to which it belongs counting from the outside.

In the lunar model, the equator of S_2 stands for the ecliptic. The angle between the equators of S_1 and S_2 is set equal to the angle between the ecliptic and the celestial equator (the obliquity of the ecliptic). The angle, now, between the equators of S_2 and S_3 is set equal to the maximum observed latitudinal deviation of the Moon from the ecliptic.[65] The Moon is affixed to the equator of S_3. According to Simplicius, S_3 spins slowly westwards, whereas S_2 rotates faster in the opposite direction (*in Cael.* 494.23–495.16 [Heiberg]).

Until recently, it was thought that, *pace* Simplicius, it must be S_3 that rotates eastwards, completing a rotation in about a month, the time the Moon needs to traverse the background of the zodiacal constellations, and S_2 that spins oppositely with a leisurely period of approximately 18.6 years, thus carrying westwards the points called "nodes", where the Moon crosses over the ecliptic in its monthly journey around the Earth–otherwise, the Moon would not spend time both above and below the ecliptic in the same month, as is observed.[66] The combined rotations of S_3 and S_2 resulted in the interval between every other return of the Moon to the

65 About 5°. For an introduction to the orbit of the Moon see Kaler (2002) 244–251.

66 See Heath (1981) 197 and Evans (1998) 307–308. For the possible origin of this mistaken view see Mendell (1998) 190 n. 14.

plane of the ecliptic, the nodical or draconitic month, being shorter than the rotational period of S_3.[67]

It is now clear that there is no real problem with the original assignation of rotational directions to the Moon's S_3 and S_2 by Simplicius.[68] Neither it nor the alternative, though, seems to be fully compatible with all of the crucial details the commentator further provides.[69] S_1, finally, accounts for the participation of the Moon in the diurnal rotation.

The Sun, too, is a point on the equator of S_3. In the Sun's model, moreover, as in the Moon's, the ecliptic is not the equator of S_3 but of S_2. Here, too, the axes on which S_3 and S_2 spin form an angle. But it is tiny (the Sun's deviation from the ecliptic is a fiction).[70] According to Simplicius, S_3 rotates eastwards at a very slow pace. It was included because at summer and winter solstice the Sun does not always rise at the same points on the horizon. S_2 spins eastwards at a much faster pace (*in Cael.* 493.11–494.22 [Heiberg]).

Conceivably, the lengths of the rotational periods of S_2 and S_3 were appropriately chosen by Eudoxus, so that the combined rotations of the two spheres resulted in the time, which the Sun took to traverse a circle almost coincident with the ecliptic, being longer than 365 days by a fraction of a day.[71]

As with the Moon, it is usually assumed in the relevant literature that, *pace* Simplicius, it must be S_2 that rotates eastwards at a very slow rate, whereas S_3 spins much faster in the same direction, for otherwise the Sun would stay for a very long time above and below the ecliptic, describing each year a small circle parallel to this great circle of the celestial sphere.[72] Perhaps this problem would not be serious, the angle between the rotational axes of S_2 and S_3 having been assumed exceedingly small.[73] It does not really exist if S_3 is assumed to spin westwards, as in the Moon's case.[74] S_1 accounts for the participation of the Sun in the diurnal rotation, which is its function in the models of the Moon and the planets, too.

S_2's equator stands for the ecliptic in the models of planets, too. Its period is equal to the tropical period of the planet, the time the planet needs to go all the way around the zodiac.[75] S_2 rotates from west to east. The celestial object itself is

67 For the various "months", i.e. the different periods associated with the Moon's complicated motion, see Kaler (2002) 233–234 and 250.

68 See Mendell (1998) 193–194.

69 See Yavetz (2003) 327–328.

70 On its possible origin see Neugebauer (1975) 629–630. Cf. Mendell (2000) 98.

71 See Mendell (2000) 95–100.

72 See e.g. Heath (1981) 198–200 and Evans (1998) 308; cf. Linton (2004) 28 n. 7.

73 For ancient values of this angle see e.g. Heath (1981) 198–200 and Evans (1998) 308.

74 See Mendell (1998) 191–193, where it is mistakenly assumed that the Sun's S_3 is said by Simplicius to rotate westwards, and that scholarly accounts interchange not only the rotational speeds reported by the commentator for S_2 and S_3 in the deferent system of the Sun but also the directions in which these spheres spin. As is recognized in Mendell (2000) 97 n. 54, however, Simplicius leaves no doubt that the Sun's S_2 and S_3 spin in the same direction, from west to east. Nevertheless, there seems to be nothing intrinsically wrong with the alternative hypothesis that the Sun's S_3, like the Moon's, spins slowly westwards.

75 For the periods of the planets, the tropical and the synodic (the latter's role in the theory of homocentric spheres will be explained below), see Evans (1998) 295.

fixed on the innermost sphere S_4. This sphere spins about an axis fixed on S_3. In its turn, S_3's own axis of rotation is fixed on the equator of S_2.

Now, S_3 and S_4 spin oppositely, but with the same period. Due to the combined rotations of these two spheres, the celestial object traces a closed curve, which is moved eastwards by the rotation of S_2. If this curve's long axis of symmetry coincides with the ecliptic, or if only the center of this axis lies on the ecliptic, depending on the reconstruction of the theory as will be explained next, then the combined rotations of all three spheres cause the planet to trace above and below the ecliptic a more complicated curve, whereupon its motion is mainly to the east but reverses occasionally, and then resumes the principal direction.

The common rotational period of S_3 and S_4 is the synodic period of the planet, the time between two successive retrogradations.

According to what can be justly called the traditional reconstruction of the theory, which is due to Schiaparelli, the planet is set on the equator of the innermost sphere S_4.[76] The curve it traces due to the combined opposite rotations of S_3 and S_4 is 8-shaped, and is known as hippopede, "horse fetter".[77] The angle at which this retrogradation generator intersects itself is equal to the inclination between the rotational axes of S_3 and S_4.

