CHAPTER

Aristotle's Astrophysics

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https://doi.org/10.1093/acprof:oso/9780198749516.003.0005
Pages 151–192
Published: November 2015

Abstract

Aristotle usually has an extremely bad reputation as a physicist among scientists and historians of science. Central to this is the treatment of his version of the geocentric conception of the cosmos, according to which the earth is at the centre of the cosmos and does not move, and which was the dominant picture in antiquity and throughout the middle ages. Aristotle's view is commonly regarded as a pernicious influence on the course of cosmology until the Renaissance, one which held sway only because of Aristotle's authority. The chapter argues that his integration of astronomy and physics—his pursuit, in a variety of works written over a long period, of the question: 'what does the world have to be like, in terms of a unified physics, if current astronomical theory is right?'—embodies a degree of comprehensiveness, sophistication, and elegance simply unparalleled in the ancient world. It is also more robust—given the astronomy of Aristotle's day—than is usually thought: the chapter considers a number of difficulties it faced (including the explanation of the light of the sun and the stars, and the notorious problem of the variation in the brightness of some heavenly bodies), and outlines responses which Aristotle either did make or could have made. The only serious rival to Aristotle's astrophysics before Kepler and Newton was the theory set out in Ptolemy's *Planetary Hypotheses*, which attempts to integrate physics with his (much more complex) astronomy: the chapter argues that for all its subtlety, this theory fares very poorly as a piece of physics. It was not, therefore, simple deference to authority which led some Islamic and Renaissance scientists to prefer Aristotle's theory even though they could not see how to square it with Ptolemaic astronomy.

Keywords: Aristotle, heavenly spheres, natural motions, teleology, De caelo, Meteorologica, Metaphysics XII, Ptolemy, Planetary Hypotheses, Eudoxus

Subject: Ancient Philosophy

Series: Oxford Studies in Ancient Philosophy

1. Introduction

ARISTOTLE usually has an extremely bad reputation, as a physicist, among scientists and historians of science. Central to this— and the focus of this article—is the treatment of his version of the geocentric conception of the cosmos, according to which the Earth is at the centre of the cosmos and does not move.[1] This was the dominant picture in antiquity and throughout the Middle Ages, though of course there were some variations on this picture: there were some people who thought that the Earth was at the centre but that it rotated on its axis,[2] quite a few people who thought that the Earth was at the centre of the cosmos but not at the centre of the universe,[3] and a very small number of people—principally Philolaus and Aristarchus—who thought that in one way or another the Earth was not at the centre of the cosmos at all.[4] Aristotle's view is that the universe consists of a single cosmos, finite in extent and spherical in shape, and of course with the Earth at its centre. What enabled the geocentric view, and in particular

Aristotle's version of it, to endure for so long—especially in the face of increasingly recalcitrant astronomical data? No doubt the answer is very complicated, and a variety of reasons were, for instance, offered by various thinkers in defence of the centrality and immobility of the Earth;[5] but a key ingredient in the answer is certainly *Aristotle*. The standard view among scientists and some historians of science, however, is that the persistence of Aristotle's theory was a matter of sadly misplaced deference to an incompetent authority, because of how bad (according to this view) Aristotle was as a physicist. Some of the carping focuses on the astronomical content of Aristotle's geocentric theory: 'his scheme was very complicated and inelegant';[6] '[he converted] an ingenious and beautiful geometrical scheme into a confused mechanism';[7] 'he [may be] seriously out of his depth'.[8] Some of it focuses on particular problems of which Aristotle him self was or should have been aware, and which have been thought damaging or even devastating for his theory.[9] But the criticism often takes a wider view, as here:

> There are also in Aristotle's writings a number of astronomical speculations, founded on no solid evidence and of little value. ... Unfortunately, the Greek astronomy of his time, still in an undeveloped state, was as it were crystallized in his writings, and his great authority was invoked, centuries afterwards, by comparatively unintelligent or ignorant disciples in support of doctrines which were plausible enough in his time, but which subsequent research was showing to be untenable.[10]
>
> Aristotle has a lot to answer for. It is his model of the cosmos ... which would colour and shape humanity's notions about the nature of the universe for almost two thousand years. But he was barking up the wrong cosmic tree; it is Aristotle ... to whom humanity owes its long and

> mistaken fixation with the geocentric universe. In fact, of all the fallacies, muddles, wrong turns and dead ends in the history of science, the Aristotelian universe was the most dramatically wrong.[11]

But this sort of view gestures, at best, at the 'that' of Aristotle's supposedly pernicious influence, not the 'why', and I think that looking at the 'why' undercuts the idea that his influence was in fact pernicious. I shall focus on a central element of the 'why' of Aristotle's continued influence, namely the way in which he undertook a thoroughgoing *integration* of astronomy—the theory of what the motions of the heavenly bodies are which produce the observed phenomena in the sky—with physics—the theory of what produces those motions, what physical reality underlies them. The Aristotelian corpus does not offer a set-piece exposition of this integration, and Aristotle seems rather to have pursued the project in a variety of works written over a long period: the now lost *De philosophia, De caelo* (especially books 1–2), *Meteor*. 1. 1–8, *Physics* 8, and *Metaph*. *Λ* 6–8—and the last of these, at any rate, is clearly a draft of work in progress which was never properly revised. This means that we have to allow for some changes of view, some mistakes, and not a few loose ends. Even so (and even setting aside the falsity of the geocentric view), there are many imperfections in this attempted integration, and of course it came to face some genuinely insuperable problems—most seriously, from the great flood of new astronomical data which became available in the Hellenistic period, both from the Near East and from the Greeks' own observations, and which made the astronomy on which it was based untenable. (And yet, as we shall see, there were those in the Middle Ages and indeed the Renaissance who, for mostly very good reasons, thought it tenable nonetheless.) For all this, as I shall argue, Aristotle's integration of astronomy and physics embodies a degree of comprehensiveness, sophistication, and elegance simply unparalleled in the ancient world. No one would rival it, in these respects, until the combined efforts, over a period of nearly two centuries, of a host of astronomers and physicists, of whom the most notable are Copernicus, Galileo, Tycho Brahe, Kepler, and Newton. I will focus on Aristotle's own theory, and will have to pass over the considerable complexities of the afterlife of his astrophysics in the period down to the Renaissance.

This idea of the integration of astronomy and physics has nothing to do with the contrast between scientific realism and *instrumentalism*, the view that an astronomical theory is no more than a device for predicting astronomical phenomena (e.g. where a planet will be at a given time), and that it makes, and should make, no claims at all as to any *causes* of these phenomena. I do not wish to cast Aristotle as a lone scientific realist pitted against philosophically austere (or philosophically misguided) instrumentalists. This picture of ancient astronomy has long been discredited: there is little or no reason for seeing any of the major figures in the history of Greek astronomy as instrumentalists.[12] Thus, for instance, Aristotle's famous 'putting together' of the heavenly spheres (which I shall discuss later) has often been taken to mark the difference between a purely geometric, instrumentalist approach on the part of the two astronomers on whom he relies, Eudoxus and Callip-pus, and Aristotle's own realist approach.[13] It is clear from the way in which Eudoxus and Callippus treat the planets separately that they were principally interested in the geometrical solution of the planets' irregular motions;[14] but that is no reason to regard them as instrumentalists who took the truth of their theories to consist in their predictive success. Whether Eudoxus and Callippus took their solutions to have direct implications for the physical mechanisms behind planetary motion is a question which we simply cannot answer.[15] Even if they did not, it is one thing not to have a view about —or much interest in—how a mathematical model is realized in the physical world: it is quite another to think that the question rests on a misguided view of the nature of science. What separates Aristotle from most other ancient thinkers, in any case, was not the fact that he thought there was a question ‘what does the world have to be like, in terms of a unified physics, if current astronomical theory is right?’, but rather the determination and sophistication with which he *pursued* this question, and the degree of success he met with in doing so.

2. Aristotle’s astronomy

The leading astronomical theory of Aristotle’s day was, essentially, that of the great mathematician Eudoxus.[16] Its two core elements were the ideas that the Earth is motionless at the centre of the cosmos, and that the apparent motions of each of the heavenly bodies could be explained in terms of combinations of unvarying, uniform, geocentric, spherical motions. I shall call these ‘perfect motions’, and the general type of theory advanced by Eudoxus—and subsequently by Callippus and Aristotle—’homocentric theory’.[17] Our principal source for their homocentric theories is Aristotle’s all too brief account in *Metaph.* Λ 8, and a longer discussion, distorted to some degree by later developments in astronomy, in Simplicius’ commentary on the *De caelo*.[18]

Homocentric theory took its starting-point from the motion of the so-called fixed stars: this motion seemed simply to require one such perfect motion per day.[19] It might also have seemed obvious that the sun’s motion was a combination of two perfect motions—a daily one like that of the fixed stars and an annual one accounting for the sun’s motion along the ecliptic—and there are signs of a two-motion scheme in parts of Aristotle’s *De caelo*.[20] It is clear from the account in *Metaphysics* Λ, however, that Eudoxus thought that the motions of the planets, including the sun, were more complex than this. Reconstructing the details of Eudoxus’ system is very difficult, given the paucity of the evidence and the problem of trying to determine exactly what phenomena it was designed to capture.[21] As Aristotle describes it, Eudoxus’ theory involved a separate set of three or four nested, rotating geocentric spheres for each of the seven planets. Within a given set, the outermost sphere rotates in a particular way about the centre of the Earth—that is, with a certain uniform speed, in a certain direction, and at a certain angle. This outermost sphere transmits its motion down to the sphere immediately inside it; this inner sphere has in addition a motion of its own, so that its overall motion is a combination of the upper sphere's motion and its own intrinsic motion. This combined motion is then transmitted down to the next sphere in, and so on; the planet is attached to the equator of the innermost sphere of the set, and it moves in a way which results from the combination of the motions of all of the spheres in that set.

In the case of each of the planets other than the sun and the moon, Eudoxus proposed a set of four spheres—perhaps (but this is highly controversial) to capture the fact that they exhibit retrograde motion.[22] Callippus added some more spheres to five of the seven planetary sets; for example, he added two more to the set for the sun, probably to yield the inequalities in the seasons—that is, the changes in the sun's angular velocity which mean that it takes different times to go through a quarter of its yearly circuit, from solstice to equinox or from equinox to solstice. Aristotle does not give us Callippus' reasons, however, and expresses some doubt as to the need for these additional spheres for the sun and the moon.

3. Aristotle's astrophysics

As I have said, the key question which Aristotle pressed was: what does the world have to be *like* if Eudoxan astronomy is right? His first step was to suppose that the heavens should actually contain hollow, nested, and geocentric spheres,[23] each of which is the subject of one of the perfect spherical motions specified by homocentric theory, and which transmits its motion downwards to the next sphere to generate the combinations of motions which the theory requires. Aristotle takes the stars and planets themselves to be spherical bodies, each of which is fixed within one of these spheres; each planet is thus moved by a set of nested spheres.

Aristotle's next step simultaneously addresses the questions 'What are the spheres made of?' and 'What is the explanation for their homocentric circular motion?'. His answer is an integral part of his element theory, set out in the *De caelo*.[24] According to this—in the barest outline—there are five elements each characterized by a 'natural motion': earth, which naturally moves in a straight line towards the centre of the (spherical) universe; fire, which naturally moves in a straight line towards the sublunary periphery of the universe; air and water, which naturally move in a straight line towards intermediate locations; and the *first body* or *aither* (located in the heavens, above fire's natural place), which naturally moves in a circle around the centre of the universe. There are, of course, important—and much-discussed—differences between the first body and its sublunary brethren. The first body is imperishable and, aside from change of place, impassive: its causal relations with the sublunary world are all one-way. But the differences should not mask the extraordinary degree to which Aristotle's cosmology and sublunary physics are unified by the idea of elemental capacities for regular motions defined by the centre and periphery of the universe.

Aristotle's theory not only accounts in a unified way for what we might call the gross phenomena of the cosmos—the local motions of sublunary bodies, the relative motion of the Earth and fixed stars, and the apparent unvaryingness of that relative motion—but it also has rich explanatory resources. Its implications, especially in relation to the finitude and shape of the universe, and the uniqueness of the cosmos, cohere in an impressive way with the conclusions of Aristotle's independent cosmological arguments, and in some cases the element theory explains features of the cosmos which he establishes independently—most notably in the case of his masterly explanation of the sphericity of the Earth in *De caelo* 2. 14. When one thinks of the elegance, simplicity, and fecundity of this approach, both in accounting (albeit in a qualitative way) for observation and in generating a systematic cosmology, the natural comparison is with Newton's laws of motion.

Of course, there are some serious and well-known difficulties with the idea of natural motion—and I do not wish to downplay these. These include the much-debated difficulties in spelling out just what sort of capacity it involves, the role (if any) of natural places, and how elemental motion differs from animal self-motion.[25] Another difficulty—on which Aristotle is silent—is understanding how, if the aither has a natural motion, there is also a need, as Aristotle thinks there is, for an Unmoved Mover as the source of its motion.[26] If such a Mover is required, then Aristotle cannot hold that the spheres are made of an element whose natural condition is to be *in motion*;[27] yet that is the natural condition of the other elements when they are moving.[28] The best solution is to weaken the parallel with the other elements somewhat, and to suppose that the body of which the spheres are composed has a natural *capacity* for circular motion which requires continuous activation by the desire of the sphere's soul and hence by an Unmoved Mover.[29] In this way, Aristotle can retain the key unifying idea of the *De caelo* that the five elements all have natural motions defined by the centre and periphery of the universe.[30]

The next ingredient of Aristotle's astrophysics is a unifying move of a different sort: the 'putting together' of the spheres and the introduction of what he calls the *back-winding spheres* (ἀνελίττουσαι). Eudoxus' theory, as we have seen, requires, for each planet, the *combination* of more than one perfect motion: so we need the idea that the motion of some heavenly spheres is transmitted to others. The basic mechanism for this—whether it was Eudoxus' idea or Aristotle's is, as I have said, unclear—is that the spheres in each planetary set are *nested*, and each sphere transmits its motion to the next sphere down. Aristotle saw that, without completely *ad hoc* restrictions—or at least without further, quite considerable, complexities—*every* sphere should transmit its motion on to the next sphere down. This means that the lowest sphere of one planetary set will transmit its own complex motion to the highest sphere of the planetary set immediately below. But if, for example, the complex motion of the sphere which carries Saturn (the outermost planet) is passed on to the first sphere in the next set, the set for Jupiter, the astronomy for Jupiter—and all the lower planets too—will come out badly wrong. Aristotle's idea was that what prevents this is a *further* group of spheres underneath each planetary set,[31] which rotate in such a way as to undo, or 'unwind', the motions of the higher set, so that in effect the set of spheres for the next planet down starts from scratch.[32] The ideas that all the spheres are connected and that counteracting spheres can block the 'inheritance' of higher motions by lower sets of spheres fit very well together, though it is true that Aristotle's account faces a number of difficulties. One key issue is that he gives no account of how the transmission of motion is effected in the first place: it seems to have the status of a basic postulate of his astrophysics. A less important problem—because apparently easy to remedy—is Aristotle's reduplication in each planetary 'system' of the diurnal motion of the sphere of the fixed stars.[33]

It is worth taking stock at this point. In Aristotle's view, the physics which underlies astronomical theory relies on the following four principles:

(i) The heavens consist in a number of fundamental bodies: these are all nested, geocentric hollow spheres. The heavens also include one other sort of body—the spherical stars.

(ii) These fundamental bodies are composed of an element whose nature it is to move in what I have called a perfect motion—a regular motion determined, as the natural motions of the other elements are, by the centre and periphery of the universe. Each fundamental heavenly body is thus the subject of exactly one intrinsic geocentric circular motion.

(iii) Each fundamental body transmits its motion down to the next such body, if there is one.

(iv) Beyond the different, nested locations of the fundamental bodies, the *only* variations in the heavenly bodies required are (*a*) the further determination of each perfect motion (its speed, direction, and angle); (*b*) the locations of the stars; and (*c*) the differences in the numbers of spheres in each planetary set.[34]

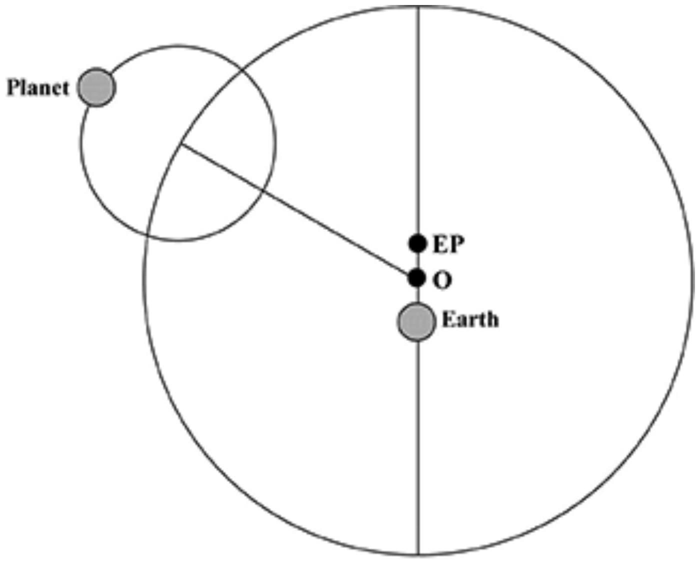
This is a system of extraordinary coherence and simplicity, which, as we shall see, many astronomers found compelling long after Eu-doxan astronomy was replaced.

The next two ingredients of Aristotle's astrophysics might seem to give succour to the idea that Aristotle's views were fundamentally unscientific and potentially pernicious. First, as is well known, Aristotle thinks that the heavenly spheres are alive and intelligent. They are inspired to move in their eternal circular paths by their contemplation of the unchanging perfection of a divine Unmoved Mover—in other words, because they desire to emulate divine perfection as well as they are able.[35] Second, Aristotle deploys teleological explanations in relation to the heavenly spheres, and also to the stars, which he also regards as living beings. Aristotle thinks that he has inescapable *physical* reasons for taking the spheres to be alive, however; and his application of teleology to these living beings is only to be expected, given its application in Aristotelian sublunary biology and its extraordinary success there. In the final section I shall argue that teleology turns out to be explanatorily fruitful in his astrophysics too. Before turning to that, however, I would like to reflect on how good Aristotle's astrophysics is, and how it can deal with some important difficulties.

4. How good is Aristotle's astrophysics?

I have already commented on the theory's simplicity, elegance, and comprehensiveness (relative to the data then current). As I have said, it is a commonplace in the history of science that it was because of the sheer authority with which Aristotle was invested that his physics continued to be pre-eminent until the time of Galileo and Kepler, and there is *some* truth in this; but it was also—and more importantly—because no one could devise a better astrophysics. It is instructive to compare it with what, to my mind, is its only serious rival in antiquity, that of Ptolemy, set out in book 2 of his *Planetary Hypotheses*.[36] Faced with a mass of new data which it seemed it could not accommodate, homocentric astronomy was replaced by a new and spectacularly successful system developed principally by Hipparchus in the second century BCE and Ptolemy in the second century CE. As far as we know, the most thoroughgoing attempt to revise Aristotle's *astrophysics* in the light of the demise of homocentric astronomy was also due to Ptolemy.[37] Aristotle's and Ptolemy's systems were, with modifications, the two dominant systems down to the time of Brahe and Kepler.[38] The most basic geometrical 'mechanisms' in Ptolemy's astronomy (see Diagram 1) are (i) the *deferent*, which revolves about the Earth either concentrically or, more often, eccentrically—that is, about a centre (O in the diagram) which is not the same as the centre of the Earth; (ii) the *epicycle*, carried round by the deferent, which rotates about its own centre in a circle which does not include the Earth, and which carries the planet; (iii) the use of what came to be called the *equant point*: some of the intrinsic circular motions in the system are not of uniform speed—i.e. not of uniform angular velocity—relative to the centre around which they rotate, but relative to another point (EP in the diagram) as far away from that centre as the Earth is and opposite to it; (iv) for Mercury and the moon the use of a ‘*crank*’—that is, motion about an eccentric point which itself rotates in a small circle (this is not illustrated in the diagram). Even at a very basic level of complexity, an astrophysics which directly embodies these mechanisms might seem impossible, especially if, like Ptolemy, one denies the existence of a void.

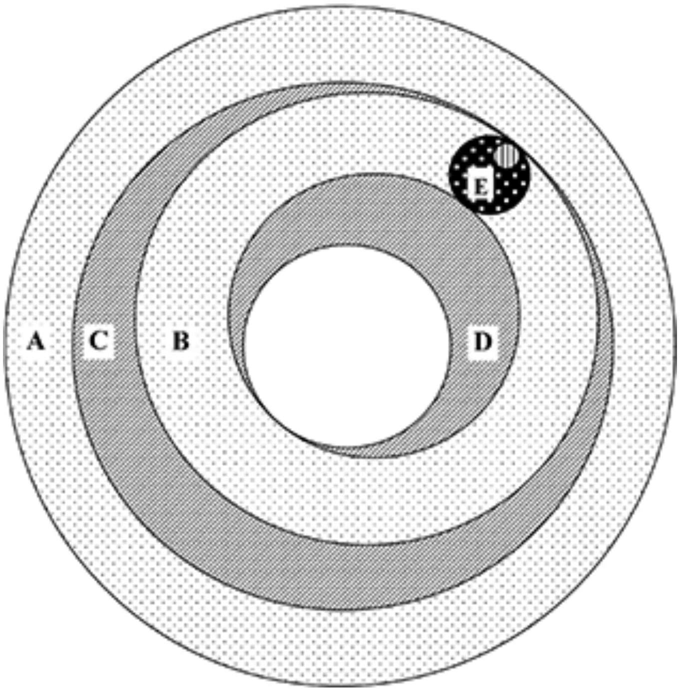
Diagram 1.



Epicycle, eccentric deferent, and equant point (*not to scale*)

Ptolemy’s solution is, in some ways, breathtaking, and deserves our admiration. A highly simplified version is given in cross section in Diagram 2.[39] Each planetary system is contained within a hollow sphere (A in the diagram) just like Aristotle’s spheres; this sphere is concentric with the Earth, and rotates homocentrically along the ecliptic.[40] It contains another concentric hollow sphere; the deferent (B) is a further sphere inside this, but off-centre, since it rotates eccentrically. It contains the epicyclic sphere(s) (E);[41] any further eccentric spheres are inside further homocentric ones. This type of arrangement leaves gaps, since each eccentric sphere is off-centre; these gaps are filled with additional aither (C and D) which allows unimpeded motion to the eccentric sphere which it adjoins. The planetary systems themselves are nested: the unshaded circle in the middle is where the lower planetary sets, and ultimately the Earth, are located.

Diagram 2.



Simplified illustration of Ptolemaic physics for a planet (*not to scale*)

In this way Ptolemy is able to retain a broadly Aristotelian picture of the heavens, as comprising a set of nested, homocentric spheres, with no void, while accommodating the mechanisms of his distinctly un-Aristotelian and un-homocentric astronomy.[42] I cannot pursue here any of the fruitful implications of this scheme—e.g. its impressive ability to yield calculations of planetary distances[43]—but I should mention another stroke of genius on Ptolemy's part. He saw that, in terms of physical structure, there was no need for every circular motion to be located in a complete *sphere*: for epicycles and deferents, 'sawn-off pieces' of spheres, of the minimum thickness required for the motion, would do (*PH* 2. 4): these are the famous 'tambourines' and 'whorls' (respectively) of Ptolemaic astrophysics.

For all its brilliance and intellectual boldness, Ptolemy's astro-physical system has some very serious deficiencies in comparison with Aristotle's. (i) Ptolemy does not have a clear or unifying account of the elemental nature of aither: he says that it is finer than the other elements, and perhaps that it comes in spherical shapes by nature;[44] but the other elements are not differentiated by their natural shape—and in any case many portions of aither in Ptolemy's scheme are not spherical.[45] (ii) More critically, Ptolemy has no good account of the physical basis of the movement of his celestial bodies. He treats each planetary system as (or as like) a living body with articulated parts which are moved in their various ways by the planet's soul—in the way in which, he says, a bird's soul moves its various parts.[46] He clearly wishes to hold that these planetary parts have a natural capacity for circular motion which is activated by their soul (*PH* 2. 3), but this view faces serious difficulties. (*a*) This circular motion can be around *any* centre, and not just around the centre of the universe: so there is no prospect of unification of this motion with the natural motions of the sublunary elements. (*b*) As I have said, the use of the equant point means that some intrinsic circular motions are not of uniform angular velocity relative to the centre around which they rotate.[47] It is, moreover, not an *accident* that they move with uniform angular velocity relative to the equant point—the equant should be what determines this feature of the sphere's motion[48]—but this fact has no physical basis in Ptolemy's system. These difficulties mean that Ptolemy really has no 'aither theory', and still less any sort of unified element theory—in sharp contrast to Aristotle. (iii) Ptolemy has nothing to say on how the aither can form articulated structures which move as a whole, while the portions of so-called 'loose aither' which fill up the gaps within a planetary system are not parts of this planetary structure and instead form a medium through which those parts can move.[49] (iv) Ptolemy vigorously rejects Aristotle's postulate that heavenly spheres transmit their motion to the next sphere inwards, and he regards each planetary system as insulated from the motion of the one above it;[50] yet the articulated parts of each system *do* transmit motion to other parts—while at the same time the 'loose aither' neither hinders the motions of these structures nor is moved around with them. Ptolemy has nothing to say on how all this can be. (v) What is the physics of how each planetary system acquires the diurnal 'primary motion?[51] On Taub's interpretation the star bestows this motion on its whole planetary system: if this is Ptolemy's view, it violates the key principle that each heavenly body is the subject of just one intrinsic circular motion. On Murschel's interpretation this motion is transmitted by the outermost shell: but then there is transmission of motion from one shell to another after all.[52] The force of at least some of these difficulties in comparison with Aristotle's astrophysics—especially those relating to non-homocentric and non-uniform motion—was clearly seen by Islamic astronomers who studied the *Planetary Hypotheses* in the ninth to fifteenth centuries.[53] They found ways to remove some of the difficulties—see (ii*b*) above—by replacing eccentrics, equantrelated non-uniform motion, and cranks by further systems of epicycles; but their solutions still required epicycles, and hence non-homocentric circular motions about many different centres—and these modifications did nothing to meet the difficulties facing Ptolemy in relation to element theory, the structure of aitherial bodies, and the transmission of motion. A sign of the strength of Aristotle's system is the fact that, even with these improvements, Ptolemy's astrophysics still seemed not to be viable to a number of Islamic thinkers—not only Aristotelian commentators,[54] but some astronomers too.[55] The position was similar in the Renaissance: some astronomers, such as Copernicus, accepted the Islamic modifications of Ptolemy's astronomy; but there were others who thought that insuperable difficulties remained, and for that reason thought that Aristotelian homocentric theory simply *had* to be correct despite the problems it posed for astronomy.[56]

5. Problems facing homocentric theory

Aristotle acknowledges in a number of places the difficulty of answering scientific questions about the heavens.[57] Nonetheless, he thinks that some things about the heavens are ‘evident to perception’;[58] and he is certainly clear that a satisfactory astronomical theory must ‘give the phenomena’.[59] He rightly does not attempt to explain every structural feature of the cosmos;[60] nonetheless, his homocentric astrophysics faces a number of difficulties of which he either was aware or could have been aware even without additional astronomical data, and which do merit a response. I shall describe the principal difficulties, together with a brief account of responses which Aristotle either did make or could have made. Note that (apart from the last one I shall mention—the variable brightness of some planets) these are all problems which Ptolemy’s system faces too.

(1) Aristotle maintains that each star is an individual living being in the form of a solid sphere, set within but distinct from the heavenly sphere which carries it around:[61] but how can it be a distinct being if both are composed of aither? Aristotle says nothing about this. He does appear to hold that the aither varies in purity, especially in the lower regions of the heavens near the moon,[62] and he could hold that the stars are distinguished from the heavenly spheres by a special degree of purity; but this does not sit well with the idea that the impurities do not exist, or tail off, in regions closer to the fixed stars. A better idea is that the stars’ aither is significantly *denser* than that of the heavenly spheres.[63] This would also give Aristotle a basis for a response to another question which he does not address: (2) why, when the heavenly spheres are transparent—which they must be, since otherwise the fixed stars and the planets above the moon would not be visible—are the stars and planets *opaque*—as they must be given Aristotle’s own data on the occultation of fixed stars and planets by the moon and other planets,[64] and the existence of solar eclipses?[65]

(3) It is a clear implication of homocentric theory that the stars are carried round by the sphere in which they are fixed; and Aristotle explicitly argues for this in *De caelo* 2. 8. It is a common complaint that since the stars are themselves made of aither, they should have a geocentric circular motion of their own. I think that this complaint is

misplaced, though Aristotle frames his argument in 2. 8 somewhat unhelpfully in terms of whether the stars move or are at rest, concluding that they are at rest,[66] and the idea that the stars are *carried* by their sphere has to be understood in a particular way. What Aristotle means in 2. 8 is that the stars do not possess their motion *independently* of the action of the spheres.[67] As we have seen, the nature of aither involves a capacity for circular motion around the centre of the universe which requires activation by something else. It also needs to be realized in a determinate way as regards speed, direction, and angle. Aristotle's view must, I think, be that the stars do indeed have the same capacity for circular motion as the heavenly spheres, but that in the case of a star this is activated by the sphere which carries it rather than by its own soul; it is likewise the sphere which gives the star's rotation its determinate character. If this is right, then a star is not carried round by its sphere as someone might carry a brick across a room—as an entirely passive object. It is more like the case of the motion of a brick held by someone who jumps off a cliff: the brick falls with its own weight (it is not dragged down by the one who one carries it, as, say, a helium balloon would be), though it would not fall at all, and/or where and when it does, without the carrier's jump.[68] This answers the complaint, although it is not quite the whole story, since, as we shall see, the planet's motion is at least part of how it attains its own good.

(4) How is it that the stars shine while the heavenly spheres do not?[69] The standard view is that Aristotle thinks that both the stars' shining and the sun's emission of heat are due to the ignition of air in the region directly below each star, caused by a motion imparted to it, from a distance, by the star in question via the fire just above the air; and it is true that Aristotle says that their heat and light are produced in this way.[70] On this view, the item that emits light when a star 'shines' is not the star itself, but a patch of burning air somewhere below it. One obvious problem, which on any interpretation Aristotle does not appear to address, is that the planets above the level of the moon are

simply not in contact with this fire at all: this imparting of motion will have to involve something like a one-way field effect rather than ordinary pushing or pulling.[71] As an explanation of the stars' shining, this 'burning air' account is quite obviously hopeless. (i) Aristotle knows about the occultation of one heavenly body by another, and he thinks that it follows immediately that the occulting body is closer to the Earth than the occulted one:[72] this inference is entirely undercut if what is rendered invisible in an occultation is in the first instance a patch of burning air in the sublunary region. (ii) Solar eclipses (in which an apparently *dark* moon makes the sun invisible) should on this account simply not happen.[73] (iii) The fact—well known by Aristotle's time—that the moon shines with light reflected from the sun[74] is very hard to square with this account, and lunar eclipses, which occur when the sun's light is blocked by the Earth, would be especially hard to account for, as would be the moon's phases. (iv) Aristotle's account of why the fixed stars twinkle and the planets do not (*De caelo* 2. 8, 290^{a}18–24) relies on the relative distances of the stars and planets (not those of their respective patches of burning air) from the observer.[75] What is more, this interpretation is flatly inconsistent with Aristotle's general account of light at *DA* 2. 7. For Aristotle, light is not a type of ray emitted by a luminous body (nor even a ray propagated by the eye, as some of his predecessors thought): it is rather the condition of transparent media such as air or water in which bodies are visible.[76] It is brought about by the action of 'fire, or something such as the body above' (412^{b}11–13). So the field-effect account of the stars' light in *De caelo* 2. 7 is not an explanation of their *shining*—their luminosity—which he should for all the reasons given above take to be an intrinsic property of the stars.[77] It is instead an explanation of the general illumination of the world around us brought about by the sun and other heavenly bodies—that is, of how they make objects around us visible without shining directly on them. This is the role of the burning air which the stars and planets produce.[78]

(5) This leaves the question why, if the other stars are luminous, the moon is not. Though Aristotle says nothing about this, nor about the question as to why the moon has a variegated surface,[79] I think that these facts may be the reason why he posits the impurities (presumably an admixture of fire) in the lower regions of the aither mentioned above. We would have to suppose that the impurities were enough to prevent luminosity, but not enough to affect the moon's opacity; unevennness in the impurities would account for the non-uniform appearance of its surface by affecting its reflectivity.
(6) How can the fact that some stars generally appear to be a different colour from others be explained if they are all composed of aither? Aristotle does not address this question; the simplest response would be to suppose that there are qualitative differences in different portions of aither. Aristotle denies that the heavenly bodies can change qualitatively; but this does not seem to rule out unchanging qualitative differences.[80] (7) Variations in the apparent colour of an individual planet such as Jupiter could be explained (as they are today) on a par with the differences in colour of the sun and moon, in terms of differences in atmospheric conditions.
(8) How can the significant variations in the brightness of individual planets be explained? This is routinely cited in histories of astronomy as a decisive objection to homocentric theory, an objection of which, moreover, Aristotle himself is supposed to have been aware.[81] This idea stems from a passage in Simplicius, quoting Sosigenes (*In De caelo* 504. 17–505. 23 Heiberg, with omissions):

> οὐ μὴν αἵ γε τῶν περὶ Εὔδοξον σώζουσι τὰ φαινόμενα, οὐχ ὅπως τὰ ὕστερον καταληφθέντα, ἀλλ᾽ οὐδὲ τὰ πρότερον γνωσθέντα καὶ ὑπ᾽ αὐτῶν ἐκείνων πιστευ θέντα. ... ἀλλ᾽ αὐτό γε τοῦτο, ὅπερ καὶ τῇ ὄψει πρόδηλόν ἐστιν, οὐδεὶς αὐτῶν μέχρι καὶ Αὐτολύκου τοῦ Πιταναίου ἐπεβάλετο διὰ τῶν ὑποθέσεων ἐπιδεῖξαι, καίτοι οὐδὲ αὐτὸς Αὐτόλυκος ἠδυνήθη· ... ἔστι δέ, ὃ λέγω, τὸ ποτὲ μὲν πλη σίον, ἔστι δὲ ὅτε ἀποκεχωρηκότας ἡμῶν αὐτοὺς φαντάζεσθαι. καὶ γὰρ τῇ ὄψει

> συμφανὲς ἐπ᾿ ἐνίων τοῦτό ἐστιν· ὅ τε γὰρ τῆς Ἀφροδίτης λεγόμενος ἀστὴρ καὶ δὴ καὶ ὁ τοῦ Ἄρεος κατὰ μέσας τὰς προηγήσεις αὐτῶν πολλαπλάσιοι φαίνονται, ὥστε ὅ γε τῆς Ἀφροδίτης ἐν ἀσελήνοις νυξὶ σκιὰς πίπτειν ἀπὸ τῶν σωμάτων ποιεῖ, . . . ἀλλὰ μὴν οὐδὲ ὡς ἐλελήθει γε αὐτοὺς ἡ ἀνισότης τῶν ἀποστημάτων ἑκάστου πρὸς ἑαυτόν, ἐνδέχεται λέγειν. Πολέμαρχος γὰρ ὁ Κυζικηνὸς γνωρίζων μὲν αὐτὴν φαίνεται, ὀλιγωρῶν δὲ ὡς οὐκ αἰσθητῆς οὔσης διὰ τὸ ἀγαπᾶν μᾶλλον τὴν περὶ αὐτὸ τὸ μέσον ἐν τῷ παντὶ τῶν σφαιρῶν αὐτῶν θέσιν.
>
> The [hypotheses] of those associated with Eudoxus do not preserve the phenomena—not just those phenomena which were apprehended later, but also those which were known earlier and were accepted by them themselves. ... But this very thing, at any rate, which is also manifest to sight, none of them until Autolycus of Pitane[82] tried to establish through hypotheses—and not even Autolycus himself was able to do this. ... What I mean is that at some times the planets appear near, while at other times they appear to have moved away from us. And in the case of some this is quite apparent to sight. For the star which is called the star of Aphrodite [i.e. Venus] and also the star of Ares [Mars] appear many times larger in the middle of their retrogressions, so that on moonless nights the star of Aphrodite causes shadows to fall from bodies. ... And yet it is possible to say that the inequality of the distances of each of the planets in relation to itself in no way escaped them [i.e. those associated with Eudoxus], for Polemarchus of Cyzicus[83] clearly recognizes it, but chooses to make little of it on the grounds that it is not perceptible, because of his greater love for [homocentric theory]. (trans. Mueller, with modifications)[84]

If this is right, the key problem was the theory's inability to allow a planet's distance from the Earth to vary. The complaint is misguided in two quite separate ways, however—and odd in another way. First, as Bowen points out,[85] Venus is not visible at all in the middle of its retrogression. As stated by Sosigenes, the recalcitrant phenomenon is *not* one 'quite apparent to sight', but rather a theoretical construction from a consequence of epicyclic astronomy: since epicycles mean that the variation in a planet's brightness *can* be explained in terms of variations in its distance from the Earth, someone might suppose that Venus will be brightest when its epicycle brings it closest to the Earth, namely at the middle of its retrogression.[86] Of course it does not follow from this that sky-gazers of Aristotle's day were not aware of changes in the brightness of some of the planets:[87] so the complaint may have *some* historical basis. That said, the way in which the complaint is odd is in what it says about Polemarchus—if he did 'recognize' these variations in actual distance, their (im)perceptibility would have been neither here nor there; if he did not, there was from his point of view simply nothing for him to 'choose to make little of'. This suggests some misunderstanding and/or hostility on the part of Sosigenes or his source.[88] In any case, the second way in which the complaint is misguided is to suppose that the *only* explanation of variation in brightness or apparent sizes which could be offered is the changes in the distance of the planet in question—so that homocentric theory simply could not offer *any* explanation: this is hardly the case. It is obvious, for instance, that atmospheric conditions affect the brightness of the sun and the moon, so a homocentric theorist could posit locally varying atmospheric conditions as the explanation; the idea that a star can move the fire and the air below it might also suggest that a star could sometimes move a patch of clearer or murkier atmosphere round with it, explaining how it could remain brighter or dimmer for significant periods of time. This sort of explanation would become inadequate only when better data revealed regularities in the change in brightness which were predictable in relation to the planet's synodic period; but such data will not have been available in Aristotle's day.[89]

Some of these responses and explanations are clearly *ad hoc*. It is not so clear that Aristotle should find this problematic, however, given his entirely sensible reservations about our ability to gain scientific knowledge of the heavens. And despite the complaints of commentators from Sosigenes on, none of these problems ought to have encouraged Aristotle simply to abandon his astrophysics.