An alternative reconstruction, due to Yavetz, sets the planet on a circle of latitude near one of S_4's poles.[78] On this reconstruction, the combined rotations of S_3 and S_4 make the planet trace an unremarkable elongated loop; unlike the hippopede, it does not intersect itself.[79] On the traditional reconstruction, the shape of the retrogradation generator depends solely on the angle between the rotational axes of S_3 and S_4. On the alternative reconstruction, it is also determined by the latitude of the planet on S_4.[80]

On Yavetz's reconstruction, moreover, the retrogradation generator's long axis of symmetry coincides with the ecliptic only if there is zero inclination between the plane of the ecliptic and that on which the axis of S_4 is set before the whole system begins to move. If this inclination is not zero, then the retrogradation generator's long axis of symmetry coincides with another great circle on S_2, but its center remains on the ecliptic, and the planet's path is still traced above and below this great circle on S_2.[81]

On the traditional reconstruction, however, the center of the hippopede's long axis of symmetry is displaced away from the ecliptic along with the rest of the axis if the angle at issue is not 90°. The hippopede's long axis of symmetry, in other words, will lie on the equator of S_2, with the planet threading its way below and

76 Schiaparelli (1875). The Italian astronomer is probably best known for his famous "discovery" of *canali* on Mars; see e.g. Lang (2003) 237–241.

77 For the hippopede see e.g. Neugebauer (1953), Riddell (1979) and, especially, the detailed treatment in Mendell (1998). On iconography of horse fetters cf. Mendell (2000) 74 n. 21.

78 Yavetz (1998) 225–237.

79 In the alternative reconstruction, too, there is a role for the hippopede, not recognized in Yavetz (1998); but see Yavetz (2001) 70–75.

80 Yavetz (1998) 226, with fig. 6 and 7 in 228. In each reconstruction, the path traced by the planet during retrogradation is markedly different.

81 Yavetz (1998) 227–229, with fig. 8 and 9.

above the ecliptic, only if it this angle measures 90°; otherwise, the entire trace of the planet will shift inappropriately to one side of the ecliptic only.[82]

1.4.3. "Failings" of the theory of homocentric spheres

Irrespective of how it is reconstructed, the theory of homocentric spheres has no predictive power, and there is no evidence that coming up with even approximately accurate predictive models of celestial motions could have been a goal of Greek astronomers in the time of Aristotle and Eudoxus.[83]

With his theory, the Cnidian astronomer seems to have solely aimed at giving an idea of how some very broad aspects of the apparent motions of the Moon, the Sun and the planets can be reproduced geometrically if all celestial motion is assumed to be undeviatingly circular and totally uniform, like the diurnal revolution of the stars. He failed, or simply was not concerned, to account for some prominent phenomena known in his time, namely the inconstant speed of zodiacal motion, whether of the Sun, the Moon or a planet, and the changes in the Moon's apparent diameter or in the brightness of the planets. His successors seem to have attempted to improve on his efforts.[84]

From Aristotle's testimony in *Metaph.* Λ 8, 1073b32–38, we know that a pair of spheres were added to the Eudoxean model of the Sun and another to the Moon's by the astronomer Callippus of Cyzicus, with whom Aristotle was personally acquainted (Simp., *in Cael.* 492.31–493.11 [Heiberg]). Why Callippus added these extra spheres Aristotle does not clarify. Simplicius, who relies on the testimony of Eudemus, says that the motivation in the case of the Sun was to account for the inequality of the seasons–a phenomenon discovered in the fifth century by the astronomers Euctemon and Meton–in other words, to render the zodiacal motion of the Sun variable (*in Cael.* 497.15–24 [Heiberg]).[85]

82 Yavetz (1998) 229–230. That the hippopede, or Yavetz' curve, had any role in the Eudoxean theory of the planets is denied by Bowen (2000b) 163–166; cf. n. 88 and 91 below.

83 "The predictive turn" of Greek astronomy seems to have occurred in the time of Hipparchus of Nicaea (second century BC), most probably under the influence of Babylonian astronomy. See Evans (1998) 212–215 on the early history of solar theory. On Hipparchus and Babylonian astronomy see Toomer (1988). More general discussion in Jones (1996).

84 It is quite likely, moreover, that the theory of homocentric spheres began to be investigated in a purely geometric context. See Riddell (1979) for an intriguing study of the theory's relevance to the problem of duplicating a cube, whose solution by Archytas of Tarentum, reportedly the teacher of Eudoxus (cf. D.L. 8.86), requires an ingenious kinematic construction of curves, exactly as does the theory of homocentric spheres. Riddell showed that Eudoxus could have provided a solution to the problem of doubling a cube via a quite simple modification to the deferent system for a planet in the theory of homocentric spheres, as Schiaparelli reconstructed it (see also Knorr [1993] 50–61). Eudoxus, though, could very well have started from geometry, and then gone on to astronomy.

85 As is clear from *in Cael.* 488.18–24 (Heiberg), Simplicius' discussion of the theory of homocentric spheres in his comments on *Cael.* B 12 is based on the second book of Eudemus' *History of Astronomy*, for the general content and organization of which see Bowen (2002a), and on a later, also lost, work *On the Unwinding Spheres* by Sosigenes (second century AD), a

Similar motivation can be plausibly assumed in the case of the Moon.[86] Later on, sometime in the third century BC, Autolycus of Pitane might have attempted to further modify the theory of homocentric spheres so as to make it yield a change in the Moon's angular size and the brightness of the planets; his effort was unsuccessful.[87]

As reconstructed by Schiaparelli, moreover, the theory of homocentric spheres fails to give retrogradations of the planets with shapes that are even remotely similar to the ones that have already been observed in the sky, but, as reconstructed by Yavetz, it can postdict the shape of retrograde paths with surprising accuracy, provided that certain parameters are chosen appropriately and that one more sphere is added each to the Eudoxean models of Mars, Venus and Mercury, a further modification Callippus introduced into the original version of the theory, according to Aristotle's testimony in *Metaph.* Λ 8, 1073b32–38.[88]

The retrograde path obtained from a planet's model, no matter whether the theory is reconstructed according to Schiaparelli or Yavetz, can be plotted pointwise on a plane with straightedge and compass, enhancing the probability that the theory of homocentric spheres arose from within geometry.[89]

teacher of Alexander of Aphrodisias (cf. n. 90 below). For Sosigenes and his lost treatise *On the Unwinding Spheres* see Moraux (1984) 335ff. It is often suggested that Simplicius knew Eudemus only via intermediaries such as Sosigenes (see e.g. Bowen [2002a] 317–318, Mendell [2000] 88–89). However, there seem to be cogent reasons to think that Simplicius had direct access to Eudemus' works; see Zhmud (1998) 218 n. 23.