6. Aristotle's astrophysical teleology

Commentators make various complaints about Aristotle's use of teleology in his astrophysics. Thus, for instance, it is sometimes claimed that Aristotle uses teleological arguments in the *De caelo* as a *deus ex machina* when he is at a loss for a non-teleological answer to structural questions which in any case, commentators sometimes feel, were better left unasked.[90] Again, it is sometimes thought that his use of teleology is tentative or provisional.[91] Not only is teleology more pervasive in the *De caelo* than these charges would lead us to expect, however, but Aristotle has a very clear and consistent position: the heavenly spheres and the stars are alive, and how they move is partly constitutive of their attaining their own good (see 2. 2 and 5; 2. 3; 2. 12). Note that Aristotle does not argue in terms of what might be the best conceivable way for things to be; nor does he appeal to what is good in some vague general sense, or to what is good for the cosmos as a whole, but rather to the good of individual substances—just as he does in biology (see pp. 183 ff. below). This is also his position in *Metaphysics* *Λ* 8, in which the teleological character of the heavenly motions is taken as a given in his argument about the number of heavenly spheres. I shall chiefly focus here on the account in Λ: there are some serious challenges here too to the idea that Aristotle is as positive and consistent in his application of teleology to astrophysics as I have suggested.

On the orthodox view of *Λ*, teleology does figure in astrophysics because of the way in which each of the heavenly spheres seeks to emulate the perfection of its Unmoved Mover, but it does not figure directly in the account of the motions of the stars and planets. On this orthodox view, the perfection which the heavenly spheres achieve—apart from any thinking which they might do—consists in their moving their bodies in an eternal, unchanging, perfect motion. This (again in addition to their thinking) is what the successful nature of their lives consists in. But if this is right, the movements of the *planets*, which this elaborate system of rotating spheres produces, seem to be no more than the incidental by-products of the arrangement: they are irrelevant to the physics of the heavens. This view is well put by Lloyd:

> The perfection of each moved mover [is] secured and exemplified by its eternal perfectly regular circular motion. … From the point of view of the entire system of 55 unmoved movers and the 55 moved movers, one cannot help thinking that the fact that there is, from time to time, a planet, such as Jupiter, … is, in a way, an irrelevance.[92]

If this were right, it would seem to be a serious defect in Aristotle's integration of astronomy and physics. I shall argue that it is not Aristotle's position, as a passage in *Λ* 8 (1074a17–31) shows. This passage provides evidence that he takes the motion of each heavenly sphere to be for the sake of the motion of a *star*:

> εἰ δὲ μηδεμίαν οἷόν τ᾽ εἶναι φορὰν μὴ συντείνουσαν πρὸς ἄστρου φοράν, ἔτι δὲ πᾶσαν φύσιν καὶ πᾶσαν οὐσίαν ἀπαθῆ καὶ καθ᾽ αὑτὴν τοῦ ἀρίστου τετυχηκυῖαν τέλος εἶναι δεῖ νομίζειν, οὐδεμία ἂν εἴη παρὰ ταύτας ἑτέρα φύσις, ἀλλὰ τοῦτον ἀνάγκη τὸν ἀριθμὸν εἶναι τῶν οὐσιῶν. εἰ γὰρ εἰσὶν ἕτεραι, κινοῖεν ἂν ὡς τέλος οὖσαι φορᾶς· ἀλλὰ εἶναί γε ἄλλας φορὰς ἀδύνατον παρὰ τὰς εἰρημένας. τοῦτο δὲ εὔλογον ἐκ τῶν φερομένων ὑπολαβεῖν. εἰ γὰρ πᾶν τὸ φέρον τοῦ φερομένου

> χάριν πέφυκε καὶ φορὰ πᾶσα φερομένου τινός ἐστιν, οὐδεμία φορὰ αὑτῆς ἂν ἕνεκα εἴη οὐδ᾽ ἄλλης φορᾶς, ἀλλὰ τῶν ἄστρων ἕνεκα. εἰ γὰρ ἔσται φορὰ φορᾶς ἕνεκα, καὶ ἐκείνην ἑτέρου δεήσει χάριν εἶναι· ὥστ᾽ ἐπειδὴ οὐχ οἷόν τε εἰς ἄπειρον, τέλος ἔσται πάσης φορᾶς τῶν φερομένων τι θείων σωμάτων κατὰ τὸν οὐρανόν.
>
> But if it is necessary to think that there could be no motion which is not bound up with the motion of a star, and further that every nature and every substance which is unaffected, and which has in virtue of itself attained the best, is an end, there would be no other nature beyond these, but [rather] it would be necessary that this be the number of the substances. For if there are others, they would cause motion as being an end of motion; but it is impossible for there to be other motions beyond the ones stated. And it is reasonable to suppose this from the things that are being moved. For if [sc. in the case of the heavens] everything that causes motion is for the sake of what is moved and every motion belongs to something which is moved, no motion could be for the sake of itself or of another motion, but it must be for the sake of the stars. For if there is to be a motion for the sake of a motion, then the latter too will have to be for the sake of something else; consequently, since it cannot go on to infinity, the end of every motion will be one of the divine bodies [i.e. in this case the stars] which are being moved in the heavens.

Aristotle is arguing here that the number of heavenly Unmoved Movers (in addition to the Prime Mover) is the same as the number of additional heavenly spheres required to explain the motion of the planets. He argues first that the Unmoved Movers are equi-numerous with the heavenly spheres, and then that there are no *more* heavenly spheres than are required to explain the motion of the stars. It is this last claim which is of interest to us. He supports it with two further claims:

(1) There could be no motion [sc. of a heavenly sphere] which is not bound up with the motion of a star.[93]

(2) The end of every such motion will be one of the stars.

The claim at 1074a25 ff. that these motions are for the sake of what is moved (the star), rather than simply for the sake of the perfection of the heavenly spheres themselves, is surprising, but we should not regard it as a momentary aberration, for a number of reasons. First, the claim is parallel to the immediately preceding one at a21–3 concerning the Unmoved Movers ('every nature and every substance which is unaffected and which has in virtue of itself attained the best is an end'). Second, a linkage of the Unmoved Movers with the motions of the stars, rather than with those of the heavenly spheres, was already foreshadowed at 1073a34–6:

> ἥ τε γὰρ τῶν ἄστρων φύσις ἀΐδιος οὐσία τις οὖσα, καὶ τὸ κινοῦν ἀΐδιον καὶ πρότερον τοῦ κινουμένου, καὶ τὸ πρότερον οὐσίας οὐσίαν ἀναγκαῖον εἶναι.
>
> For the nature of the stars is eternal, being a substance of some kind, and the mover must be eternal and prior to what is moved; and what is prior to a substance must be a substance.

Throughout chapters 6 and 7 Aristotle has argued for the existence of unmoved substances on the basis that there are eternal circular motions, and that these require an unmoved cause; these circular motions are plainly the motions of the spheres, not of the stars. The same is true of the present chapter, in which it is the number of moving spheres, not the number of moving stars, which determines the number of Unmoved Movers. Yet here Aristotle talks of the stars as if they are the things which are primarily moved by the Unmoved Movers.

So Aristotle does include teleology in his system, and it seems that he takes motions of the whole system of 55 or 49 spheres to be explained by the goodness of the movements of the planets. Aristotle's astronomical physics is unified with his sublunary physics in a satisfying manner after all. It may, however, seem as if Aristotle as I interpret him has jumped from the frying pan into the fire. It is a key principle of Aristotle's teleology that a teleological explanation of why *X* has a certain feature or behaves in a certain way must cite the good of *X*:

> καὶ πάντως ἀποδοτέον τὸ διὰ τί, οἷον ὅτι ἐκ τοῦδε ἀνάγκη τόδε (τὸ δὲ ἐκ τοῦδε ἢ ἁπλῶς ἢ ὡς ἐπὶ τὸ πολύ), καὶ εἰ μέλλει τοδὶ ἔσεσθαι (ὥσπερ ἐκ τῶν προτάσεων τὸ συμπέρασμα), καὶ ὅτι τοῦτ᾽ ἦν τὸ τί ἦν εἶναι, καὶ διότι βέλτιον οὕτως, οὐχ ἁπλῶς, ἀλλὰ τὸ πρὸς τὴν ἑκάστου οὐσίαν. (*Phys.* 2.7, $198^{b}5$–9)
>
> We must explain the *why* in every way, namely ... [a list of the various ways, concluding with teleology:] ... and because it is better thus—not without qualification, but with reference to the essential being of each thing.[94]

Indeed, this *should* be a key principle of Aristotelian natural teleology: it is hard to make any sense of the idea that the features or behaviour of a natural substance are, in virtue of that substance's own nature, sensitive primarily to the good of something *else*—unless we import a designer or a cosmic nature.[95] As I have said, Aristotle appears to conform to this principle in the teleology of the *De caelo*. On the interpretation of *Λ* 8 which I have just sketched, however, the heavenly spheres are teleologically connected to the good of *other* things—the stars. This might seem to suggest that the heavens form a quite different sort of teleological system: the *perfection* of the motions of the spheres—the unvaryingness of their uniform, circular motion—does indeed serve the good of the spheres themselves in the way traditionally understood, but their most important features, astronomically speaking—their particular speed, direction, and so on—are teleologically explained by the way in which they, in concert with the rest of the motions in the same planetary set, serve the good of the *stars*. So, it seems, either we have to accept that Aristotle believes in some form of communitarian teleological system in the celestial region, or we will have to play down the idea that the motions of the spheres really are for the sake of the stars. I shall argue that we are in fact obliged to do neither.

At this point, however, someone might raise an objection to the very idea that we should apply the *Physics* principle to this case, because the heavenly spheres are *agents*. Aristotle says nothing about the conditions governing the reaction of the soul of a heavenly sphere to its Unmoved Mover. Since the model appealed to is that of love and the object of love, we might suppose, as this objection holds, that we should think of the heavenly sphere by way of analogy with a human deliberative agent (though it presumably has no alternatives to choose between, so it can hardly *deliberate*). Moreover, it is quite unclear whether its single option for physical movement is given to it by something internal and psychological, or by the physical configuration of its body and the surrounding bodies, or even in some other way. Just as he is silent on the 'mechanics' of the transmission of motion from one sphere to the next, Aristotle is silent in *Λ* on whether the angle, direction, and speed of a sphere's own intrinsic rotation are determined by physical structures—the location and nature of physical axes of rotation, etc.—so that the heavens are like a vast clock, in which love plays only the role of the weights on the pendulum, or whether they are principally a matter of the *form* of the sphere—and if so whether this is a matter of the choices and desires of the heavenly sphere.[96] It is thus unclear how far we should think in terms appropriate to, or suggestive of, deliberative agents, and how far in terms appropriate to natural teleology.

Let us suppose (as I am quite inclined to) that the spheres act principally on the basis of desires, and also (as I am inclined *not* to) that this means that the *Physics* principle does not apply. It seems that an analogous problem arises nonetheless. On the standard view, the soul of a heavenly sphere is inspired to activate the motion of its spherical body because in this way the soul–sphere compound comes closest to the perfection of the Unmoved Mover which inspires it. Once again, even the partial subordination of this motion to the good of something else (the *star*) makes little sense: the motion of the star might be a good *by-product* of the sphere's pursuit of perfection—though that would be the unsatisfactory position with which we began —but could hardly be an additional *end*. And it will turn out that, just as the problem is similar, the solution is similar also.

Turning back to the *Physics* principle, first of all, I shall argue that we can understand the idea that the motion of the spheres is genuinely for the sake of the stars in such a way that it is compatible with the principle; if this is right, we do not have to accept either horn of the dilemma I sketched earlier. The principle requires the final cause of *X*'s being *F* to be a good for *X*: this leaves open the possibility that *X*'s being *F* might be for the sake of something else, *Y*, *providing* that benefiting *Y* in the relevant way is itself good for *X*. So, I suggest, the heavenly sphere contributes to the motion of its star because the latter's motion in some way benefits the sphere itself. It is hard to see what *consequential* benefit the heavenly sphere might derive from the motion of its star: a more promising possibility, however, is that the motion of the star *constitutes* a benefit to the sphere. What we should suppose is that the motion of the star is closely connected with the perfection of the heavenly sphere: in other words, we should suppose that contributing to the star's motion is itself a part of what the sphere does to emulate the perfection of its Unmoved Mover. This could only be the case, or could only reasonably be the case, if we suppose that Aristotle thinks that the path of the star across the heavens is a supremely beautiful thing.

Construed in this way, contributing to the star's motion could indeed be part of the perfection achieved by the heavenly spheres. We can now see how Aristotle can say that the motions of the heavenly spheres are for the sake of the motions of the stars *and* continue to hold the *Physics* principle: perfection, for a heavenly sphere, *consists* (or partly consists) in helping to create beauty in the cosmos.[97] A parallel account can be given if we think of the spheres as more like deliberative agents. The line of thought just sketched shows how the spherical motion of the sphere can, compatibly with Aristotle's other commitments, be taken to be aimed at producing the motion of the star: it does not matter, for present purposes, whether we take *being aimed at* to be a non-psychological or a psychological matter. In the latter case, a comparison with a particular sort of craft may be helpful. In crafts such as that of dancing, the product aimed at is not something distinct from the high-level exercise of the craft—the distinction between ποίησις and πρᾶξις, production and action, is all but lost. The best life for the dancer consists in the making of excellent or beautiful dancing. Activities of this kind are not *merely* the production of some external good thing, the performance: it is in these activities that the performer realizes her own perfection. She aims at the making of beauty, but only, or principally, because that is what it is for her to realize her own perfection as a dancer. Whether this relation is solely *constitutive*, or *motivational* as well—so that she aims at the beauty of the dance because she aims at the realization of her own perfection—is another and trickier question, which does not matter for my present purposes and which I shall not address. Of course the differences between a heavenly sphere and a craftsman are many; but what I am suggesting is that—if we take it to be like a deliberative agent—the sphere aims at the maintenance of a beautiful feature of the cosmos in something like the way the dancer aims at creating a beautiful dance. We can now see how Aristotle can think that the motions of the heavenly spheres are for the sake of the motions of the planets *and* for the good of the spheres themselves: it is part of the best life for them to create beauty in the cosmos.

This, I think, is the keystone of Aristotle's astrophysics, whose merits I have tried to outline in this paper: the heavenly spheres are like dancers. Some ancient philosophers believed in the music of the spheres—that the spheres made a wonderfully harmonious sound as they went round in their circular paths.[98] Aristotle does not believe this, of course. But what I am suggesting is that he does believe in the *dance* of the spheres—an eternal and wonderful dance about the still centre of the Earth.

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Notes

1 In Aristotle’s usage, which I shall follow, ‘stars’ (ἄστρα/ἀστέρες) refers not only to what we normally call the stars (the so-called unwandering (ἀπλανεῖς) or fixed stars), but also to what most Greeks thought of as the seven ‘wandering stars’, or planets (πλάνητες/πλανῆται)—Saturn, Jupiter, Mars, Venus, and Mercury, together with the sun and the moon (but not, generally, the Earth, since, according to most ancient ways of

thinking, the Earth does not move). I shall use 'cosmos' as a term of art for a system containing Earth, planets, and fixed stars. Some ancient thinkers thought the cosmos in which we live comprises the whole of the universe (τὸ πᾶν); others thought that the universe extended infinitely beyond our cosmos. This is a more relaxed us- age than the one explored in T. Kukkonen, 'On Aristotle's World', *Oxford Studies in Ancient Philosophy*, 46 (2014), 311–52: according to that usage, only a world which possesses something like the elevated kind of unity which according to Plato's *Republic* is bestowed by the Form of the Good counts as a cosmos.

2 Possibly Plato (*Tim*. 40 B 8–C 3 (but see *Tim*. 39 B–C); Arist. *De caelo* 2. 13, 293^{b}30–2; Plut. *Plat. quaest*. 1006 C 1–11); Hicetas of Syracuse (5th cent. BCE: Cic. *Acad*. 2. 123); Heraclides of Pontus and Ecphantus (a 4th-cent. BCE Platonist and Pythagorean respectively: Diels, *Dox. Gr*. 378); Seleucus (mid-2nd-cent. BCE: see the Plutarch passage just cited; Stob. 1. 38. 9).

3 Anaxagoras (*c*.500–428 BCE), Democritus (*c*.460–?), Epicurus (341–270), and the Stoics.

4 Philolaus of Croton (*c*.470–*c*.385 BCE) and perhaps some other Pythagoreans: the Earth, the sun, and seven (*sic*) other planets go around a 'central fire' (Arist. *De caelo* 2. 13, 293^{a}17–27); Aristarchus of Samos (*fl*. *c*.280) advanced a heliocentric system in which the Earth moves around the sun and also rotates about its own axis (Archim. *Aren*. I. 4–5; Plut. *De facie* 922 F 4–923 A 6).

5 At *De caelo* 2. 14, 296^{a}24–297^{a}8, Aristotle gives two arguments based on natural motions, and one based on the idea that if the Earth were a planet, it ought, as the other planets do, to have a complex motion rather than a simple one: but then the apparent motion of the fixed stars would be very different from what it is. He also points out that the Earth's being stationary is consistent with the astronomy. That someone appealed to the (apparent) absence of stellar parallax is suggested by Aristarchus' claim about the size of the Earth relative to the size of the cosmos (see reference in n. 4); Aristarchus' defence was used by Ptolemy (*Synt*. I. 6) and by Copernicus (*De revolutionibus* I. 10 (this work was begun in 1515 and first published in 1543); cf. Assumption 4 in the *Commentariolus* (1514)). A more physical argument for the Earth's immobility is offered by Ptolemy (*Synt*. I. 7).

6 D. Leverington, *Encyclopedia of the History of Astronomy and Astrophysics* [*Encyclopedia*] (Cambridge, 2013), 67; cf. 18.

7 A. Berry, *A Short History of Astronomy* [*Astronomy*] (London, 1898; repr. New York, 1961), 29: '[Aristotle] treated the spheres [of Eudoxus and Callippus] as material bodies, thus converting an

ingenious and beautiful geometrical scheme into a confused mechanism'; cf. D. R. Dicks, *Early Greek Astronomy to Aristotle* [*Early Greek Astronomy*] (London, 1970), 203.

8 G. E. R. Lloyd, '*Metaphysics* Λ 8' ['Λ 8'], in M. Frede and D. Charles (eds.), *Aristotle's* Metaphysics *Lambda: Symposium Aristotelicum* [Metaphysics *Lambda*] (Oxford, 2000), 245–73 (this quotation 261); cf. D. J. Furley, 'Aristotle the Philosopher of Nature' ['Aristotle'], in D. J. Furley (ed.), *From Aristotle to Augustine*, Routledge History of Philosophy, 2 (London, 1999), 9–39 at 18. I address this charge in L. Judson, *Aristotle*, Metaphysics *Λ: A Translation and Commentary* [Metaphysics Λ] (Oxford, forthcoming), notes on ch. 8.

9 I discuss some of these problems in sect. 5.

10 Berry, *Astronomy*, 33; cf. O. Pedersen, *Early Physics and Astronomy: A Historical Introduction*, 2nd edn. (Cambridge, 1993), 69–70: 'In its Aristotelian version, the system survived for a very long time among scholars whose veneration for Aristotle, combined with their scanty mathematical equipment, made them ignorant of the deficiencies of the concentric system.'