86 See Mendell (1998) 256.

87 Simp., *in Cael.* 504.22–505.11 (Heiberg); on what Simplicius says here about Venus see Bowen (2002b) 161. For the dates of Autolycus see Mendell (2000) 126 n. 98. What Autolycus actually did is unknown; Mendell (2000) 128 suggests that he might have attempted to remedy the situation not geometrically but via some physical assumptions.

88 Yavetz (1998) 243ff. (for Callippus see 257ff.; cf. Heglmeier [1996] 62–68). Operating within the reconstruction of the theory which is due to Schiaparelli, Mendell (1998) 216–217 thinks it very likely that Eudoxus thought of retrograde motion "qualitatively as a phenomenon requiring explanation". This point can be used as an argument in favor of the traditional reconstruction of the theory; but see Yavetz (1998) 246ff. Goldstein (1997) 4 doubts the importance of retrogradations in fourth-century-BC Greek astronomy. His skepticism is supported strongly by Bowen (2001) 812–817/821–822 and (2002b) 157–158; see, however, the valid objections in Mendell (1998) 264 n. 5. Representing retrogradations need not have been the motivation for the introduction of the hippopede–at least not in the case of all planets. This is one possibility, alongside the representation of the distance from the Sun of Mercury and Venus, the two interior planets, and of the invisibility periods of all planets; see the conclusions in Mendell (1998) 228–229 (cf. 255–256 on Callippus). Mendell's study of the mathematics of the hippopede shows that the theory of homocentric spheres, as traditionally reconstructed, can represent to some degree a number of planetary phenomena, none of which, though, can be selected as the theory's empirical foundation in light of this mathematics alone. This can be an artefact of the dearth of historical evidence at our disposal concerning the theory; alternatively, it might show the fertility of Eudoxus' brainchild, provided that Aristotle and Simplicius, on whose testimony our reconstructions of it rest, are mainly correct (cf. below, n. 91).

89 The pointwise construction is presented in Yavetz (2001) 77ff. For the possible importance of pointwise construction of curves in the time of Eudoxus cf. the interesting attempt at recovering Menaechmus' solution to the problem of doubling a cube in Knorr (1993) 61–66. The emphasis on the possible emergence of the theory of homocentric spheres within a geometric

Neither of the two reconstructions can mimic the variation in the shape of the retrograde path from one retrogradation to the next. Nor do they fare any better with the uneven bunching of retrogradations around the zodiac, for neither of them yields variable speed of zodiacal motion.

The problem is hinted at by Simp., *in Cael.* 32.16–22 (Heiberg):

> Οἱ γὰρ περὶ Εὔδοξον καὶ Κάλλιππον καὶ μέχρι τοῦ Ἀριστοτέλους τὰς ἀνελιττούσας σφαίρας ὑποθέμενοι ὁμοκέντρους τῷ παντὶ δι' ἐκείνων ἐπειρῶντο σώζειν τὰ φαινόμενα περὶ μὲν τὸ τοῦ παντὸς κέντρον πάσας λέγοντες κινεῖσθαι τὰς σφαίρας, τῶν δὲ ἀπογείων καὶ περιγείων καὶ τῶν δοκούντων προποδισμῶν καὶ ὑποποδισμῶν καὶ τῶν ἐν ταῖς κινήσεσι φαινομένων ἀνωμαλιῶν τὰς αἰτίας οὐκ ἰσχύοντες κατ' ἐκείνας τὰς ὑποθέσεις ἀποδιδόναι.
>
> The school of Eudoxus and Callippus and until Aristotle, assuming the unwinding spheres to be homocentric with the whole, attempted to save the phenomena through them, claiming that the spheres revolved about the center of the whole, but were unable to use these hypotheses to give an account of apogees and perigees, and of what seems to be direct and retrograde motion, and of the observed anomalies in the [celestial] motions.[90]

1.4.4. Aristotle's physicalization of the theory of homocentric spheres

The Eudoxean theory of homocentric spheres is sketched out by Aristotle, in *Metaph.* Λ 8. As is clear from the above, this is one of only two sources on which reconstructions of the theory are based, the other being Simplicius' extensive commentary on *Cael.* B 12.[91]

Nothing in *Metaph.* Λ 8 hints at the materiality of the spheres at issue, but this is implicit.

In *Cael.* B 12, where the theory is undoubtedly presupposed, they are said to be spherical shells of an unnamed matter (293a4–11). That the first simple body is the only appropriate sort of matter is a reasonable assumption.[92]

context does not imply that Eudoxus had no concern with the fit of his theory with the phenomena of the sky (cf. Yavetz [1998] 252–253). On this view of the theory's provenance, it might very well be the case that Schiaparelli and Yavetz have not in fact put forth competing reconstructions of the theory of homocentric spheres–they have instead recovered two different versions of it, both of which Eudoxus and his associates studied geometrically and with a view to possible applications in astronomy (cf. above, n. 84).

90 "The account of apogees and perigees" can be best understood as the explanation of the variations in the size of the Moon and the brightness of the planets via the assumption that each of these seven celestial objects revolves about the Earth at a variable distance, unlike in the theory of homocentric spheres, where all celestial objects orbit the Earth each at a constant distance (cf. Simp., *in Cael.* 504.22–26 [Heiberg]). The anomalies mentioned here are the variable speeds of zodiacal motions. The expression "unwinding spheres", which also appears in the title of Sosigenes' treatise mentioned above, in n. 85, is a metonymy for a system of homocentric spheres; see Mendell (2000) 92–93.

91 The reliability of Aristotle and Simplicius as sources for our knowledge of early Greek planetary theory, and so any reconstruction of a Eudoxean theory of the planets from the testimony of Aristotle and Simplicius, is summarily rejected by Bowen (2002b).

92 Cf. Gill (1991b) 260 n. 46.

The theory of homocentric spheres calls for an onion-like structure of the heavens consisting in twenty-six spherical shells of the first simple body. If we add the extra–let us call them "Aristotelian"–shells of the first simple body that allow the outermost "Eudoxean" shell in an inferior celestial object's deferent system to spin in the same sense and with the same period as the outermost shell in the Saturnian deferent system, the number of spherical shells of the first simple body making up the heavens increases to forty-three, and is raised to fifty-five, when the improvements of Callippus of Cyzicus on the original theory of homocentric spheres are taken into consideration (1073b32–1074a12).[93]

As seen above, to better account for phenomena which Aristotle does not explain in *Metaph.* Λ 8, Callippus added two spheres to Eudoxus' solar system of homocentric spheres, two to the lunar, and a sphere each to the systems for Mercury, Venus and Mars (for the planets, Simp., *in Cael.* 497.22–24 [Heiberg], notes only that Eudemus, in his *History of Astronomy*, had explained the modifications).

This addition necessitates a further addition of five Aristotelian shells to the original seventeen such shells.

Aristotle, however, has some qualms, which he does not explain, about adding an extra two spheres each for the Sun and the Moon. Accordingly, he proceeds to reduce the number of spherical shells of the first simple body making up the heavens from fifty-five to forty-seven (1074a12–14). In all probability, this is a scribal error, or a calculational error on Aristotle's own part, for the subtraction of four shells from a total of fifty-five and a further subtraction of two more, the Aristotelian shells required by the two shells which have already been subtracted from the deferent system of the Sun, yields forty-nine, not forty-seven.[94]

1.4.5. The unmoved movers in the heavens

The rotation of each of these spherical shells, the natural motion of the first simple body constituting each of them, has a so-called unmoved mover as its final, and perhaps efficient, cause; bringing about motion without being itself in motion, a celestial unmoved mover is a perpetually active and disembodied intellect (*Metaph.* Λ 7, 1072a19–b3 and b13–24).[95]

93 On the Aristotelian shells, which Aristotle himself calls "unwinding", see Appendix 8. Participating in the rotation of a superior shell can be thought of as natural motion; see n. 112.

94 See Simp., *in Cael.* 503.10–20 (Heiberg) and Alex. Aphr., *in Metaph.* 705.39–706.8 (Hayduck). Sedley (2000) 331 n. 7 attributes the reduction in the number of the celestial unmoved movers from fifty-five to forty-nine to Aristotle's numerological concerns; see 3.2.2, however.

95 Aristotle thinks of unmoved movers as the originative links in the causal chains leading not only to substantial change in which individuals of various animal kinds are generated but also to our production of artifacts and effects of all kinds; see *Ph.* Θ 5, 256a4–21, and the discussion in Gill (1991a) 198–202. The belief that, ultimately, unmoved movers cause all heavenly motion makes good sense within Aristotle's physics. It is celestial motions that cause the traditional four simple bodies to constantly turn into one another, thereby underpinning all substantial change and anthropogenic production. What is said in *Metaph.* Λ 7 to be a final cause is the prime unmoved mover in the heavens, more on which below, but the same is clearly as-

The shell of the first simple body, whose rotation such a mover causes, is said in *Metaph.* Λ 7 to respond to its mover in a way that leaves no doubt that this shell is ensouled (1072b3–4).[96]

The moving disembodied intellect is perhaps to be understood as being simply the rotational period and direction of the shell which it moves, and the angle made by the equator of this shell with the referent plane of the equator of one of those other shells with which it forms a system. This set of parameters constitutes an intelligible form identical with the intellect whose eternally active thought thinks and knows this form.

For Aristotle, the active intellect, the part of the soul that is capable of thought and knowledge, is identical with the object of its thought and knowledge, the form of something external to the soul somehow mapped on the intellect without informing a material substratum.[97] It is by somehow sharing the same thoughts with its unmoved mover, where these thoughts are "stored", that the soul of a spherical shell of the first simple body causes the infinitely many different values the parameters of the shell's rotation might take to collapse into a definite outcome.[98]

The nutshell of the cosmos, the spherical shell of the first simple body in the mass of which the stars are fixed, is made to move rotationally by the prime unmoved mover, under which the unmoved movers of all other shells of the first simple body are. How Aristotle understands the relation between the prime unmoved mover and its many subordinates is unclear.

Given his explicit parallel in *Metaph.* Λ 10 of the prime unmoved mover with the general of an army (1075a11–25), it seems that this celestial unmoved mover somehow "coordinates" all other such movers, perhaps in the sense that the intelligible form with which it is identical is a principle of them all. Indeed, the equator of the starry shell of the first simple body that the prime unmoved mover causes to rotate diurnally functions as the ultimate reference plane, to which the equators of all encased shells must be inclined each at the appropriate angle, and it is the rotational period of this shell that measures those of the encased shells.[99]

Aristotle might further believe that the prime unmoved mover coordinates all of its subordinates also in the sense that it always thinks, and thus is, the abstract mathematical structure realized materially in the heavens that is always being partially thought by the subordinate unmoved movers, each one of them thinking only the part appropriate to itself.