11 J. al-Khalili, *Pathfinders: The Golden Age of Arabic Science* (London, 2010), 208–9. Compare A. Koestler, *The Sleepwalkers: A History of Man's Changing Vision of the Universe* (London, 1959), ch. 5: whereas with Aristarchus 'Greek science was on the straight road to the modern universe', Plato, Aristotle, and Ptolemy took it down an 'extraordinary cul de sac' (68): '[Aristotle's system of planetary spheres] was an extremely ingenious system—and completely mad, even by contemporary standards' (73); 'Aristotle had a millennial stranglehold on physics and astronomy' (64). A more judicious view can be found in S. Toulmin and J. Goodfield, *The Fabric of the Heavens: The Development of Astronomy and Dynamics* [*Fabric*] (Chicago and London, 1961), 105–12.

12 The picture was principally due to Paul Duhem ('Σώζειν τὰ φαινόμενα' , *Annales de philosophie chrétienne*, 6 (1908), 113–38, 277–302, 352–77, 482–514, 561–92; translated as *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo*, by E. Doland and C. Maschler (Chicago and London, 1969)); for discussion see L. Wright, 'The Astronomy of Eudoxus: Geometry or Physics?', *Studies in the History and Philosophy of Science*, 4 (1973), 165–72; G. E.R. Lloyd, 'Saving the Appearances', *Classical Quarterly*, NS 28 (1978), 202–22 (repr. with a new introduction in id., *Methods and Problems in Greek Science* (Cambridge, 1991), 248–77); A. Musgrave, 'The Myth of Astronomical Instrumentalism' ['Astronomical Instrumentalism'],

in G. Munévar (ed.), *Beyond Reason: Essays on the Philosophy of Paul Feyerabend*, Boston Studies in the Philosophy of Science, 132 (Dordrecht, Boston, and London, 1991), 243–80. Wright argues against the view that Eudoxus was an instrumentalist and in favour of the view that he was attempting ‘to do explanatory, physical astronomy’. His principal argument is that no one who sought a purely predictive device for planetary motions would confine themselves to homocentric motions. But while it may be incompatible with a thoroughly instrumentalist approach, accepting this constraint is compatible with regarding a proper theory of planetary motion as a matter of geometry alone (especially in the context of Plato’s claim that true astronomy was (non-instrumentalist but) purely geometrical).

13 See e.g. Berry, *Astronomy*, quoted in n. 7 above; T. S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Cambridge, Mass., 1957), 79; M. L. Gill, ‘Aristotle on Self-Motion’, in M. L. Gill and J. G. Lennox (eds.), *Self-Motion from Aristotle to Newton* [*Self-Motion*] (Princeton, 1994), 15–34 at 33 n. 53; J. North, *Cosmos: An Illustrated History of Astronomy and Cosmology* (Chicago and London, 2008), 81.

14 Note that in each system Aristotle describes the first sphere as ‘that of the unwandering stars’: this is acceptable for the specification of separate models, but would not do for a physical system, which only contains one sphere for the fixed stars, not seven. On the other hand, Aristotle may only mean that the first sphere in each case has the same motion as the sphere of the fixed stars. At the same time, when Aristotle talks of *spheres* in the schemes of Eudoxus and Callipus, he draws no distinction between (merely) geometrical spheres and physical ones; but it is hard to draw any conclusions from this one way or another, since we cannot exclude the possibilities (i) that Eudoxus and Callipus may have had physical spheres in mind, (ii) that they used the term ‘sphere’ with a similar lack of distinction, and (iii) that, with his eye on his own theory, Aristotle may be recasting an account given in terms of spherical *motions* in terms of the motions of spheres.

15 Nor, for that matter, does being a realist about the heavenly spheres *require* their being connected in the way Aristotle supposes: the ‘Eudoxan’ systems of spheres could, in principle, be set concentrically in the heavens, with connections within each system but none between systems (and the discussion in *De caelo* 2. 12 seems to presuppose that the sets of heavenly spheres envisaged there are not interconnected: see I. Bodnár, ‘Eudemus’ Unmoved Movers: Fragments 121–123b Wehrli’, in I.

Bodnár and W. W. Fortenbaugh (eds.), *Eudemus of Rhodes* (New Brunswick, NJ, and London, 2002), 171–89 at 177 n. 7); for a different view see H. J. Easterling, 'Homocentric Spheres in *De caelo*,' *Phronesis*, 6 (1961), 138–53 at 141–3.

16 Beyond his purely mathematical work we know remarkably little about Eudoxus. His dates are uncertain, but probably fall within the range 410/390–360/ 340 BCE); it is not known when Eudoxus developed his astronomical theory. It was probably set out in a book called *On Swift Things* or *On Swiftnesses* (Περὶ ταχῶν), which is now lost, and to which only one explicit reference survives (Simpl. *In De caelo* 494. 11–12 Heiberg).

17 Callippus is said to have been a student in Eudoxus' school in Cyzicus; we know that he worked in Athens and devised an astronomically important 76-year cycle to harmonize the solar and lunar years, a cycle which seems to have commenced in June 330 BCE. Commentators have argued that Callippus' work on homocentric theory must also date from about this time or later, but there is little basis for this. It is unclear whether or not Callippus wrote a book on homocentric theory; if not, Aristotle must be reporting lectures or discussions. (Simplicius says that he worked with Aristotle, 'correcting and amplifying Eudoxus' discoveries with [him]' (*In De caelo* 493. 5–8 Heiberg); but this may simply be someone's inference from *Metaph*. *Λ* 8.)

18 Simpl. *In De caelo* 488. 18–24, 493. 4–506. 8 Heiberg, translated in I. Mueller, *Simplicius*, On Aristotle, *On the Heavens, 2. 10–14* (London, 2005), and in A. C. Bowen, *Simplicius on the Planets and their Motions: In Defense of a Heresy* [*Simplicius on the Planets*] (Leiden and Boston, 2013). Although he gives the name of Eudoxus' book (see n. 16), Simplicius almost certainly did not have a copy; in addition to Aristotle's text he relies heavily on a book (now lost) by a philosopher and astronomer of the 2nd cent. CE, Sosigenes, called *On the Back-Winding Spheres*. Simplicius probably had this book in front of him—but it is possible, if rather less likely, that his knowledge of it was only by way of Alexander of Aphrodisias' now lost commentary on the *De caelo*, on which Simplicius also draws. Sosigenes was an Aristotelian, and taught Alexander of Aphrodisias; but he is highly critical of homocentric theory, which by his time had long been discarded in favour of accounts using eccentric and epicyclic motions—the type of astronomical theory on which Ptolemy put his stamp in Sosigenes' own day. For information about Eudoxus Sosigenes drew on a history of astronomy by Aristotle's pupil Eudemus (another lost book): we do not know whether Sosigenes used other sources, nor whether he had

access to Eudoxus' own book, though this latter seems unlikely. Despite his usual reliability and acuity, Simplicius' testimony has therefore to be approached with great care: for a trenchantly sceptical stance see B. R. Goldstein, 'Saving the Phenomena: The Background to Ptolemy's Planetary Theory', *Journal for the History of Astronomy*, 28 (1997), 1–12; A. C. Bowen, 'Simplicius and the Early History of Greek Planetary Theory' ['Greek Planetary Theory'], *Perspectives on Science*, 10 (2002), 155–67, and id., *Simplicius on the Planets*; there is some rebuttal in H. Mendell, 'The Trouble with Eudoxus' ['Trouble'], in P. Suppes, J. Moravcsik, and H. Mendell (eds.), *Ancient and Medieval Traditions in the Exact Sciences: Essays in Memory of Wilbur Knorr* (Stanford, 2000), 59–138.

19 Or rather once in a period very slightly (about four minutes) less than a solar day. This one-sphere scheme takes no account of the phenomena known as precession (not to be discovered for another two centuries) and nutation (not to be discovered for another two thousand years).

20 2. 2, 285^{b}27–33; 2. 10; 2. 14, 296^{a}34–^{b}3; but one chapter (2. 12) clearly presupposes a detailed multi-motion scheme (see n. 15). It seems as if the *De caelo* does not have an entirely consistent view, and it may be that 2. 12 is a later insertion.

21 The astronomical data available to Eudoxus will have been extremely limited and often qualitative in nature, but beyond that little is clear.

22 See G. V. Schiaparelli, *Le sfere omocentriche di Eudosso, di Callippo e di Aristotele* (Milan, Naples, and Pisa, 1875); Dicks, *Early Greek Astronomy*, 183–8; H. Mendell, 'Reflections on Eudoxus, Callippus and their Curves: Hippopedes and Callippopedes', *Centaurus: International Magazine of the History of Mathematics, Science, and Technology*, 40 (1998), 177–275, and id., 'Trouble'; I. Yavetz 'On the Homocentric Spheres of Eudoxus', *Archive for the History of Exact Sciences*, 51 (1998), 221–78, and id., 'A New Role for the Hippopede of Eudoxus', *Archive for the History of Exact Sciences*, 56 (2001), 69–93; Bowen, 'Greek Planetary Theory'; G. E.R. Lloyd, 'The Varying Agenda of the Study of the Heavens: Mesopotamia, Greece, China', *Asia Major*, 21 (2008), 69–88; Judson, Metaphysics *Λ*, notes on ch. 8.

23 In modern usage these are, strictly speaking, called *shells*. I shall follow ancient usage and call them *spheres*, except where this might cause confusion.

24 *De caelo* I, especially chs. 2–4 and 8; 2, especially chs. 3–4.

25 See e.g. S. M. Cohen, 'Aristotle on Elemental Motion', *Phronesis*, 39 (1994), 150–9, M. L. Gill, *Aristotle on Substance: The Paradox of*

Unity (Princeton, 1989), 235–40, I. Bodnár, 'Movers and Elemental Motions in Aristotle' ['Elemental Motions'], *Oxford Studies in Ancient Philosophy*, 15 (1991), 81–111.

26 For discussion see e.g. W. K. C. Guthrie (ed. and trans.), *Aristotle:* On the Heavens [*On the Heavens*] (London and Cambridge, Mass., 1939), Introduction, and the works cited in n. 29.

27 This may have been his position when writing much of the *De caelo*, but if so this must pre-date the arguments for the Unmoved Mover: see L. Judson, 'Heavenly Motion and the Unmoved Mover' ['Heavenly Motion'], in Gill and Lennox (eds.), *Self-Motion*, 155–71 at 158. In *Physics* 8 he argues that the four sublunary elements do have an external cause of motion in whatever causes them to come into existence or removes an obstacle to their natural motion; but since the spheres are ungenerated and there are no obstacles to their motion, he cannot suppose the role of their external source of motion to be the same. It might be in the spirit of this account to hold that it is the spheres' nature to move, and that the Unmoved Movers' role is to sustain the spheres' *existence*; but this would be impossible to square with the claim that the Unmoved Movers accomplish their task as objects of the spheres' love.

28 These elements of course have a disjunctive natural condition: to be moving towards their natural place or to be at rest in that place.

29 So Judson, 'Heavenly Motion', and id., Metaphysics Λ, Prologue to chs. 6–7; Bodnár, 'Elemental Motions'. For a contrary view see S. Waterlow, *Nature, Change, and Agency in Aristotle's* Physics: *A Philosophical Study* (Oxford, 1982), ch. 5 and Appendix to ch. 5.

30 A further problem emerges, however, if this view is combined with another idea to which Aristotle commits himself—that eternal things possess no unrealized potentialities (see e.g. *Phys*. 3. 4, 203^b30; *Metaph*. *Λ* 6, 1071^b12–21; *N* 2, 1088^b14–28): he would, in my view, be best advised to give up or modify this idea (see Judson, Metaphysics *Λ*, Prologue to chs. 6–7).

31 Except of course the lowest set, that of the moon, which needs no back-winding spheres.

32 'Back-winding spheres' seems to have later become a general name for spheres of any sort in a homocentric theory, presumably because in later centuries Aristotle's scheme was considered the most authoritative version of the theory.

33 For discussion see N. R. Hanson, 'On Counting Aristotle's Spheres', *Scientia*, 98 (1963), 223–32 (revised version in id., *Constellations and Conjectures*, ed. W C. Humphreys, Jr (Dordrecht and Boston, 1973)); J. B. Beere, 'Counting the

Unmoved Movers: Astronomy and Explanation in Aristotle's *Metaphysics* XII. 8', *Archiv für Geschichte der Philosophie*, 85 (2003), 1–20; I. Bodnár, 'Aristotle's Rewinding Spheres: Three Options and their Difficulties', *Apeiron*, 38 (2005), 257–75; Judson, Metaphysics Λ, notes on 1073^{b}38–1074^{a}5. The best explanation of why Aristotle faces this difficulty seems to be that he has stuck too closely to the individual planetary systems of Eudoxus and Callippus when integrating them into a connected system. As Eudoxus and Callippus construct them, each planetary system starts with a sphere which has the same motion as that of the fixed stars. Aristotle takes this over into his scheme, quite rightly introduces back-winders, and (presumably) gets as far as seeing that there is no need to counteract the diurnal motion, since this is common to all the planets; but does not get as far as thinking that this means that the first sphere in each planetary system needs to be removed as well. This suggests that *Λ* 8 represents a very early stage of working out his integration of the planetary systems.

34 Aristotle leaves open two possible answers to the question of how many spheres are needed:

(*a*) Fixed stars 1; Saturn 4 + 3; Jupiter 4 + 3; Mars 5+4; Venus 5+4; Mercury 5+4, Sun 5+4; Moon 5 = 56.

(*b*) Fixed stars 1; Saturn 4 + 3; Jupiter 4 + 3; Mars 5+4; Venus 5+4; Mercury 5+4, Sun 3 + 2; Moon 3 = 50 (but the manuscripts say 47 [sc. + 1 for fixed stars = 48]).

The complaints that Aristotle's system is 'highly complex … very complicated and inelegant' (Leverington, *Encyclopedia*, 67), and 'completely mad, even by contemporary standards' (Koestler, *The Sleepwalkers*, 73, quoted inn. ii) derive ultimately from Ptolemy's complaint that far fewer than 56 spheres are needed: but see n. 52.

35 Aristotle thinks that each heavenly sphere contemplates a different, unchanging god, so that there is one god for each of the spheres which astronomical theory requires.

36 For Stoic and Epicurean approaches, see M. J. White, 'Stoic Natural Philosophy (Physics and Cosmology)', in B. Inwood (ed.), *The Cambridge Companion to the Stoics* [*Companion*] (Cambridge, 2003), 124–52, and A. Jones, 'The Stoics and the Astronomical Sciences', ibid. 328–44. Book 2 of *Planetary Hypotheses*, and part of book I, survive only in an Arabic translation of the whole work. The Greek text of the rest of book I and a German translation of most of the Arabic version is in J. L.

Heiberg (ed.), *Claudii Ptolemaei opera quae exstant omnia*, ii. *Opera astronomica minora* (Leipzig, 1907); B. R. Goldstein, 'The Arabic Version of Ptolemy's Planetary Hypotheses' ['The Arabic Version'], *Transactions of the American Philosophical Society*, 57 (1967), 3–55, contains a facsimile of the Arabic version. For commentary on Ptolemy's physics see L. C. Taub, *Ptolemy's Universe: The Natural Philosophical and Ethical Foundations of Ptolemy's Astronomy* (Chicago and LaSalle, 1993); A. Murschel, 'The Structure and Function of Ptolemy's Physical Hypotheses of Planetary Motion' ['Ptolemy's Physical Hypotheses'], *Journal for the History of Astronomy*, 26 (1995), 33–61; P. Barker, 'Copernicus and the Critics of Ptolemy' ['Copernicus'], *Journal for the History of Astronomy*, 30 (1999), 343–58; A. Jones, 'Ptolemy's Mathematical Models and their Meaning' ['Ptolemy's Mathematical Models'], in G. Van Brummelen and M. Kinyon (eds.), *Mathematics and the Historian's Craft: The Kenneth O. May Lectures* (New York, 2005), 24–42; J. Feke, 'Ptolemy in Philosophical Context: A Study of the Relationships between Physics, Mathematics, and Theology' (Ph.D. thesis, University of Toronto, 2009). Ptolemy says that he expects his work to be helpful to instrument-makers in constructing physical planetaria, but is clear that he is principally doing physics—witness, for example his interest in the order and distances of the planets (see Taub, *Ptolemy's Universe*, 112), his explanation of how the planetary systems are moved by their souls (see p. 168 below), his arguments in favour of 'sawn-off pieces' rather than complete spheres (Taub, *Ptolemy's Universe*, 114–17), and the deployment of astro-physical arguments and conclusions even in the *Syntaxis* (see 1. 3–7 on the nature of aither and on the position, shape, and immobility of the Earth, and 9. 2 (uniform circular motions are proper to the nature of divine beings)). The astronomy which lies behind the *Planetary Hypotheses* is set out in Ptolemy's *Syntaxis mathematica*, or *Almagest* (the text is in J. L. Heiberg (ed.), *Claudii Ptolemaei opera quae exstant omnia*, i/1–2. *Syntaxis mathematica* (Leipzig, 1898 and 1903), translation and commentary in G. J. Toomer, *Ptolemy's* Almagest (London, 1984).

37 Ptolemy's system does owe a certain amount to earlier thinkers, since a heavenly structure of the same basic kind—but reflecting Hipparchan rather than Ptolemaic astronomy—is assumed in a work written earlier in the 2nd cent., Theon of Smyrna's *Mathematics Useful for Reading Plato*, 178. 3–189. 18. (The text is in E. Hiller (ed.), *Theonis Smyrnaei philosophici Platonici Expositio rerum mathematicarum ad legendum Platonem utilium* (Leipzig, 1878); see Jones, 'Ptolemy's Mathematical Models', 27 and 33. I

am grateful to the *OSAP* referee for bringing Theon to my attention.) Theon's structure is significantly simpler, as it incorporates epicyclic spheres but not eccentric ones, and lacks Ptolemy's tambourines and whorls (see p. 167 below); and apart from one analogy between the sun and the heart to explain why the most important planet need not occupy the middle of the cosmos (187. 13–188. 7), Theon offers no account, as Ptolemy will attempt to do, of the nature of the heavenly bodies or of their motions (though he may have accepted Aristotle's five-element system: 149. 15–24). From the way he presents it, it seems unlikely that Theon was the originator of this material (and, as he makes clear, his account of astronomy is heavily indebted to the Peripatetic Adrastus (perhaps writing at the beginning of the 2nd cent.), but we simply do not know what work others may have done in this area. The extraordinary impact of Ptolemy's work had the consequence that little care was taken subsequently to preserve earlier astronomical writings; just as the history of homocentric theory after Aristotle—whether it became the dominant account, and if so, the course of its demise and the rise of eccentric/epicyclic theory in its place—is almost entirely obscure, so, apart from Theon, is the prehistory of Ptolemy's astrophysics.

38 Renaissance thinkers knew of Ptolemy's system (though not as Ptolemy's) via Islamic sources: see pp. 169–70. A key text in the dissemination of this system was Georg Peurbach's *Theoricae novae planetarum* (published by Regiomontanus in Nuremberg, *c*. 1473).

39 A number of the details of Ptolemy's system are disputed or uncertain, not only because of differences in scholarly opinion but also because we lack the Greek text of *PH* 2 (see n. 36). I largely pass over these difficulties in what follows.

40 It may be that this sphere is itself contained within a further homocentric sphere, whose rotation of this sphere gives the planet its diurnal motion around the Earth (but Ptolemy is unclear or ambivalent about this: see problem (5) below).

41 This may be a single sphere or a double epicycle: see Murschel, 'Ptolemy's Physical Hypotheses', 43–50.

42 This is why Ptolemy thinks he can assess the relative complexity of Aristotle's system and his own simply in terms of the number of spheres required: see n. 52 below. There is much debate as to how far Ptolemy was an 'Aristotelian' or a 'Platonist'; for some discussion see Taub, *Ptolemy's Universe*, 119–24. Though his disagreements with Aristotle are of course very extensive, my inclination is to suppose that Ptolemy's only unequivocally

Platonist move is to suppose that the planets' souls are the originators of motion without the need for an Unmoved Mover (though see *Synt*. 1. 1; Feke thinks that Ptolemy only rejected the idea that the Unmoved Mover was an efficient cause of heavenly motion ('Ptolemy in Philosophical Context', ch. 2 and 213–14)).

43 *PH* 1, part 2: translation and commentary in Goldstein, 'The Arabic Version'; see also G. J. Toomer, 'Ptolemy and his Greek Predecessors' ['Predecessors'], in C. Walker (ed.), *Astronomy before the Telescope* [*Astronomy*] (London 1996), 68–91 at 90–1.

44 *PH* 2. 3; cf. *Synt*. I. 3 (this is what he may mean by its being more (geometrically) homoeomerous).

45 The shapes of bodies and parts of bodies in Ptolemy's system include shells, whorls, and tambourines, as well as the various regular and irregular shapes of the portions of the aither which fill up the places left between these various parts and between eccentric shells and their surrounding sphere.

46 *PH* 2. 3 and 7; see Taub, *Ptolemy's Universe*, 119–24; Murschel, 'Ptolemy's Physical Hypotheses', 38–41.

47 This and the next point contradict Ptolemy's own commitment to uniform circular motions in *Synt*. 9. 2 (see n. 36) and in *PH* 2. 3.

48 This is because the equant is in effect equivalent (in geocentric terms) to the empty focal point of a heliocentric planetary ellipse conforming to Kepler's laws: see e.g. M. Hoskin, 'Astronomy in Antiquity' ['Antiquity'], in id. (ed.), *The Cambridge Illustrated History of Astronomy* [*History of Astronomy*] (Cambridge, 1997), 22–49 at 43.

49 These parts apparently are not distinguished by variations in density, but by variations in 'power' (*PH* 2.5, discussed in Feke, 'Ptolemy in Philosophical Context',208–13): this explains little.

50 He has Aristotle's system, with its unwinders, in his sights; but he also denies that this kind of transmission of motion can occur at all (though see problem (v) for Ptolemy's own system below).

51 For discussion see Taub, *Ptolemy's Universe*, 118–19; Murschel, 'Ptolemy's Physical Hypotheses', 42–3.

52 It is worth noting that Ptolemy claims that his system is much less complex than Aristotle's (*PH* 2.6; see Taub, *Ptolemy's Universe*, 119; Murschel, 'Ptolemy's Physical Hypotheses', 50–2). This is because he is thinking in terms of the number of *spheres*: with the introduction of sawn-off pieces, Ptolemy says that he only needs 22 spheres, compared to Aristotle's 56. That Ptolemy's system explains much more complex phenomena is of course not in doubt; but basing his judgement of the simplicity of his system on the number of spheres is quite unwarranted: the number of different kinds of functional parts, the total number of

such parts, and the number of centres of motion all need to be taken into account as well.

53 The most important were Naṣīr al-Dīn al-Ṭūṣī (1201–74) and Ibn al-Shāṭir (1304–75): see V. Roberts, 'The Solar and Lunar Theory of Ibn al-Shāṭir: A Pre-Copernican Copernican Model', *Isis*, 48 (1957), 428–32; E. S. Kennedy and V. Roberts, 'The Planetary Theory of Ibn al-Shāṭir', *Isis*, 50 (1959), 227–35; E. S. Kennedy, 'Late Medieval Planetary Theory', *Isis*, 57 (1966), 365–78; M. Hoskin and O. Gringerich, 'Islamic Astronomy', in Hoskin (ed.), *History of Astronomy*, 50–67 at 50–63; G. Saliba, *Islamic Science and the Making of the European Renaissance* [*Islamic Science*] (Cambridge, Mass., and London, 2007), chs. 3–4. Some Renaissance astronomers, including of course Copernicus, also regarded these features of Ptolemaic physics as unacceptable, and adopted the Islamic solutions to them (see N. M. Swerdlow, 'Astronomy in the Renaissance' ['Renaissance'], in Walker (ed.), *Astronomy*, 187–230 at 200–5; Barker, 'Copernicus'; B. R. Goldstein, 'Copernicus and the Origin of his Heliocentric System', *Journal for the History of Astronomy*, 33 (2002), 219–35; D. Knox, 'Copernicus's Doctrine of Gravity and the Natural Circular Motion of the Elements' ['Copernicus's Doctrine'], *Journal of the Warburg and Courtauld Institutes*, 68 (2005), 157–211).

54 Most importantly Ibn al-Rushd (Averroes, 1126–98). He set out a number of these difficulties in his commentary on *Metaphysics Λ* (though he confessed to being baffled by the astronomy involved). He objected to the existence of many centres of celestial circular motion required by eccentrics and epicycles (cf. my difficulty (ii*a*) above), and to the existence of 'superfluous bodies in heaven, with no purpose but filling [i.e. filling the spaces left by eccentric spheres]': his objection seems to be teleological (*Commentary on Lām* 1661–2: C. Genequand, *Ibn Rushd's Metaphysics: A Translation with Introduction of Ibn Rushd's* Commentary on Aristotle's *Metaphysics*, Book Lām [*Ibn Rushd's Metaphysics*] (Leiden, 1984), 178). Cf. Barker, 'Copernicus', 344–9.

55 Most notably Nur al-Dīn al-Biṭrūjī (d. *c*. 1204), who developed a homocentric astronomy (Saliba, *Islamic Science*, chs. 3–4); his teacher, Ibn Ṭuyfayl (c.1 105—85), who also rejected Ptolemaic astronomy, taught Ibn al-Rushd (Genequand, *Ibn Rushd's Metaphysics*, 54).

56 '[In the sixteenth century] the choice in astronomy was between Averroist natural philosophers, who wanted (but could not provide) an astronomy that met contemporary standards for positional calculations, and Ptolemaic astronomers, who wanted

(but could not provide) a natural philosophy that met contemporary standards for physical reasoning about celestial motions’ (Barker, ‘Copernicus’, 345). Copernicus’s astrophysics seems to have been a sort of Aristotelianized version of Ptolemy’s: see Knox, ‘Copernicus’s Doctrine’. Renaissance astronomers who endorsed homocentric astrophysics (though they rejected al-Biṭrūjī’s version) included Regiomontanus (1436–76), as well as Giovanni Battista Amico (*De motibus corporum coelestium iuxta principia peripatetica sine eccentricis et epicyclis*, first published in Venice in 1537) and Girolamo Fracastoro (*Homocentrica*, first published in Venice in 1538): see N. M. Swerdlow, ‘Aristotelian Planetary Theory in the Renaissance: Giovanni Battista Amico’s Homocentric Spheres’, *Journal for the History of Astronomy*, 3 (1972), 36–48; id., ‘Renaissance’, 201–3, and id., ‘Regiomontanus’s Concentric-Sphere Models for the Sun and Moon’, *Journal for the History of Astronomy*, 30 (1999), 1–23; M. Di Bono, ‘Copernicus, Amico, Fracastoro and Tūsī’s Device: Observations on the Use and Transmission of a Model’, *Journal for the History of Astronomy*, 26 (1995), 133–54; M. H. Shank, ‘Regiomontanus and Homocentric Astronomy’, *Journal for the History of Astronomy*, 29 (1998), 157–66; Barker, ‘Copernicus’.

57 ‘We are far removed from the objects of our attempted enquiry, not in the obvious sense of spatial distance, but rather because very few of their attributes are perceptible to our senses’ (*De caelo* 2. 3, 286a4–7). ‘We have very little to start from, and we are situated at a great distance from the facts in question’ (*De caelo* 2. 12, 292a14–18). ‘Our studies of [eternal substances], though they are valuable and divine, are fewer; for in relation both to the things on the basis of which one would investigate them and the things about which we long to know, the things which are evident to perception are altogether few … our contact with [eternal things] is slight’ (*PA* 1. 5, 644b24–8 and 31–2).

58 Though he sometimes overstates the case: see *Λ* 7, 1072a21–6, and 8, 1073a28–32.

59 See Λ 8, 1073b34–8, and the complaint made against the Pythagoreans at *De caelo* 2. 13, 293a23–30. Aristotle refers three times to astronomical observations which he has either made himself or has heard about from those who did (*De caelo* 2. 12, 292a3–9, and *Meteor*. 1. 6, 343b11–12 and 343b30–2: for discussion see I. Bodnár, ‘Aristotle’s Planetary Observations’, in D. Føllesdal and J. Woods (eds.), *Logos and Language: Essays in Honour of Julius Moravscik* (London, 2008), 243–50).

60 He does not, for instance, attempt to explain why there are just

the planets that there are, any more than he attempts to explain why there are just the animal species that there are. He warns against expecting an explanation for everything at *De caelo* 2. 5, 287b28–32.

61 When Aristotle says that the crucial point is that the stars have a share in life and action (*De caelo* 2. 12, 292a18–21), some commentators take him to be saying only that we must think of them *as if* they have life; but that he thinks that by being moved they achieve their own good is not in doubt. For the claim that they are distinct beings see *De caelo* 2.7; *Meteor*. 1. 3, 339b16–19.

62 *Meteor*. 1. 3, 340b6–10.

63 This suggestion is found in Alexander's lost *De caelo* commentary, quoted by Simplicius (*In De caelo* 436. 4–20 Heiberg). That the sun is dense is hinted at, though not expressly stated, at *Meteor*. 1. 3, 341a23–8.

64 *De caelo* 2. 12, 292a3–9; *Meteor*. 1. 6, 343b30–2, cited in n. 59.

65 It also gives him a basis for the luminosity of the fixed stars and the planets (except for the moon), given that the spheres are not luminous (I discuss this controversial point in (4) below). Again, it is instructive to compare Aristotle's account with Ptolemy's. Ptolemy speaks as if the whole of a planetary system (except for the loose aither) constitutes the body of the planet in question; but he offers no account of what differentiates the visible part of the planet from the rest of its body, or of what differentiates each of its articulated parts from the others.

66 Aristotle uses 'at rest' (ἠρεμεῖν and cognates) of the stars at 289b2–7 and 290b11; his conclusion at 289b32–3 is τὰ δὲ ἄστρα ἠρεμεῖν καὶ ἐνδεδεμένα τοῖς κύκλοις φέρεσθαι. Istvan Bodnár has suggested in conversation that Aristotle should say that the star is simply a part of its sphere, and that the whole ensemble moves as a unit. This would meet the difficulty, but it does not seem to be Aristotle's view, at least in the *De caelo*.

67 Cf. οὐ κινεῖται δι' αὑτῶν at 2.9, 291a27.

68 The parallel is by no means perfect, of course, since the brick does not have a blank capacity for rectilinear motion, and the star's motion is activated but never *begun* by the action of its sphere.

69 Ptolemy makes the stars shine 'of their nature'; but has no explanation of why the heavenly spheres, whorls, etc., do not also shine, other than to say that they have different powers.

70 *De caelo* 2. 7. *Meteor*. 1. 3, 341a12–36, gives a similar account of the stars' production of heat. Earlier in 1.3 and in 1.4 Aristotle explains that the fire whose natural place is immediately above that of air is not flame—which is, as it were, *ignited* fire—but a

highly inflammable stuff he calls ὑπέκκαυμα (340b9–27; 341b12–24).

71 Various ways to avoid this field-effect account have been suggested, none of which is acceptable. (i) Each star protrudes from its sphere, and the bulge this causes extends down to the sublunary fire and so can push it. But any such protrusion and/or bulge would interfere with the motion of all the spheres below the star in question (unless aither had radial motion as well as circular motion, so that each sphere could be deformed by the bulge: but Aristotle denies this). Moreover, pushing or pulling ought to involve drag on the heavenly sphere, which Aristotle does not countenance. (ii) Simplicius supposes that the fire's motion is generated by rays (ἀκτῖνες) emitted by the star (*In De caelo* 441. 2–5 Heiberg). But either these rays are material, in which case the star must lose matter (which Aristotle denies), or they are immaterial, in which case the explanation is no different from that of the field-effect account. (Simplicius says (441. 2–5) that these rays are matterless (ἀύλους) butbodily or corporeal (σωματικάς:); there is no reason to doubt the text and to suspect that it should read 'bodiless' (ἀσωματικάς; so I. Mueller, *Simplicius*, On Aristotle, *On the Heavens, 2. 1–9* (London, 2004), 149 n. 381), since in the same sentence Simplicius describes the heavenly spheres as bodily but matterless.) (iii) The fire and air involved are not in their natural sublunary regions, but are small pockets immediately below each star (so Guthrie, *On the Heavens*, 178–9; J. Thorp, 'The Luminousness of the Quintessence' ['Luminousness '], *Phoenix*, 36 (1982), 104–23). But Aristotle's explanation in *Meteor*, 1. 3 is firmly embedded in an account of the natural places of fire and air; this is confirmed by the fact that his explanation of how individual stars produce comets appeals to exactly the same effect of igniting air, and this effect is explicitly said to be in the sublunary air (*Meteor*. 1. 7–8, especially 344a33–b12 and 345b31–346a9a). This account of comets means that Aristotle is in any case committed to a field-effect theory for this type of case: so there is little point in trying to avoid it in the case of the light and heat of the stars.

72 See *De caelo* 2. 12, 292a3–9 (cf. *Meteor*. 1. 6, 343b30–2); both passages are cited in n. 59.

73 Gregory, who outlines a number of these difficulties, tries to meet this objection (A. Gregory, 'Plato and Aristotle on Eclipses', *Journal for the History of Astronomy*, 31 (2000), 245–59 at 246): he argues that in a solar eclipse the interposing moon might interfere with the 'burning air' effect of the sun, and might itself appear dark in comparison with the bright daylight around it.

But the moon does not in general appear dark in daylight—it appears pale, and the brighter the daylight the paler it appears.

74 That *all* the planets except the sun shine with reflected light was not evident in Aristotle's time.

75 Cf. the explanation of the apparent rotation of the sun at 2. 8, 290[a]13–18.

76 My interpretation is indebted on this point to Thorp, 'Luminousness', 121–3, though I disagree with his paper on most other points (in particular his view that what I call 'general illumination' is on a par with the luminosity of what Thorp calls the 'cloud of light' of (e.g.) a floodlit stadium viewed from a distance). Aristotle uses 'rays' (ἀκτῖνες) of the sun's heat quite often in the *Meteorologica*; he uses it of light in his own person only at *DA* 1. 2, 404[a]3–4 (a casual use referring to shafts of dusty light), and at *Meteor*. 3. 4, 374[a]35–[b]5 (in the course of his explanation of how rainbows can be produced in rooms partially in shadow and partially illuminated by the sun). When he speaks of what we would call the light of the sun or other stars he sometimes uses 'light' (φῶς), but his usual term is 'brightness' (τὸ λαμπρόν).

77 With a physical basis, as I have suggested, in their density.

78 The *De anima* passage just quoted might suggest that the 'body above' can make things visible in a way parallel to that of fire: Aristotle is probably thinking that the luminous stars make *themselves* visible in the way they do by activating the transparency of the medium.

79 Lloyd, '*Λ* 8', 249, makes the latter point.

80 We should not expect Aristotle to try to explain why there is a blue star (say Sirius) in a certain place rather than a yellow star, any more than he tries to explain why just these planets exist: see n. 60.

81 Kuhn, *The Copernican Revolution*, 59; Koestler, *The Sleepwalkers*, 68 (this is part of what lies behind his claim that Aristotle was 'dishonest'); Toomer, 'Predecessors', 73 ('neither [Aristotle] nor anyone else could answer this fundamental objection against a homocentric system. Eudoxus' proposal was a dead end'); Lloyd, '*Λ* 8', 250 ('It was not as if this phenomenon went unnoticed among Aristotle's contemporaries. An extended passage in Simplicius … suggests that already in the late fourth century BC the variations in the brightness of the planets were known *and had been taken to imply that their distances from the Earth vary*. The point is a fundamental one, since if that conclusion were accepted, that would be disastrous for the concentric sphere model'—my italics); North, *Cosmos*, 84; Leverington,

Encyclopedia, 18. There are more cautious formulations in O. Neugebauer, *The Exact Sciences in Antiquity*, 2nd edn. (Providence, 1957), 154–5; Toulmin and Goodfield, *Fabric*, 119–20; Musgrave, 'Astronomical Instrumentalism', 259–60 and 276 n. 39; Hoskin, 'Antiquity', 36; and Furley, 'Aristotle', 18.

82 Probably *fl.c.*300 BCE.

83 Apparently a contemporary of either Eudoxus or Callippus: see Simpl. *In De caelo* 493. 4–8 Heiberg.

84 Note that, in the absence of telescopes, it is natural to run together, in the case of stars other than the sun and the moon, changes in brightness and changes in apparent size, as Sosigenes does here (cf. Bowen, 'Greek Planetary Theory', 161); neither of these is equivalent to a change in (real or) apparent *distance*, however: see below.

85 'Greek Planetary Theory', 161–2.

86 A less technical version of the same move is evident in the claim that 'at some times [the planets] appear near, while at other times they appear to have moved away from us': what appears is a change in brightness or apparent size (see n. 84): the idea that the planets seem to be nearer or further away incorporates an *explanation* of the phenomenon, not the phenomenon to be explained. Thus Copernicus also looks through the lens of later astronomy when he writes in his *Commentariolus*, 'Callip-pus and Eudoxus, who endeavoured to solve the problem by the use of concentric spheres, were unable to account for all the planetary movements; they had to explain not merely the apparent revolutions of the planets but also the fact [*sic*] that these bodies appear to us sometimes to mount higher in the heavens, sometimes to descend; and this fact is incompatible with the principle of concentricity' (E. Rosen, *Three Copernican Treatises: The* Commentariolus *of Copernicus, The* Letter against Werner, *The* Narratio Prima *of Rheticus* (New York, 1939), 57).

87 I do not endorse Bowen's outright denial of this possibility ('Greek Planetary Theory', 161). He argues that the changes in the brightness of Venus (which are small because its coming nearer to the Earth is offset by its phases) cannot be detected by the naked eye: this seems to be a matter of dispute. In any case, the brightness of Mars varies visibly.

88 It may be, for instance, that what Polemarchus 'recognized' was that some planets vary in *brightness*, but that he denied that this variation should be explained in terms of a variation in their distance, on the grounds that no changes in planetary distances could be perceived (i.e. that these planets do not ever *look* closer or further away).

89 For discussion of some later, more informed criticisms see B. R. Goldstein, 'The Pre-Telescopic Treatment of the Phases and Apparent Sizes of Venus', *Journal for the History of Astronomy*, 27 (1996), 1–12. In one of the omitted passages Sosigenes also talks about the variations in the apparent size of the sun and the moon: similar considerations apply to this problem (especially given the well-known phenomenon of the sun or moon appearing larger when it is on the horizon), and perhaps even to the problem of annular eclipses (also mentioned in the Simplicius passage, 504. 30 ff. Heiberg).