If so, the spherical shell of the first simple body whose parts are the stars is the only one whose soul does not fully share the thoughts of its unmoved mover. In this respect, however, this shell is similar to all the other shells it contains, for its soul, too, shares the thoughts of the prime unmoved mover only in part.

sumed to apply to all the other celestial unmoved movers. On their possibly being not simply final but also efficient causes of motion see Graham (1999) 179–180.

96 The shell is said to be moved by its "desire" for the mover; see Gill (1991b) 260 n. 44. On desire and celestial souls see also Falcon (2005) 87–97.

97 See *de An.* Γ 4, 429a10–29, Γ 7, 431b17, and Γ 8.

98 Cf. Gill (1991b) 263.

99 For the conception of the prime celestial unmoved mover as coordinator of its many subordinates see Gill (1991b) 263–265.

1.4.6. *Ph.* Θ 10 and the theory of homocentric spheres

Metaph. Λ, and chapter 8 in particular, carries forward *Ph.* Θ. In this elaborate book, Aristotle argues at length that to answer the question why motion and change in the cosmos are eternal, we must posit the existence of an immaterial unmoved mover as first cause of all motion, prerequisite of all change, and specifically of "the first motion"–eternal rotation of one single object. The cause of this motion, however, must be itself unmoved. For, otherwise, we could not avoid wondering what might cause it to move, and so on *ad infinitum*. Moreover, had this cause been something material, it would not have been unmoved, let alone caused eternal locomotion.[100]

Aristotle, however, does not explain which object this unmoved mover causes to rotate, and how. But in *Ph.* Θ 10 he obscurely remarks that the unmoved mover is "situated" at the circumference of the object it causes to perform eternal rotational motion, and specifically there where this motion is swiftest–i.e. where in the cosmos motion is swiftest (267b6–9). From this we can infer that in *Ph.* Θ he introduces the prime unmoved mover, which causes the physical analogue for the concept of the star-spangled celestial sphere to rotate once a day, from east to west. In Aristotle's cosmos, the swiftest motion is of a point at the equator of this spherical shell of the first simple body.[101]

In *Ph.* Θ 5, moreover, Aristotle leaves open the possibility that the full explanation of eternal motion and change in the cosmos might require a multitude of unmoved movers, apparently because the diurnal rotation is not the only eternal motion in the celestial realm, though he does not try to hide his preference for a single unmoved mover (259a6–13).

This is compatible with what is said in *Metaph.* Λ 8, and thus it has been assumed that *Ph.* Θ must have been composed before *Metaph.* Λ, where, it should be noted, the focus before ch. 8 is on the unmoved mover responsible for the rotation of the spherical shell of the first simple body carrying the stars round, as is clear from the opening of ch. 7 (1072a19–23).[102] One can thus assume that *Ph.* Θ 5, and so *Ph.* Θ as a whole, must have been written by Aristotle with the theory of homocentric spheres in mind.[103] This does not seem to be the case, however.

The single object's rotation brought about by the unmoved mover that is introduced in *Ph.* Θ is clearly assumed in *Ph.* Θ 10 as the only, or the most, uniform motion, sc. in the cosmos (267a21–b6). Aristotle states explicitly at the beginning of *Cael.* B 6, 288a13–17, his belief in the uniformity of the diurnal rotation of the spherical shell of the first simple body with the stars as its fixed parts, and there

100 An unmoved mover as first cause of motion seems to be tacitly introduced in *Ph.* H 1; for the unjustly unfavorable reception of this interesting book see Wardy (1990) 85–87.

101 Cf. Graham (1999) 177–178. A point at the equator of any spherical shell of the first simple body which is inside the shell carrying the stars round fixed in its mass, even if it rotates with the same period as the starry shell, moves with a slower linear speed, though at the same angular rate, since the radii of the two shells are unequal. See also 2.2.1 on "the first rotation".

102 See Ross (1936)101–102 and cf. Graham (1999) 108. For *Metaph.* Λ 8 as possibly a later addition to the book see Guthrie (1934), Frede (1971) 66–70. But cf. Frede (2000) 47–48.

103 Cf. Ross (1936)101–102, Gill (1991b) 257–258, Graham (1999) 119.

can be no doubt that the rotations of all other shells of the first simple body assumed in *Metaph.* Λ 8 to be nested within this starry shell are also unwaveringly uniform. Nowhere does Aristotle say this, but according to our sources, the point of the theory of homocentric spheres was to explain the observed motions of the Sun, the Moon and the planets as resultants of circular, uniform motions.[104] Nothing suggests that Aristotle might have been unaware of this. If so, since the spherical shell of the first simply body in whose mass the stars are fixed moves, according to *Ph.* Θ 10, with the only, or the most, uniform motion in the cosmos, it can be concluded that *Ph.* Θ does not tacitly posit below this shell all the other shells of the first simple body assumed in *Metaph.* Λ 8 to make up the heavens. In other words, Aristotle did not write *Phys.* Θ presupposing a cosmology based on a version of the theory of homocentric spheres.[105]

It can be objected that (a) when Aristotle says in *Ph.* Θ 10 of the diurnal revolution of the stars–the rotation of their deferent shell of the first simple body–that it is the only, or the most, uniform motion in the cosmos, he in fact compares it with the spiral motion of the Moon, the Sun or a planet having in mind the theory of homocentric spheres, not with the uniform rotation of any of these spheres, or of its *Metaph.* Λ 8 physical analogue; (b) uniformity here is both of speed and of the path of motion, for in Aristotle's physics uniformity can be understood in either way, as is clear from *Ph.* E 4, 228b15–28, and, as already pointed out, the theory of homocentric spheres was unable to reproduce the non-uniform speed of the zodiacal motion of the wanderers–we can assume that Aristotle did not care about this inability for the sake of the argument.