90 The context of each of the *De caelo* passages quoted in n. 57 is the posing of a high-level causal question about the structure of the cosmos—Why does the entire cosmos not rotate with the same circular motion as the sphere of the fixed stars? Why does the number of spheres associated with a planet increase and then decrease as one descends from the fixed stars to the moon? In both cases Aristotle couples his statement of the difficulties with a clear resolve to answer the question nonetheless. In the latter case Aristotle appeals to teleology, and in the former to something like the notion of hypothetical necessity, Aristotelian teleology's running mate (see *Phys*. 2. 9). Teleological considerations also appear in the explanation in 2. 2 and 5 of why the outermost sphere rotates in the direction it does; and he deploys something akin to his 'nature does nothing in vain principle' in 1. 4, 2. 8, 2. 9, and 2. 11. If teleology seems fantastical here, compare Ptolemy's explanation of why Mercury and the moon (the two lowest planets, in his system) have more complex motions than the higher planets: 'the spheres nearest to the air move with many kinds of motion and resemble the nature of the element adjacent to them [i.e. air]' (Taub, *Ptolemy's Universe*, 111): since the air does not, in his view, affect the motion of a planet (e.g. by making it irregular), Ptolemy's explanation here is simply that there is an *ad hoc* affinity between the natures of the lowest two planetary beings and that of the nearby air.

91 Although it is true that Aristotle does not use the language of 'for the sake of *X*' except at 2. 3, 286^{a}8–9, a being's own good is the final cause *par excellence*; this undermines Leunissen's claims that (2. 3 apart) Aristotle's explanations do not refer to final causes and that he must think that 'teleology is not readily discernible in the case of the heavens' (M. Leunissen, *Explanation and Teleology in Aristotle's Science of Nature* (Cambridge, 2010), ch. 5; this quotation 153).

92 Lloyd, '*Λ* 8', 254 and 265; cf. 254: 'the specifications mentioned

[axis, speed of rotation, order/position in the total nest of spheres] do not, of course, detract from the perfection of each moved mover, secured and exemplified by its eternal perfectly regular circular motion.' Cf. also M. Scharle, 'Elemental Teleology in Aristotle's *Physics* 2. 8', *Oxford Studies in Ancient Philosophy*, 34 (2008), 147–83 at 159: 'The heavenly spheres directly imitate the Prime Mover's perfection by eternally moving in perfect circles.'

93 Some commentators think that the 'back-winding' spheres are not bound up with the motion of their star, since they make no contribution to it; and so they constitute a problem for premiss (i) (see Dicks, *Early Greek Astronomy*, 207 and 264 n. 403). One response to this is to see their contribution as belonging to the next star down; but it has to be said that Aristotle always counts them as part of the set of spheres for the star above them. A better response is that the back-winding motions are bound up with the motion of the star above by being an essential part of a complete system which produces the star's motion while not affecting the other stars (see Bodnár, 'Aristotle's Rewinding Spheres', 263 n. 13).

94 Compare *IA* 2, 704[b]15–17 ('Nature brings about nothing in vain, but always the best of the possibilities, in its essential being, in relation to each kind of animal'). Sedley defends a weaker reading of the *Physics* passage in D. Sedley, 'Is Aristotle's Teleology Anthropocentric?', *Phronesis*, 36 (1991), 179–96, and id., '*Metaphysics* Λ 10' ['Λ 10'], in Frede and Charles (eds.), Metaphysics *Lambda*, 327–50; this reading is criticized in I. Bodnár, 'Teleology across Natures' ['Teleology'], *Rhizai*, 2 (2005), 9–29, and in L. Judson, 'Aristotelian Teleology' ['Teleology'], *Oxford Studies in Ancient Philosophy*, 29 (2005), 341–66 at 359–62. Bodnár sees the need to take into account the point that the stars are 'beneficiaries' of the motions of the spheres (25–6); but he does not do this by *connecting* the good of the stars and the good of the spheres in the way I will suggest. For a discussion of teleology in Λ 10 see Sedley, 'Λ 10' and id., 'Teleology, Aristotelian and Platonic', in J. G. Lennox and R. Bolton (eds.), *Being, Nature, and Life in Aristotle: Essays in Honour of Allan Gotthelf* (Cambridge, 2010), 5–29; Bodnár, 'Teleology'; Judson, Metaphysics Λ, Prologue to ch. 10 and commentary.

95 See D. Charles, 'Teleological Causation in the *Physics*', in L. Judson (ed.), *Aristotle's* Physics: *A Collection of Essays* (Oxford, 1991), 101–28; Bodnár 'Teleology'; for defence and explanation of the idea that Aristotle restricts teleological explanation in biology to individual substances and their species, see L. Judson, 'Chance and "Always or For the Most Part" in Aristotle', in id.

(ed.), *Aristotle's* Physics, 73– 99; id., 'Teleology'.

96 There is a hint in *De caelo* 2. 2 that the direction of rotation is due in some way to the form of the sphere; but it is only a hint, and it leaves open precisely our present question, since to say that a living substance's activities are due to its form or soul is not yet to say whether or not they are the products of desire. See Judson, 'Heavenly Motion', 159–61.

97 Cf. *De philosophia*, fr. 12a Ross (fr. 10 Rose^{3}; S.E. *M*. 9. 22): '… seeing by day the revolution of the sun and by night the well-ordered movement of the other stars, they thought that there was a god who was the cause of such movement and good order'; cf. also fr. 13 Ross (fr. 12 Rose^{3}; Cic. *ND* 2. 37. 95). Note that in introducing the idea of the beauty of the cosmos I am not intending to introduce any form of anthropomorphism: I am supposing Aristotle to regard this sort of beauty as an objective feature of the world, which humans may discover and to which they may react—as they are said to do in the *De philosophia* passage—but which they do not construct.

98 De caelo 2.9, 290^{b}21-9.

 I am grateful to audiences in Budapest, Cambridge, Oxford, and Pisa for their comments on various ancestors of this paper, and especially to Gábor Betegh, István Bodnár, David Charles, and an anonymous *OSAP* referee for their comments on earlier versions.

Counting the Unmoved Movers: Astronomy and Explanation in Aristotle's *Metaphysics* XII.8

by Jonathan B. Beere (Princeton)

Abstract: I discuss Aristotle's use of astronomy in *Metaphysics* XII.8 to determine the number of divine intellects. Commentators have been perplexed by the astronomical system that Aristotle gives, because it involves mathematically superfluous spheres. I argue that this astronomical system is not merely a mathematical description of phenomena, but a causal account of the motions of the heavens. The idle spheres thus play an essential role in the system, because they are the proper cause of the diurnal revolution of the planets around the earth. I argue that this demand for explanation is neither immoderate nor unreasonable.

In Aristotle's *Metaphysics*, we are repeatedly promised a discussion of non-sensible immaterial substance. Yet only in Book XII does Aristotle fulfill this promise. His account begins in chapter 6 with an argument for the existence of at least one non-sensible immaterial substance, and continues in chapter 7 with a series of conclusions about the nature of such substances: They are purely active, immortal intellects, and substances of this kind are the ultimate principles of the world. Chapter 8 then describes how to determine the number of ultimate principles. There are as many ultimate principles as there are pure intellects, and as many pure intellects as there are heavenly motions. And there is already a science to tell us how many heavenly motions there are: astronomy.

Why does Aristotle care about the number of unmoved movers? Some suggest that the chapter is "gratuitous polemic" against the Platonists.[1] In fact, it is an integral part of the promised theory of non-sensible substance. Any account of the ultimate principles of being should include some reasoned method of determining how many principles there are. Similarly, in *Physics* I, Aristotle canvasses various answers to

[1] Cf. Lloyd 2000, 253. Lloyd provides quite a thorough discussion of chapter 8. See also Michael Frede's introduction to the same volume for a thorough discussion of the twelfth book as a whole and of chapter 8's role in it.

Archiv f. Gesch. d. Philosophie 85. Bd., S. 1–20

ISSN 0003-9101

the question of how many principles there are (although those are not the principles of all being, but only of changing things). This question does not spring from an arbitrary zeal for counting unmoved eternal substances[2], but from the general project of giving an account of the principles of being. This constraint would apply equally to an account according to which the ultimate principles of being are material substances, such as air, earth, fire, and water; that account has to fend off such questions as, 'Why not wine?' and 'Why include air, earth, and fire?' Any metaphysical theory is defective if it cannot answer these questions and others like them. And conversely, to show how to determine the number of principles with precision is a great virtue of a metaphysical theory, even if the number of principles remains unknown because of the limitations of our natural science.

In chapter 8 of *Metaphysics* XII, Aristotle wants to show that, given the best contemporary astronomical theories, the number of pure intellects can reasonably be accepted to be 55. But his primary goal is not that we accept that there are 55 pure intellects, but rather that we accept that, as far as his account of the ultimate principles of being is concerned, nothing is lacking for such a demonstration. As soon as the astronomy is in place, an answer to the question, 'How many principles are there?' is determined and readily available. Aristotle claims, very reasonably, that this is a strength of his theory, and he further claims that it is a weakness of 'the supposition of ideas' that it cannot provide a non-arbitrary criterion for the number of principles.[3] Aristotle's metaphysical theory is in a state comparable to a theory which estab-

[2] Cf. Lloyd 2000, 253.

[3] Whether this critical remark about the ideas is fair is not a question I will address. There is a great deal to say about whether or not it is arbitrary for the decade to be the principle or principles. My view of the criticism of the supposition of ideas differs from either of the views considered by Lloyd, who writes, following David Charles, "Aristotle's complaint might be [1] that the Platonists did not have demonstration as their goal: or [2] that they did not take themselves to be subject to proper scientific constraints in the first place" (2001, 253). If the former, the implicit contrast with Aristotle himself would have Aristotle taking demonstration as a goal. But Aristotle not only has demonstration as a goal; he can show us in detail how the demonstration would go, if we knew enough astronomy. There is nothing lacking from his account of the principles of being; what is lacking, rather, is some astronomy. He advances this as a strength of his theory. I am uncertain whether this is the same as the second option considered by Lloyd, but I am inclined to think not. On my view, Aristotle is not merely bound by the constraints of science in general; he has worked out in detail an account of the principles of being that makes immediately clear how to determine, in a feasible way, how many there are.

lishes that the elements to be listed on the periodic table of elements are the principles of being, but does so in the absence of a complete and definitive periodic table. In Aristotle's case, it is not chemistry but astronomy that provides the non-metaphysical information, and astronomy is said here to be "most proper to philosophy of the mathematical sciences" (1073b4f.). The main part of chapter 8, devoted to enumerating the postulated spheres, is thereby characterized as belonging to a branch of mathematics.

For this reason, it is puzzling to find certain spheres in the system which are mathematically superfluous. A system that differed from Aristotle's only by lacking these spheres would make precisely the same predictions about all heavenly phenomena. Two questions arise about those 'idle' spheres. (1) Since each sphere moves the one below it, why do the 'idle' spheres need their own movers? (2) Since they are mathematically superfluous, why do they have any role in this ostensibly mathematical system? My argument aims to answer these questions, which continue to puzzle commentators such as Heath, who writes, "Aristotle could […] have dispensed with the [redundant spheres] […] without detriment to the working of his system […] [and thereby] have saved six spheres out of his total number."[4]

We will respond to the first question by describing the *way* each sphere carries the one below it, and we will answer the second by recognizing that Aristotle is guided not only by mathematical considerations, but also by considerations about what constitutes a *per se* cause. Since

[4] See Heath 1913, 219. Mendell agrees: "Aristotle seems to over count the first sphere for every planet" (2001, 82; see generally 81–83). Yavetz also expresses perplexity about the issue (1998, 237 n. 16). Ross (1924, *ad loc.*) says, "Aristotle might have reduced the total number of spheres by six"; similarly, Neugebauer (1975, 685). Frede raises this question, too (2000, 38). Dicks attempts to rebut Ross, saying "But the poles of B [corresponding, in our discussion, to the last of Saturn's unwinding spheres] are not the poles of the sphere of the fixed stars […], whereas it is an essential part of the system that the first sphere of each set must represent the latter exactly; hence the 2 spheres *cannot* be replaced by 1. That is why Aristotle himself emphasizes that the purpose of his counteracting spheres is to 'restore to the same function *as regards position*' the first sphere of the following planetary set" (1970, 202). But why is this an "essential part of the system"? What sort of a system is this, such that the positions of the spheres' axes should be so important? Even granting Dicks' questionable gloss of 1074a3 – the Greek mentions neither the function nor the position of an axis – the deeper question is in what sense Aristotle thought the orientation of the axis matters, since it does not matter mathematically. According to my account below, it is not the orientation of axes that concerns Aristotle, but the importance of there being a *per se* cause for the diurnal revolution of the planets.

Aristotle does draw on non-mathematical assumptions, we will have to revise, or at least qualify, our statement that chapter 8 embodies a mathematical, as opposed to natural, science.

Let us sketch Aristotle's spherical system. Some aspects of the system are clear from Aristotle's text, while other aspects have been reconstructed based on later reports, especially Simplicius' commentary on *de Caelo*. The traditional reconstruction of Schiaparelli (1875) has been questioned recently, but my arguments are independent of this controversy. All accept that Aristotle begins with the theory of Eudoxus, along with its modification by Callippus, in which each complex heavenly motion is analyzed in terms of the motion of spheres. Eudoxus and Callippus analyzed the heavenly motions one at a time. One system of spheres describes the motion of the sun; a similar but separate system describes the motion of the moon; and so on with each of the five planets. In each system, the complex motion of a single heavenly body is represented as the composite motion of concentric spheres, each rotating equably around an axis and each (except, of course, the outermost) with the poles of its axis at rest relative to the surface of the preceding sphere.[5] The third and fourth spheres create a figure called by Simplicius a "horse-fetter" (ἱπποπέδη) which is a figure-eight.[6] The hippopede moves along the line of the ecliptic, while the planet moves along the hippopede.[7] The hippopede is a result of placing the fourth sphere

[5] It is not necessary that the spheres be conceived by Eudoxus and Callippus as progressively smaller; all may have the same radius. There is little evidence about whether Eudoxus and Callippus understood their scheme as a mere mathematical model or as (also) a physical model. I have tried to phrase this initial description so as not to beg the question. See below for further discussion. Wright (1973) discusses this question in connection with Eudoxus, Musgrave (1991) discusses it more generally from the pre-Socratics through Ptolemy.

[6] Yavetz questions even whether the sources require us to reconstruct a theory in terms of a hippopede. His argument hinges on an attack on the credibility of Simplicius. His view his rebutted by Mendell (2001). But Bowen (2001) makes a renewed attack on the reliability and informativeness of Simplicius. His paper begins with a discussion of general historiographical issues relevant to ancient astronomy.

[7] It had been thought until very recently that the hippopede was supposed to account for retrogression: When the planet's motion along the hippopede is in the same direction as the hippopede's motion along the ecliptic, the planet surges ahead; when the planet's motion along the hippopede is in the direction opposite to the hippopede's motion along the ecliptic, the planet stands still or retrogresses. The width of the hippopede determines how far above and below the ecliptic the planet wanders. This assumption has been challenged by a series of recent articles: Yavetz 1998, Mendell 1998 and 2001. See the previous note for some remarks on Yavetz. Mendell (1998) treats various cases in great detail, treating the slow and fast planets separately, and arguing that retrogradation might have been relevant to the slow planets (but that other phenomena too might be the relevant ones), but that retrogradation could not be relevant for the fast planets. These papers also contain citations of much other relevant second-

within the third, rotating (1) in the opposite direction to the third (2) at the same speed as the third (3) around a different axis from the third.[8] Henry Mendell has proved that "Any motion of two spheres may be decomposed into a motion of S_1 and a motion on a hippopede"[9]. The beauty of this theorem is that it shows us that the hippopede is not merely the figure that happens to be created in this spherical system. Rather, the hippopede is the key to understanding the composition of motions in any system of equably rotating, homocentric spheres.[10]

After sketching the Eudoxan systems and Callippus' modifications of them[11], Aristotle states his requirement that all the spheres for all the planets work together in one system. This requirement bears generally on the mathematical status of Eudoxus' and Callippus' work and Aris-

ary literature. A broader question, crucially important for the reconstruction of Eudoxus' and Callippus' systems, is whether retrogradation was known to early ancient astronomers at all. This is denied by Goldstein (1997), rebutted by Yavetz (1998, 225 n5) and Mendell (1998), and maintained again by Bowen (2001).

[8] Demonstrations that this arrangement does produce a hippopede can be found in many of the relevant secondary texts. Of the demonstrations I have seen, by far the best, in my opinion, is that in Mendell 2001, 65ff. Mendell's exposition is entirely geometric, carefully avoids anachronism, and is supplemented by diagrams. He cites ancient texts that contain the relevant theorems. More detailed discussion of the hippopede can be found in Mendell 1998. Yavetz gives a reconstruction in terms of modern spherical coordinates in his Appendix B. Explanations can also be found in Heath (1913, 203 footnote) and Neugebauer (1975, 678).

[9] Mendell 1998, 186.

[10] Note, however, that this theorem does not in itself rebut Yavetz's view (for which see note 6), since the proof of the theorem relies on the very assumption that Yavetz questions, namely that the curve is traced by a point *on the equator* of the inmost sphere.

[11] Callippus, Aristotle tells us, kept Eudoxus' spheres, but added several that he claimed were necessary "if one is going to account for [ἀποδώσειν] the phenomena" (1073b37). Aristotle delivers no explicit judgment or argument about the relative merit of Callippus' and Eudoxus' accounts. He seems ambivalent: He accepts Callippus' view for the planets, and countenances (but does not advocate) rejecting it for the sun and moon. This is taken by Lloyd as a sign of Aristotle's confusion: Aristotle "expresses his hesitancy in a context and in a manner that – if the reconstruction [of Eudoxus' and Callippus' theory] is sound – may suggest he is seriously out of his depth", writes Lloyd (2000, 261). Lloyd is in this paper reworking, in a more cautious vein, the argument he had presented in his 1996 paper. In the later paper, unlike the earlier, Lloyd accepts that it is far from clear whether the astronomy of Aristotle's day decisively favored Callippus' system over Eudoxus'. And it is, moreover, far from clear whether the traditional reconstruction of the Eudoxan-Callippan theory is sound (see note 7). Indeed, Neugebauer wrote that we should "admit our total ignorance of the character of Callippus' modification of the Eudoxan model" (1975, 684). Mendell tempers Neugebauer's claim, saying "although our ignorance may no longer be total, it is still quite profound" (1998, 256).

totle's use of it, but its immediate consequence is the introduction of 'unwinding' spheres to allow for a unified system:

> It is necessary, if the spheres *when put together* [*into one systematic whole*] [συντεθεῖσαι] are going to account for the phenomena, that for each of the planets there be additional [ἑτέρας] spheres, fewer by one [than the spheres in the isolated system], which reverse [the motions of those spheres] and always restore to the same placement [εἰς τὸ αὐτὸ τῇ θέσει] the first sphere of the star positioned below. (1073b38–74a4)

Before addressing the philosophical ramifications of the one-system requirement, we should understand its astronomical ramifications. What are these unwinding spheres and how do they make possible the integration of the various Eudoxan systems into a single Aristotelian one? The problem Aristotle faces is that Eudoxus' systems cannot simply be put together as they stand.[12] To see why, consider, for instance, the four spheres associated with Saturn; these are the four spheres most remote from the earth. The first corresponds to the sphere of the fixed stars, the second corresponds to the ecliptic, and the third and fourth, as a pair, create a hippopede with appropriate width. Suppose we add the next planet, Jupiter, simply by placing Jupiter's first sphere within Saturn's last, and then Jupiter's other spheres within that one. Jupiter itself would have a motion far more eccentric than any actual planet, because the positions and speeds of its second, third, and fourth spheres are calibrated on the assumption that its first sphere has the motion of the fixed stars. Jupiter's motion *relative to its own first sphere* would be unchanged, but its absolute motion (i.e., its motion relative to the earth) would no longer resemble its motion in the heavens, since Jupiter's first sphere would not move with an equable rotation, but rather with the motion imparted by the last of Saturn's spheres.