The comparison, however, in (a) is quite unlikely if the spiral motion of the Moon, the Sun or a planet is assumed to result from a combination of a number of uniform rotations of spherical shells of the first simple body, "copies" of the deferent shell of the stars and thus naturally comparable to it, all the more so since their rotations are causally prior to the observed motions they produce. There is no point in comparing these observed motions with the diurnal rotation of the deferent shell of the stars and then declaring the latter, alone or especially, uniform in either sense of the term, if the former are each conceived of as resulting from the combined rotations of a number of deferent shells, each of which is as uniform a motion, once again in either sense of the term, as the diurnal rotation of the deferent shell of the stars (cf. ch. 3, n. 16).

Aristotle's remark in *Ph.* Θ 10 that the diurnal revolution of the stars, i.e. the rotation of their deferent shell of the first simple body, is the only, or the most, uniform motion makes good sense only if this revolution is compared with each wanderer's zodiacal motion as is observed–that is, without its being understood within the framework of the physicalized theory of homocentric spheres. In *Ph.* Θ 10 Aristotle thinks that the five planets, the Sun and the Moon travel round the heavens without each being attached to the innermost of a number of simultaneously rotating deferent spherical shells, all of them made up of the first simple body. As re-

104 Simp., *in Cael.* 488.10–24 and 492.31–493.11 (Heiberg), translated below, in 3.1.
105 Cf. Easterling (1961) 138–148 on *Cael.* A–B, except B 12, on which see below, 3.3.

gards uniformity of speed, he does not know whether each of these seven celestial objects always takes the same time to travel round the zodiac or not; if the second, whether the variation is random or not, and in either case, whether the different parts of a wanderer's zodiacal path in which the celestial object speeds up or slows down might change in a manner obeying any short- or long-term regularities.[106] In other words, there are certain senses in which the zodiacal motion of the wandering celestial objects could be only less uniform, with regard to speed, than the diurnal revolution of the stars, which is the rotation of their deferent shell of the first simple body, not completely non-uniform.[107]

It should be noted here that the planets, the Sun and the Moon are clearly said in *Cael.* B 6 to move against the background of the stars non-uniformly–with regard to speed, as appears from the context–whereas the diurnal rotation of the deferent spherical shell of the stars is uniform. This passage, 288a13–17, does not acknowledge the possibility that the zodiacal revolutions of the seven wanderers are only less uniform than the diurnal rotation of the deferent shell of the stars, not completely lacking uniformity.[108] There is no reason why Aristotle would deny uniformity of path to the zodiacal motion of the Sun, or consider this motion to actually follow a path (imperceptibly) less uniform than the diurnal circles of the stars, unless he did so to bring the Sun into line with the planets and the Moon.

He could think of the Moon as moving round the Earth not in a perfect circle in order for their separation to vary, which could explain the changes in the apparent diameter of the Moon, but also be ready to concede that this path is very much like a circle, and this is perhaps the reason why the Moon's orbit might be said to be neither absolutely non-uniform nor as uniform as the perfectly circular orbits followed by the stars in their diurnal motion. Viewed very broadly, as eastward motions, the paths in which the planets travel through the zodiac could also be said to be similar to–and thus sharing only to some degree the uniformity of–the diurnal, perfectly circular paths of the fixed stars (cf. below, n. 113).

Perhaps Aristotle prefers to think that the diurnal revolution of the stars–the rotation of their deferent shell of the first simple body–is the sole, and not simply the most, uniform motion in the whole of the heavens, as regards both speed and shape of path, but it is not unlikely that he considers the zodiacal motion of the Sun as following a path which is as circular–and thus uniform with regard to form–as the diurnal circle of any star. When he says in *Ph.* Θ 10 that the diurnal rotation of the deferent shell of the stars is the sole, or the most, uniform motion in the cosmos, he might opt for the first possibility with uniformity of speed paramount in his mind, regarding which the Sun's zodiacal motion lacks uniformity as much as that of the planets and the Moon does, in contrast to the diurnal rotation of the deferent shell of the stars. His opting for the first possibility, moreover, might be suggested by the above mentioned passage from *Cael.* B 6, where he says with-

106 In *R.* 7, 530a4–b4, Plato seems to think that all astronomical periods are inconstant and vary randomly. See Gregory (2000) 64–67.

107 *Ph.* E 4, 228b18–19, seems to suggest Aristotle's belief in a continuous gradation from perfect uniformity to complete non-uniformity. Cf. Ross (1936) 633 *ad loc.*

108 *Cael.* B 6, 288a13–17, is discussed below, in 3.1 and 3.2.1; cf. *Cael.* B 10, 291a34–b1.

out qualification that the zodiacal motion of the wanderers is non-uniform–as regards speed–unlike the diurnal rotation of the deferent shell of the stars.

If Aristotle thinks of this motion as the only, or the most, uniform in the heavens, which is suggested by *Ph.* Θ 10 and *Cael.* B 6, then it is hard to believe that he also considers the theory of homocentric spheres an even approximately correct physical description of this cosmic realm.[109] What we must not lose sight of is the fact that in *Metaph.* Λ 8 he outlines the theory of homocentric spheres, and sketches a structure of the heavens based on it, simply in order to give an example of how astronomy may contribute, with its study of celestial motions, to precisely determining the multitude of the unmoved movers that might be needed to explain the eternity of motion and change in the cosmos. From this, however, it does not follow that Aristotle accepts the theory of homocentric spheres, in its Callippean or Eudoxean version, as guide to the structure of the heavens, which seems to be suggested by *Ph.* Θ 10 and *Cael.* B 6, too, contrary to what is read in the relevant literature (cf. Simp., *in Cael.* 505.27–506.8 [Heiberg]).

1.5. WHAT COMES NEXT

The third chapter of the present book is a fuller defense of this thesis. The second chapter argues that when Aristotle came up with the concept of the first simple body, he considered this new type of matter to be only the filler of the uppermost place of the cosmos, where the stars are, and the constitutive matter of these celestial objects alone, not of the planets, the Sun and the Moon, too.

Originally, that is, within Aristotle's cosmology the first simple body served the limited purpose of turning the astronomical concept of the celestial sphere into a physical object–a diurnally rotating shell of matter, in the mass of which the stars were fixed as its parts, and thus the crust of the remaining cosmos. At the time, Aristotle thought that the cosmic stratum of the simple body fire reached up to the lower boundary-surface of the one single shell of the first simple body, filling up the remaining part of the heavens, and also making up the planets, the Sun and the Moon.

Later on, Aristotle thought he had strong reasons to extend dramatically the cosmological role of the first simple body into that of a sole upper body, a single filler of the heavens and constituent of all celestial objects. He dilated its spherical shell so as to include the seven wanderers, and shrank compensatorily the underlying spherical layer of fire around that of the adjacent air. *Cael.* A 2–3 date from the first phase, *Mete.* A 2–3 from the second. *Cael.* B 7, and perhaps B 8, was written in view of the expanded role of the first simple body.

109 The view rejected here seems to be supported by Lloyd (1996) 168, who says that the theory of homocentric spheres "was supposed to give a good first-stage approximation to a solution" to problems posed by the speed of the zodiacal motion of the non-fixed celestial objects, and the stations and retrogradations of the planets, "which Aristotle himself felt confident enough about to adapt for his own metaphysical purposes" (showing the existence of order in the heavens). Cf. Falcon (2005) 75 n. 19.

Carried round diurnally, like the stars, with the surrounding mass, the five planets, the Sun and the Moon, unlike the stars, were not thought of as being fixedly embedded in it, but as being able to pursue, simultaneously with their participation in the diurnal rotation, each a characteristic motion in the opposite direction, which was not analyzed into uniform and circular components, as in the *Metaph.* Λ 8 cosmology, which is based on the theory of homocentric spheres.

Aristotle does conclude in *Cael.* B 8 that neither the stars nor the other celestial objects, the planets, the Sun and the Moon, move "by themselves", for all of them are spherical, and thus lack protruding locomotive organs, nor do they appear to roll (290a7–b11; cf. *Cael.* B 11). This does not entail the *Metaph.* Λ 8 cosmology, however.

He shows first that the stars do not trace their parallel diurnal circles moving independently of the surrounding mass, but as fixed parts of this mass, and then proceeds to bolster his conclusion based on the obvious sphericity of the Sun and the Moon, which he extends to all celestial objects. From this, however, it does not follow that the five planets, the Sun and the Moon are each fixed in a spherical deferent shell, just as the stars are fixed in a single such shell.

If it did–from the principle invoked in *Cael.* B 11, 291b17–18, "what holds of one celestial object holds of all"–it could also follow that the stars, too, have zodiacal motion. A celestial object does not move zodiacally just as naturally moving matter–or matter forced to move by some naturally moving matter–moves: for its zodiacal motion is also caused by a soul–see below–which must be unlike the soul of a terrestrial animal. Following Plato (*Lg*. 10, 899a2–4), Aristotle might consider a celestial soul capable of bringing about motion thanks to its having "extremely amazing powers"–that is, even if what it moves lacks locomotive organs, being spherical, and does not roll. Now, the Sun and the Moon have observedly spherical shape, lack locomotive organs, and do not roll. So, if all celestial objects can be plausibly assumed to be spherical and also not to roll, this supports, if applied to the stars alone, the already established conclusion that these celestial objects move by being fixedly embedded in the rotating mass of a deferent spherical shell.

However, this conclusion need not apply to each of the five planets, the Sun and the Moon (on *Cael.* B 8 see also Appendix 7).

If so, Aristotle's cosmology is totally in line with what was observationally known in his day about the motion of each planet, the Sun and Moon, for it assumes that each of these celestial objects moves zodiacally, opposite to the direction of the fixed stars, just as it appears to do.

A conception of the physical structure of the heavens based on the theory of homocentric spheres, in either of its versions available to Aristotle, yields zodiacal motions of the five planets, the Sun and the Moon which are incompatible with observation, strikingly so in the case of the planets.

When the upper body in the realm of the planets, the Sun and the Moon was the simple body fire, the diurnal motion of each of these seven celestial objects was enforced, being due to participation in the diurnal rotation imposed on the cosmic layer of fire by the overlying spherical shell of the first simple body. Its zodiacal motion was due to its motive and guiding soul, which might or might not have been considered immediately subordinate to an unmoved mover.[110] The deferent shell of the stars was in all probability assumed from the beginning to be guided by its own soul, which determined the direction and the period of the rotation of this shell–the natural motion of the first simple body.[111] Subsequently, with the promotion of the first simple body into the sole upper body, the diurnal motion of the Sun, the Moon and all five planets became natural.[112]

What about their zodiacal motion, however? If it followed perfectly circular paths and had uniform speed, it could be thought of as the natural motion of the first simple body, the souls of the planets, the Sun and Moon only guiding it, each of them being guided in its turn by an immaterial unmoved mover. But it is not circular–probably with the sole exception of the Sun–nor does it have uniform speed. How could it be the natural motion of the first simple body?[113]

110 For views on the position of the celestial unmoved movers in the evolution of Aristotelian physics see the survey in Graham (1996) 171–172.

111 I agree with Ross (1936) 97–98 that Aristotle's explanation of celestial motion in the *de Caelo* requires souls; for the opposite view see Guthrie (1939) xxix–xxxvi. Although Aristotle strongly denies in *Cael*. B 1, 284a27–31, that the spherical shell of the first simple body with the stars as its parts is constrained by a soul to undergo eternal rotation which is not the natural motion of the first simple body, in *Cael*. B 2, 284b6–34, this shell is said to be alive and ensouled. Aristotle, moreover, says in *Cael*. B 5 that the direction of its diurnal rotation, from east to west, is not accidental but what is best for it, for nature always does choose the best from among all available possibilities (288a2–12). Nature here can be plausibly identified with the shell's soul. Its role is thus not to power the shell's rotation but to fix its direction, probably its period, too, collapsing into a single actuality the existing possibilities for how fast the first simple body constituting the shell undergoes its natural motion, as well as in what direction (cf. above, 1.4.5). That souls are also involved in the motions of the planets, the Sun and the Moon is assumed in *Cael*. B 12, 292a18–21. A denial in *Cael*. B 9, 291a22–26, that all celestial motion is either due to soul or enforced, i.e. mechanically, must be read within its context. What Aristotle thinks not to be either due to soul or enforced is celestial motion not as he understands it but through a stationary medium; cf. ch. 2, n. 42, and 3.4.3. Celestial souls differ radically from terrestrial ones; see Falcon (2005) 87–97.