Aristotle solves this problem by interposing unwinding spheres between the two sets of Eudoxan spheres to cancel the motions of Saturn's 4 spheres. How many unwinding spheres are needed? If Saturn's four spheres are S_1 (fixed stars), S_2 (ecliptic), and S_3 and S_4 (hippopede), then the first unwinding sphere should undo the motion of S_4. How should this unwinding sphere move? Its *per se* motion should be a rotation around the same poles as S_4 with the same speed as the rotation of S_4, but in the opposite direction. Think of the motion of each sphere as the sum of its own rotation and the motion of the sphere above, and, for the case of the first unwinding sphere below Saturn, represent this as follows: *motion of the unwinding sphere* = *motion of* S_4 + *rotation of the unwinding sphere*. In this formula, replace *motion of* S_4 with its expansion according to the same principle. And replace *rotation of the unwinding sphere* with an alternative description, *cancellation of the rotation of* S_4. This yields, *motion of the unwinding sphere* = (*motion of* S_3 + *rotation of* S_4) + *cancellation*

12 This was pointed out already by Sosigenes *apud* Simplicius, *in libros de Caelo* II.12, The whole passage from 498.1 through 504.15 is relevant to the Aristotelian system, but on this problem in particular see 498.1 to 499.15, especially 499.1 ff.

of rotation of S_4 = motion of S_3. In short, since the first unwinding sphere cancels the motion of S_4, its resulting motion is that of sphere S_3.

Likewise, a second unwinding sphere, undoing the motion of S_3, has as resultant motion the motion of S_2, and a third, undoing the motion of S_2, has the resultant motion of S_1, i.e., the motion of the sphere of fixed stars. At this point, we can stop adding unwinding spheres and place Jupiter's Eudoxan spheres within the last of Saturn's unwinding spheres.[13] A corresponding system of unwinding spheres for Jupiter will make way for Mars's Eudoxan system, and so on. A complete table of the spheres can be found in the appendix.

A series of redundancies has entered the system with the unwinding spheres. The first of Jupiter's Eudoxan spheres appears redundant, since both it and the adjacent sphere, Saturn's last unwinding sphere, both move in the same way as the fixed stars. There are several points in the system at which this occurs: between Saturn and Jupiter, Jupiter and Mars, Mars and Venus, Venus and Mercury, Mercury and the Sun, and the Sun and the Moon. The number of spheres could be reduced by six without disrupting the mathematics of the system. It is all the more noteworthy that Aristotle neglects to mention the dispensability of these spheres, since he *does* mention that one might omit some of the Callippan spheres (1074a10–14).[14] Of course, the Callippan spheres and the 'idle' spheres are not on a par, since the Callippan spheres are putatively necessary to account for the phenomena, whereas the 'idle' spheres are not. But this makes it all the more noteworthy that he does not consider eliminating the 'idle' spheres. Aristotle is following the outstanding astronomers of his day, but not slavishly. He does not

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[13] Mendell suggests that one might add yet another sphere (2001, 82). Aristotle, he says, "forgets to unwind the first sphere for every planet". He means that, although the third unwinding sphere (for Saturn) has the motion of the fixed stars, that sphere has itself unwound S_2, not S_1, which still needs unwinding. But why should S_1 be unwound? The mathematics of the system remains the same whether S_1 is unwound or not. Aristotle understands the mathematics well enough to know that no further unwinder is needed. The point of the unwinders is to prevent the various planetary systems from interfering with one another, and that has already been achieved without specifically unwinding S_1. This does not, of course, answer the question why the 'idle' spheres should be present, but the answer I will give below does not entail, or even suggest, that the S_1 needs an unwinder of its own.

[14] The alternative number given in the manuscripts, 47, appears not to be the correct number. If 55 is the correct number of spheres for Aristotle's version of the Callippan system, then, given the modifications he mentions, the alternative number should be 49. The number 47 is the *lectio difficilior* and it is in all the manuscripts cited in the standard apparatus. But I am inclined to conjecture, with Sosigenes *apud* Simplicius, that the text should read 49. There are, however, alternative explanations. See Ps.-Alexander and Ross 1924, *ad loc*.

simply take over the Eudoxan-Callippan systems by rote and therefore keep the 'idle' spheres. On the contrary, he must be strongly committed to them. Only if we cannot find any good reasons for including the 'idle' spheres should we concede that they are truly superfluous.

Even in antiquity, there was confusion about whether or not to include the 'idle' spheres. Simplicius praises Sosigenes for having understood that Aristotle intended these apparently superfluous spheres to be parts of the astronomical system:

> Next, one must realize that the eighth sphere [of the whole system] is the first sphere of Jupiter. Sosigenes understood rightly that the first sphere of Jupiter is *not* the last of the three unwinding spheres [= seventh sphere of the whole system] – which some people actually think, viz., that the last of the spheres that unwind the upper motions will be the first of those moving the star below, [e.g.,] that the seventh sphere and what we have called the eighth sphere, i.e., Jupiter's first sphere, are the same. [This must be wrong,] since they, in trying to save the number of unwinding spheres stated by Aristotle, turn out to count the same sphere twice. (502.20–27)[15]

Why then are the 'idle' spheres present?[16]

Aristotle's view looks even more perplexing when we consider that the spheres in question are not merely idle, but are downright problematic for his own project of counting the divine movers. Each 'idle' sphere has its own mover because each sphere requires a rotation about its axis, as well as the motion imparted by the sphere above. Yet each 'idle' sphere moves with exactly the same motion as the sphere above it, so that it would seem to have no need for an additional divine mover to rotate it. How then is Aristotle entitled to count movers for the 'idle' spheres?[17]

A more precisely imagined picture of the spheres will answer this question. The last of Saturn's unwinding spheres has a special feature, because its resultant motion, unlike that of most other spheres in the system, is an equable rotation. The special feature is that it has two sets of poles, the poles around which its unmoved mover rotates it and the poles around which its *resultant* rotation occurs. The latter set of poles

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15 Μετὰ δὲ ταύτην ὀγδόην λοιπὸν νοητέον τὴν πρώτην τοῦ Διός, ὀρθῶς Σωσιγένους ἐπιστήσαντος, ὡς οὐκ ἔστιν ἡ τελευταία τῶν τριῶν ἀνελιττουσῶν πρώτη τῶν τοῦ Διός, ὅπερ τινές ᾠήθησαν, ὅτι ἡ τελευταία τῶν τὰς ἐπάνω φορὰς ἀνελιττουσῶν πρώτη ἔσται τῶν τὸν ὑποκάτω ἀστέρα φερουσῶν, ὡς εἶναι τὴν αὐτὴν ἑβδόμην τε καὶ ἥν ἡμεῖς φαμεν ὀγδόην πρώτην οὖσαν τῶν τοῦ Διός· τοῦτο γὰρ συμβαίνει αὐτοῖς δὶς τὴν αὐτὴν ἀριθμεῖν σῴζειν πειρωμένοις τὸν ἀριθμὸν τῶν ἀνελιττουσῶν τὸν ὑπὸ τοῦ Ἀριστοτέλους λεγόμενον.

16 See below, note 26, for Simplicius' answer.

17 Edward Hussey (private communication) drew my attention to this problem.

corresponds to the poles of the fixed stars.[18] The first set of poles is in motion; the second set of poles is at absolute rest (like the poles of the sphere of the fixed stars). The latter poles, at absolute rest, are the very points in which the poles of the *next* sphere, Jupiter's first, are fixed. Hence the upper sphere imparts no motion to the lower, which in turn needs its own unmoved mover in order to move at all. The same obtains for every 'idle' sphere. Hence each 'idle' sphere requires its own mover, without which it would be at absolute rest.

Indeed, quite generally, no sphere is *rotated* by any other. The spheres rotate not because of other spheres, but because of unmoved movers. In most cases, the upper sphere does impart some motion to the lower sphere, namely by causing its poles to revolve, but in the special cases of the 'idle' spheres, this does not occur.

It may be objected that my interpretation helps itself too easily to the counterfactual, *if the 'idle' spheres were not rotated by unmoved movers, they would be motionless.* This objection would emphasize that the heavenly spheres are mechanically interrelated physical bodies, and urge that any interpretation should accept the mechanical fact of friction. If friction plays a role, the counterfactual is falsified: the 'idle' spheres would *not* be motionless, even if they were not rotated by unmoved movers.

I offer three replies. First, it is far from clear that there is friction in the celestial realm, filled as it is with aether and topical matter. Because Aristotle believes that celestial substances are of a radically different nature from sublunary substances, the assumption that the celestial spheres are bodies does not entail that a complete description of their motion and its causes will mention friction. The evidence of *de Caelo* is equivocal (see book II, chapters 1, 4, and 7). Second, even granting that there is friction in the heavens, it is far from clear that the friction would produce an equable rotation. Thus the objection must make not the relatively modest claim that there is some friction in the heavens, but that this friction would produce precisely the correct rotation; otherwise, a special mover will be required for each sphere. Aristotle evidently does assume that the 'idle' spheres require movers, and so evidently assumes either that there is no friction or, at least, that such friction would not have the appropriate effect. Third, even if there were in the celestial realm friction with the appropriate effect, the 'idle' spheres need unmoved movers for the same reason that, I argue below, the 'idle' spheres are needed, namely that, without them, a phenomenon (in this case, the rotation of an 'idle' sphere) would lack a *per se* cause. The unmoved movers make it the case that the 'idle' spheres are moved *per se*, even if it is false that the 'idle' spheres would be at rest, if they were not moved by unmoved movers.

Another objection to my interpretation might lead in the opposite direction, alleging that I have overemphasized the mechanical aspects

[18] They correspond to the poles of the sphere of the fixed stars in the sense that the line joining the poles of the sphere of the fixed stars will pass through them.

of the spherical system, which should be understood as a purely mathematical model. It might be a purely mathematical model in (at least) two ways: by being an empirically adequate but literally false representation of the motions and their causes, or by making no causal claims of any kind.

If it is purely mathematical in the former sense, then the spheres do not exist, but are mathematical fictions employed to save the phenomena. But there is no reason to suppose that this is what Aristotle believed, it requires an instrumentalist view of geometry that Aristotle did not hold, and it is unclear what motivation an ancient astronomer would have for developing such a model.[19] While it is clear that the system does remarkably well at saving the phenomena, the system is not well-suited to making predictions, as is well-argued by Wright.[20] He points out that the Babylonian predictive method made for easier computations, since it relied simply on numerical astronomical coordinates and algorithms for extrapolating from them, while the Eudoxan scheme, under the constraint that the earth be located at the center of the concentric spheres all rotating *equably*, not only makes computation tremendously complex (as can be seen by anyone who tries to work out merely how the hippopede is created), but also seems to make it impossible to save some important phenomena, as was recognized quite early in antiquity.[21]

Even if the Eudoxan system is not a predictive tool, it may be claimed to be a mathematical model in the sense that it includes no causal claims or information; the mathematics requires only that each sphere have its poles at rest relative to the sphere above it, not that those poles be attached so that one sphere is literally carried by another. The theory is silent as to why the poles are at rest relative to the sphere in question.

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[19] Ptolemy's system does not provide a counter example. His alleged motivation for thinking in terms of a mathematical model is that his system of spheres seems mechanically impossible. But even so, he may well have thought of the spheres postulated by the system as existing physical bodies. See Lloyd 1991 for a very helpful criticism of Duhem's view of ancient mathematical astronomy, from Plato to Proclus. He concludes, "Where it is perfectly fair to say that the Greeks distinguished, even contrasted, mathematics and physics, it is an exaggeration to claim they advocated a mathematical astronomy divorced from physics or sought to liberate astronomy from all the physical conditions imposed on it" (275).

[20] See Wright 1978. Mendell (1998, § 4) sketches an ingenious method of plotting points using the Eudoxan system, not by calculation, but by the use of fixed-length strings and model globes. Yavetz too discusses this issue (1998, 241ff.). It is quite possible that such a method was used by ancient astronomers.

[21] Why precisely the system of homocentric spheres was rejected is a very difficult question, discussed in detail in Mendell 2001.

But this interpretation too attributes to Aristotle a notion of mathematical model without a motivation. The surrounding context clearly indicates that Aristotle is concerned about causes, e.g., unmoved movers. Why is he silent about the causes of the fact that various spheres have motions other than the motion caused by their unmoved movers? Because he took for granted the obvious and modest conclusion that the poles of every sphere (except the first) are in fact fixed in the surface of the previous sphere.

Even more important, Aristotle's insistence on the unwinding spheres shows that the Eudoxan system (as Aristotle took it) does not stop short at the claim that the poles of inner spheres are at rest with respect to outer spheres, but specifies the cause of this relation, namely that the poles of every sphere are fixed in the surface of the preceding sphere. If Aristotle's Eudoxus had said only that the poles of inner spheres are at rest relative to the outer spheres, it is very hard to see why Aristotle would have invented the unwinding spheres, rather than taking the simpler route of rejecting the constraint that *every* sphere's poles be at rest relative to the preceding sphere. If the only motivation for this constraint were mathematical, i.e., to make the predictions correspond to the phenomena, then one would expect Aristotle to nest the systems without connecting them to one another. Jupiter's first sphere would then not be disturbed by Saturn's last sphere because there would be no mechanical link between them. The fact that Aristotle refuses to take this route shows that even the original Eudoxan system, or Aristotle's version of it, is not a mathematical as opposed to mechanical model. It contains claims about causal connections. We need not accept Heath's assertion that "Aristotle […] transformed the purely abstract and geometrical theory [of Eudoxus] into a mechanical system of spheres"[22]. Rather, I

[22] Heath 1913, 217. See also 225. This view has been accepted by later commentators. As Dicks writes, "Obvious difficulties arise if we enquire too closely into the actual *physical* connection of the spheres [in Eudoxus' theory]. For example, if the heavens really operated in this manner […] how did astronomers ever manage to make the observations that lay behind the original Eudoxan scheme […]?" (1970, 203; my italics) I think that this specific question is rather shallow (obviously the spheres are not visible), but the general concern is important. Behind it lies Dicks' understanding of "[Aristotle's] mechanistic view of the structure of the universe" (*ibid.*). Similarly, Ross writes, "Eudoxus and Callippus had offered a purely *geometrical* account of the planetary system; Aristotle aims at a *mechanical* account, and cannot isolate the system of one planet from that of the next" (1924, 391; my italics). There is no good evidence that the contrast between Eudoxus' astronomy and Aristotle's should be drawn in these terms. (The astronomy described in *Republic* VII is not good evidence about Eudoxan astronomy.)

suggest that Eudoxus' theory is the skeleton of a causal account, in the sense that it explains the motion of each sphere insofar as it is carried by the sphere above, but not the rotation of each sphere. Aristotle, preserving the basic structure of the skeleton, puts flesh on it and brings it to life, by providing causes for the rotations of the several spheres and by putting them all together into one system. The one system requirement does not run counter to Eudoxus' project, but rather extends it.

The concern with causes suggests a way to answer the second question raised at the beginning of this paper, the question why the 'idle' spheres are present at all. Since Saturn's last unwinding sphere has the same motion as the fixed stars, it has two axes, with different explanations for its motion around each. It has a 'proper' axis, around which its unmoved mover rotates it, thereby creating the motion which is essential to its role in the whole system and which cancels the motion of the sphere above. It also has an 'improper' axis, being the *last* of Saturn's unwinding spheres, so that its resultant motion, like its motion in its own right, is an equable rotation. If, among Jupiter's spheres, there is no sphere that *properly* (rather than incidentally) has the motion of the fixed stars, then Jupiter's motion will be said, on Aristotle's standards, to lack a proper cause, because nothing in the world will be responsible for Jupiter's daily motion around the earth. Since Jupiter is a planet, a wanderer detached from the fixed stars, an astronomical theory must account for the fact that, despite its detachment, Jupiter makes the same daily orbit as the fixed stars. And it must account for this fact not only in the sense of saving it as a phenomenon, but in the sense of giving a *per se* cause for it. It is in this sense that Aristotle's astronomy is not merely mathematical; it is required not only to save the phenomena, but to explain them in a richer sense, namely by way of *per se* causes.

Let us compare the explanations of Jupiter's motion with an 'idle' sphere and without it. If Jupiter's four Eudoxan spheres are labelled J_1, J_2, J_3, and J_4, so that J_1 is the 'idle' sphere, the explanation of Jupiter's motion would begin something like this:

> Jupiter moves as it does because the sphere on which it sits, i.e., J_4, moves as it does. But why does J_4 move as it does? (1) Because a divine mover rotates J_4 about its axis and (2) because sphere J_3, in which J_4 is situated, has precisely the motion it has.[23]

[23] I take the divine mover to be self-explanatory, not in need of further explanation; whereas (2) does need further explanation. "Self-explanatory" is to be understood in a very strong sense: they account for themselves, are responsible for themselves, as no other beings in the universe are. One might or might not be satisfied with this, but that is irrelevant to the character of Aristotle's theory.

Why does J_3 move as it does? (1) Because a divine mover rotates J_3 about its axis and (2) because sphere J_2, in which J_3 is situated, has precisely the motion it does have. But why does J_2 move as it does?

The explanation of J_2's motion will, like the other explanations, refer to (1) J_2's divine mover and (2) the motion of another sphere in which J_2 is situated. This other sphere must have the motion of the fixed stars, since Jupiter orbits the earth daily, but this constraint is compatible with this sphere's either being sphere J_1, the 'idle' sphere, or being the last of Saturn's unwinding spheres; both of these have the motion of the sphere of the fixed stars. To continue the story on the hypothesis that the 'idle' sphere, J_1, is absent:

J_2 moves as it does (1) because a divine mover rotates J_2 around its axis and (2) because *the last of Saturn's unwinding spheres* has the motion it has. The explanation of (2) will, of course, take the same form as the explanations already given, the motion for each sphere being partly explained by its own divine mover, partly by the motion of a higher sphere. The motion of the higher sphere will stand in need of further explanation until we reach the sphere of the outer heaven. In this way the motion of sphere J_2 is explained, and so is the motion of Jupiter.

Why then is Jupiter swung round the heaven with the same daily motion as the stars? There is no being, divine or otherwise, which explains this motion as such, for the motion merely supervenes on some brute facts about the arrangement of spheres and the divinely caused motions of the other spheres. We need not only to explain why the sphere in which J_2 is situated has such and such a speed around such and such an axis, but also to give a *per se* cause for its motion being *the same as* the motion of the fixed stars. One could not say that the sphere of the fixed stars itself is responsible for this, since its motion has been filtered out by unwinding spheres. But lacking a *per se* cause for this crucial feature of the motion of the sphere prior to J_2, we also lack a *per se* cause for the most obvious of Jupiter's motions, its daily orbit around the earth.

Now let us consider how the explanation would run with the 'idle' sphere, J_1, restored:

J_2 moves as it does (1) because a divine mover rotates it around its axis and (2) because sphere J_1 has precisely the motion it has. J_1 moves as it does (1) because a divine mover rotates it around its axis and (2) because the last of Saturn's unwinding spheres *has no effect* on the motion we are trying to explain.