112 Since a planet, the Sun and the Moon must also move opposite to the diurnal rotation, but the natural motion of the first simple body cannot be simultaneously in opposite directions, if the first simple body can undergo natural motion only, we need to distinguish between its "passive" and "active" natural motion. Consider a spherical shell of this simple body in the *Metaph*. Λ 8 cosmology. It undergoes "passive" natural motion in following the rotation of the shell inside which it is nested and which does not spin in the direction of its rotation–its "active" natural motion–but oppositely. The opposite rotation, however, could be the motion proper to this mass of the first simple body, which is why we can consider it a "passive" natural motion. If the Aristotelian heavens are structured as proposed here, the participation of the Sun, the Moon and the planets in the diurnal rotation was considered their passive natural motion when Aristotle came to think of them as consisting of the first simple body. In executing passive natural motion, the seven wandering celestial objects followed the diurnal rotation of the shell of the first simple body whose non-fixed parts, unlike the stars, they were. But the zodiacal motion of these masses of the first simple body could not be easily thought of as active natural motion of the first simple body, guided in each case by a soul. See the following discussion. In Aristotle's surviving works there is no mention of species of natural motion.

113 In *Cael*. B 10, 291a34–b10, Aristotle assumes that each of the wandering celestial objects moves zodiacally along its own circle. However, since this passage, which is quoted and translated below, in 2.2.1, is incompatible with a conception of the heavens based on the theory of

The soul of a wanderer could "tell" it to vary the pace of its natural motion as necessary. A planet could slow down so much that from the Earth its motion would be seen to temporarily come to a stop, though in fact it does not. The changes in the direction of its motion could also be guided by its soul–if the direction of the natural motion of the first simple body is chosen by a soul. But the natural motion of the first simple body has uniform speed and is eternal because this simple body is ungenerated, indestructible and totally changeless, and its natural motion is circular. How the expanded role of the first simple body–whose nature is to always orbit circularly and uniformly a point on an axis passing through the center of the cosmos–as filler of the whole of the heavens and single constituent of all celestial objects could be brought into line with the lack of circularity in the zodiacal motion of at least the planets, as well as with the lack of uniform speed in the zodiacal motion of all wanderers, was perhaps one of the toughest open problems in Aristotle's cosmology.

He need not have considered it solvable, assuming that he thought of the heavens as intrinsically intelligible, though not fully intelligible to us.[114]

homocentric spheres (see 3.1, 3.2.1, with n. 16, and 3.4.1), the unqualified assumption–in a certain sense allowable within the framework of the theory of homocentric spheres–that at least each planet moves along a circle against the backdrop of the zodiacal constellations should not be understood literally (cf. above, 1.3.4 and 1.4.6). The same must hold for Aristotle's characterization of all celestial objects as τὰ ἐγκύκλια σώματα or τὰ ἐγκυκλίως φερόμενα σώματα (*Cael.* B 3, 286b6–7, and *Mete.* A 2, 339a12–13); cf. the expression τὰ φερόμενα τὴν φορὰν τὴν ἐγκύκλιον in *Cael.* B 14, 296a34–35, for the planets, the Sun and the Moon as sharing in the diurnal rotation and simultaneously undergoing zodiacal motion (see also *Metaph.* Λ 8, 1073a28–32). Easteling (1961) 138–148 argues that in *Cael.* A–B Aristotle operates not with the *Metaph.* Λ 8 cosmology, which is based on the theory of homocentric spheres, but with Plato's Timaean cosmology, where the planets, the Sun and the Moon perform their zodiacal motions in coplanar circles, centered on the Earth. Even if Plato could account for the retrogradations of the planets in the manner Knorr (1990) 313–317 suggests, however, the *Timaeus* circular motion of the planets among the stars of the zodiacal constellations cannot easily be accommodated with Aristotle's awareness that the planets and the Moon vary their distances from the Earth (see Simp., *in Cael.* 505.21–27 [Heiberg] = Arist., fr. 211 Rose; translation below, in 3.6). Assuming that some parts of the first simple body move naturally in circles not homocentric with the cosmos is no less problematic than assuming that there are some parts of this simple body which move naturally not in circles. For another problem arising from Aristotle's broad conception of the first simple body as sole upper body see ch. 2, n. 65.

114 See Falcon (2005) ch. 4. Cf. also the comparison in *Cael.* B 4, 287b14–21 (translated at the end of 3.7 below), of the first simple body with water, air and fire in terms of subtlety of texture, and thus in terms of the closeness to "geometric" perfection of the shape the mass of each of these simple bodies can take on at the cosmological scale; but fineness and coarseness, according to *GC* B 2, 329b15–330a29, derive from the basic tangible qualities, out of which the traditional simple bodies, unlike the first simple body, are thought to be constituted, so it is not clear how the first simple body can be considered much finer, or much more "fluid", than even fire (cf. Appendix 5). Whether Aristotle's heavenly stuff is hard or fluid was a much discussed issue in medieval cosmology (see Grant [1996] 324ff.). Aristotle, however, certainly thinks of the first simple body as a tenuous–actually, the most tenuous–fluid, and need not have been disturbed by the notion that some parts of it–the wandering luminaries–plow through the rest of its mass, despite his implicit reference in *Cael.* B 8, 290a5–7, to the continuity of the *ouranos* (for the meaning of the term *ouranos* in the context of these lines see Appendix 7).