On this account, Jupiter orbits the earth daily because sphere J_1 is rotated by its own divine mover with the same motion as the outer heaven. The last of Saturn's spheres should be mentioned in any candidate explanation of Jupiter's motion, since, if the motion of Saturn's last sphere were different, Jupiter's motion would be different. But in the explanation as I have sketched it, the force of the reference to Saturn's last sphere in (2) is not to indicate in what direction the explanation must continue, but to specify why the explanation stops here. The spheres in question, while mathematically idle, are not explanatorily idle, for without them Jupiter's daily orbit would be an incidental feature of the cosmic harmony, not properly explained by a cause of its own, just as the motion of a barnacle on a ship's hull lacks a proper cause.[24] The barnacle is *per se* stationary; it is only the ship (or the ship-barnacle composite) that is moved *per se*. Indeed, Aristotle himself concludes that not only the daily rotation of the fixed stars but "each of these motions too must be caused *per se* [καθ' αὑτήν] by an unmoved and eternal mover" (XII.8, 1073a32–34).[25] We need not assume that all events whatsoever have *per se* causes, only that, faced with a choice between two theories about eternal features of the world, one of which leaves certain eternal motions without full-fledged, *per se* explanations, we surely should prefer the theory that offers the more complete explanations, other things being equal.[26]

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[24] This solution can be directly extended to solve a problem raised by Yavetz (1998, 237 n16), who observes that not only the first, but also the second sphere for each planet might have been eliminated. This requires a modification of the system of unwinders. In Aristotle's system, the unwinder of the ecliptic sphere of (say) Saturn has precisely the speed that cancels the motion of Saturn's ecliptic sphere; but that sphere might have a speed such that its resultant motion is the motion of Jupiter's ecliptic sphere. If the unwinder's speed is set in this way, then Jupiter's ecliptic sphere is redundant. And so throughout the system, the ecliptic spheres are eliminable. But this would result in a theory according to which there is no *per se* cause for the motion of the planets along the ecliptic, and this, if I am correct, is a worse theory, not a better one.

[25] He is speaking here of the criterion by which we count unmoved movers, and hence presumably he has in mind primarily the relationship between a given sphere and its unmoved mover, not the question how many spheres there should be in the system. What is important for our purposes is that he here clearly accepts the having of a *per se* cause as a desideratum for the theory. I am arguing that we can see that this criterion as relevant not only to the unmoved movers, but also to the 'idle' spheres.

[26] Simplicius reports that Theophrastus called the unwinding spheres "compensating" (ἀνταναφεροῦσαι), by which he meant something different from what Aristotle meant by "unwinding" (504.5–6). The poles of the spheres must (δεῖ) line up (κάθετον πίπτειν) "for only in this way, says Theophrastus, is it possible for the motion of the fixed stars to produce all things (as we have already said [it does]), and he is correct" (οὕτως γὰρ μόνως, φησίν, ἐνδέχεται τὴν τῶν ἀπλανῶν φορὰν ἅπαντα ποιεῖσθαι, καθάπερ ἤδη ἔθαμεν, εὖ λέγων; 504.14–15). This solution is similar in spirit to the one I offer, but I cannot see how the 'idle' spheres could

But are other things equal? An objector might develop a counter-argument in two stages, saying first that the 'idle' spheres do not complete the explanations of planetary motions, since in either case Jupiter's motion is partly caused by features of a network of spheres, and second that the two theories are not equal in respects other than explanatory completeness, since the theory with 'idle' spheres violates the principle of parsimony.

Our objector begins by observing that our formulations mentioned only two components for the explanation of, say, the motion of Jupiter's sphere, J_4: 'J_4 moves as it does (1) because a divine mover rotates the sphere about its axis and (2) because sphere J_3 has precisely the motion it does'. We omitted a crucial part of the explanation: 'and the poles of the axis of J_4 are fixed in the surface of sphere J_3 and the angle between the axes of J_4 and J_3 is x'. Indeed, determining the angles between the third and fourth spheres of the various planets was a crucial step in reconstructing the Eudoxan theory. When comparing two versions of the theory, we saw that the 'idle' spheres allow for fuller elaboration of the second part of the explanation, but our objector points out that they cannot eliminate or elaborate the (omitted) third component, the relations between spheres. According to the objector, the conceit of the 'idle' spheres theorist is that the arrangement of the network, being a brute fact, itself stands in need of explanation, whereas the postulated divine movers are self-explanatory, and therefore do not stand in need of any further explanation. But why are the angles of inclination between the axes of the spheres not also in need of explanation?

The objector confronts Aristotle with a dilemma. On the one hand, if Aristotle would extend the demand for explanation to cover all brute facts, then he must postulate divine beings as causes for every last feature of it – to explain why the angle of the ecliptic is 1/15 of a circle, why the number of spheres is 55. Are we to countenance a host of divine beings that cause the angles between various spheres to be just so many degrees?[27] Such a strategy, because it ignores all considerations of parsimony, would undermine our explanations, not enrich them. It would not explain, but merely stipulate that certain features of the world count as explained. On the other hand, if Aristotle balks at this proliferation of causes and agrees that parsimony is a consideration, then he should eliminate not just a few of these gratuitous divine movers, but all of them, and their 'idle' spheres too. Whether we account for the motion of Jupiter with the 'idle' sphere or without it, *both* explanatory factors must come into play – the arrangement of spheres and the *per se* motion of the preceding sphere. The alleged superiority of the explanations with 'idle' spheres is exposed as spurious, since its guiding principle leads to unbridled postulating of causes.

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make such a difference. It is true that the motion of the 'idle' spheres mimics that of the fixed stars, but how could that entail that their presence allows the motion of the fixed stars to produce everything?

27 Lloyd does think of the unmoved movers as causing the spheres not only to rotate with a certain speed, but to have their axes at certain angles (2000, 254).

I grant that features of the network remain unexplained, but this does not undermine Aristotle's justification for postulating divine movers in the cases where he does. Our objector agrees that the divine movers make some contribution to explanation.[28] He should, therefore, also agree that the explanation of the heavenly phenomena, in particular of the diurnal rotations of the planets, is more complete to the extent that it can refer to some entity whose causal efficacy is directed toward these effects, rather than merely to brute facts about the network. The principle of parsimony should here be applied at the level of *per se* causes, not of spheres or divine movers. Aristotle should advocate the theory that uses the fewest causes while giving all the heavenly motions *per se* causes, even if this theory uses more spheres and divine movers than another theory which robs some heavenly motions of *per se* causes. But Aristotle should prefer this same theory to another in which all the heavenly motions have *per se* causes *and* unneeded *per se* causes are postulated for a variety of irrelevant facts. There is no more reason to postulate an unmoved mover to account for the angle between the ecliptic and the equator than there is reason to postulate an unmoved mover accounting for the existence of worms or of two basic pairs of opposites in the simple bodies.

The acceptability of the 'idle' spheres becomes clearer if we achieve greater precision about what these divine movers are, or rather, about what it means for there to be *many* such movers. Given their divine perfection, why is a single unmoved mover insufficient to cause all the heavenly motion, as long as that motion is conceived as a single extremely complicated motion? In the argument about how to count the unmoved movers (1073a26ff.), Aristotle adduced the premise, "one eternal motion is caused by one eternal mover", rather than (in the spirit of the parsimonious objector) postulating a single unmoved mover for the whole. What notion of explanation could have brought the philosopher to invoke a whole array of unmoved movers when it is not even clear whether they can be distinct from one another? All that is said in the text emphasizes their likeness to one another: ever-living, self-thinking thoughts. At the end of the chapter, Aristotle says that whatever is one in form can be many in number only by having matter (1074a32–34). Since these divine beings lack matter but are many in number, they must differ in form. I conjecture that the form of a divine mover is "what causes such and such a motion", from which it follows

[28] This might be challenged, of course, but it is a challenge beyond the scope of this paper.

that two movers cannot cause one motion because their forms would be identical and so they would be just one mover.[29]

This does not, however, eliminate the possibility that one mover causes all the heavenly motions: Why cannot the first unmoved mover have the form 'what causes *all* these motions' or 'what causes this *single*, very complicated motion'? If one were to insist that the motion of the heaven is one motion, could one in fact describe it as such, i.e., without reference to the multitude of spherical motions? Even if so, the heavenly motion would thereby lose its circularity, to which Aristotle is committed on other grounds (*de Caelo*, I.2).[30] The loss of the circularity of the motion would, furthermore, make the Aristotelian theory an empirically adequate but false mathematical model, which is not the kind of theory it is.

If, on the other hand, the first unmoved mover were thought to cause a plurality of heavenly motions, then the first unmoved mover could be only one part among several of the explanation of the motion of any particular sphere. The governing principle here was first thematically discussed by Socrates in the *Phaedo* where he avoids either giving a single cause for both being smaller and being larger or giving many causes for being two (100c9ff.); it is that one cause has one effect and one effect has one cause. If we do not preserve this principle, then our explanations lose their force altogether, because the crucial question remains unanswered even after the cause is cited, namely, 'Why did it have

[29] I do not find in the literature a satisfying discussion of the premise, 'one eternal motion is moved by one mover'. Ross provides no more than a reiteration of the conclusion: "Since every eternal motion requires an eternal cause, and there are other eternal motions […], each of these requires an eternal substance as mover. […] There must be as many such substances as there are motions" (Ross 1924, 382). Lloyd (2000, 254) presents an alternative interpretation grounded on the perfection of the motions rather than the perfection of their movers: Because the motions are perfect, we cannot explain the differences between motions on the grounds that some achieve their goals more effectively than others; we must therefore have recourse to a multitude of movers (which are, in a way, goals). This alternative has two weaknesses. First, it omits the possibility of a single motion being caused by multiple movers. Second, on the assumption that a single mover can cause all the heavenly motions, why must the differences between the motions betoken an imperfection in the spheres (i.e., lesser ability to fulfil a goal)? This begs the question, which is whether a single unmoved mover can be a τέλος for the system of motions *as a whole*, a reasonable notion if one is, like Aristotle, impressed by the perfection of the whole system. In that case, the differences in the motions of the spheres would reflect not differing degrees of perfection, but differing roles in the fulfillment of a complicated τέλος.

[30] I am indebted to Sarah Broadie for this point.

this effect (out of the range of possible effects)?' Certainly one cause can in a sense have many effects, for the same man can build many houses; but Aristotle shows his awareness of this problem by saying that, properly, what produces a house is the art of house-building, which produces nothing but houses and by which all houses are produced.[31] Whatever the complexities and difficulties of this view about artistic production, we can see that the features of a particular house are explained either by the art itself (which, for instance, made the best of a bad building site) or by external interferences (for instance, the roof is missing because of a tornado). But this yields no helpful analogy with the heavenly realm, for no interferences occur there and so no causes account for the differences in the ways that the various spheres follow the unmoved mover's lead. As Lloyd observes[32], given the perfection of the spherical motions, their differences cannot reflect varying degrees of success in imitating the first unmoved mover. To count one mover per motion is to compromise between parsimony and extravagance, on rather complicated grounds.

Aristotle might thus offer a convincing rebuttal to the objection that his astronomical system is overburdened with unmoved movers. There are precisely as many unmoved movers as there are heavenly spheres. And however many heavenly spheres there are, certainly each planet has a sphere that an unmoved mover causes to revolve daily. Without these mathematically superfluous spheres, a cardinal feature of the heavenly motion would have no more explanation than a chance encounter in the agora. These apparently idle spheres are not idle in a system that, while apparently mathematical, is actually governed by a notion of explanation that insists on the principle of one cause-one effect and that has a strong but not overriding preference for including *per se* causes for eternal features of the world.[33]

[31] This is not a strictly accurate characterization of Aristotle's view, since he thinks that arts can produce both members of a pair of opposites (*Metaphysics* IX.2). But this is not relevant for our purposes.

[32] See note 29 above.

[33] I would like to thank Sarah Broadie, Ursula Cooper, John Cooper, Michael Frede, Kinch Hoekstra, Edward Hussey, Andrew Sage and Christian Wildberg, without whose criticisms and suggestions this paper would have remained a private experiment, and Verity Harte, without whose encouragement this paper would never have been written in the first place. Henry Mendell provided enormously helpful comments, which saved me from serious errors.

Appendix:
Table of Heavenly Spheres According to Aristotle and Callippus

Aristotle's unwinding spheres are listed in the form "$\text{sphere}_1/\text{sphere}_2$", where the unwinding sphere has the *same poles* as sphere_1 but opposite motion and hence cancels sphere_1's motion, and the unwinding sphere has the same *resultant motion* as sphere_2. "Sphere_1" indicates the poles, "sphere_2" indicates the motion. Thus S_4/S_3 cancels the motion of S_4, and has a resultant motion just like S_3. Reading a row of the chart from left to right, one sees how the unwinding spheres progressively reverse the motions of the spheres above.

S_1 and S_2 represent the sphere of the fixed stars and the 'ecliptic' sphere respectively. Each planet after Saturn has a pair of spheres that corresponds to but is distinct from S_1 and S_2. Beside those lower, corresponding spheres, I have marked (S_1) and (S_2) to bring out the correspondence. Each sphere marked (S_1) revolves once per day, but the speeds of the spheres marked (S_2) vary from planet to planet.

Saturn	S_1	S_2	S_3	S_4		S_4/S_3	S_3/S_2	S_2/S_1	
Jupiter	J_1 (S_1)	J_2 (S_2)	J_3	J_4		J_4/J_3	J_3/J_2	J_2/J_1	
Mars	A_1 (S_1)	A_2 (S_2)	A_3	A_4	A_5	A_5/A_4	A_4/A_3	A_3/A_2	A_2/A_1
Venus	V_1 (S_1)	V_2 (S_2)	V_3	V_4	V_5	V_5/V_4	V_4/V_3	V_3/V_2	V_2/V_1
Mercury	H_1 (S_2)	H_2 (S_2)	H_3	H_4	H_5	H_5/H_4	H_4/H_3	H_3/H_2	H_2/H_1
Sun	X_1 (S_1)	X_2 (S_2)	X_3	X_4	X_5	X_5/X_4	X_4/X_3	X_3/X_2	X_2/X_1
Moon	L_1 (S_1)	L_2 (S_2)	L_3	L_4	L_5				

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MAX-PLANCK-INSTITUT FÜR WISSENSCHAFTSGESCHICHTE
Max Planck Institute for the History of Science

2005

PREPRINT 289

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Forthcoming in
Apeiron: a journal for ancient philosophy and science
<http://www.utexas.edu/cola/depts/philosophy/apeiron/>

Aristotle asserts at 1073b10-13 that he intends to give in *Metaphysics* XII.8 a definite conception about the multitude of the divine transcendent entities, which function as the movers of the celestial spheres. In order to do so, he describes several celestial theories. First Eudoxus's, then the modifications of this theory propounded by Callippus, and finally his own suggestion, the introduction of yet further spheres which integrate the celestial spheres into a single overarching scheme. For this, after explaining the spheres providing the component motions of each planet, Aristotle introduces so-called rewinding spheres (*anelittousai*), which perform contrary revolutions[1] to the ones performed by the spheres carrying the planet.

The aim of this setup is that the spheres carrying the next planet can be attached directly to the last rewinding sphere of the preceding planet.[2] As a result of the operation of the rewinding

[1] I will describe a revolution as contrary to another one if and only if [1] the two revolutions have the same period, [2] are around the same axis, and [3] revolve in an opposite sense.

Note that the use of the term `contrary' is my shorthand. Aristotle rejects in *de Caelo* I.3 270a12-22 that celestial revolutions could have contraries indeed that is a key component in his proof of the eternity and inalterability of the celestial realm. As the considerations of *de Caelo* I 4 make it clear, both topological and dynamical contrarieties are ruled out (cf. further n. 11). Topological contrariety is ruled out, because revolutions do not occur between contrary regions, i.e. regions of different status, like the rectilinear motions between up and down or right and left. Dynamical contrariety is not applicable to the celestial domain, because if one circular motion were eliminated by the influence of another one, this would make either or both of these revolutions superfluous. (I owe the distinction of topological and dynamical contrariety to Jim Hankinson.)

Later, at *de Caelo* II.2 285b28-33 when Aristotle talks about the motions of the planets, he says that they are contrary to the diurnal celestial revolution of the fixed stars. My terminology is a more restricted variant of that usage (cf. also *de Generatione et corruptione* II.10 336a23-31).

[2] `But it is necessary, if all the spheres combined are to render the phenomena, that for each of the planets there should be other spheres (one fewer than those hitherto assigned) which do the rewinding and bring back to the

spheres, the motions of the preceding planet will not carry over to the next planet.[3] But Aristotle constructs this scheme in a strange fashion. He submits that in the case of each planet we do not need as many rewinding spheres as the number of the spheres carrying the planet, but rather one fewer. As a result the last rewinding sphere (e.g., in the case of Saturn, Saturn$_{rew\ 2\to 1}$), to which the first sphere of the next planet (in this case, Jupiter$_{w\ \to 1}$) is attached, is not stationary.[4] Instead, after all the rewinding it has the same motion as the first sphere of the upper planet. As the first spheres of all the planets perform the same motion—the diurnal celestial motion, which is most perspicuous in the case of the fixed stars—we have to admit some rather strange consequences. Either we have to admit that Aristotle's account contains an embarrassing slip, and consequently the first sphere of the lower planet (Jupiter$_{w\ \to 1}$) does not move in relation to the last sphere of the upper one (Saturn$_{rew\ 2\to 1}$), in which case it cannot have an unmoved *mover*. Even if in each case there is a transcendental entity which governs the motion of the first sphere of the embedded planetary systems,[5] all that transcendent entity does is that it instructs the sphere not to modify the motion taken over from the last sphere of the preceding planet. Other alternatives are to suggest some realignment of the Aristotelian celestial mechanism, either by introducing new rewinding spheres, or by dropping some of the spheres which carry the planets. Yet a further alternative could be to maintain, as Jonathan Beere submitted in a recent article,[6] that Aristotle's celestial setup can be salvaged if the motion of the last spheres of each upper planet is not transmitted to the first sphere of the following planet. If this motion is not transmitted, the

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same position in each case the first sphere of the star which is situated below; for only this way can they all carry out the motion of the planets.' (Metaphysics XII.8 1073b38-1074a5, Revised Oxford Translation, somewhat modified)

[3] See Simplicius, *Commentary on* de Caelo, 504.9-10

[4] See the Appendix for the description of the notation I use to refer to planetary spheres and their motions.

[5] In what follows I shall use the expression "planetary system" to refer to those spheres which directly provide the component motions of a planet. Such planetary systems are composed of the sphere that contains the planet, and the ones immediately preceding this sphere, up until (but excluding) the rewinding spheres of the preceding planet. My terminology is modeled on Simplicius's usage at *Commentary on* de Caelo, 490.20 and 29, where he speaks about the *suntaxis* of the spheres carrying a planet.

[6] Jonathan B. Beere, "Counting the Unmoved Movers: Astronomy and Explanation in Aristotle's *Metaphysics* XII.8," *Archiv für Geschichte der Philosophie* 85 (2003), 1-20.

embedded sphere will also need an unmoved mover.

In what follows I will submit that the project Aristotle pursues in this chapter—to provide a unified celestial mechanism which satisfies his strictures of causal relevance—will incur some significant difficulty on any of the above alternatives. But these inherent difficulties are different in the case of each alternative. Hence, a discussion of these alternatives can shed light on possible considerations shaping the account Aristotle endorsed among the several problematic options.

1

The last rewinding sphere of the preceding planet (e.g., in the case of Saturn, $\text{Saturn}_{\text{rew } 2\to 1}$), after all the winding and rewinding, performs the daily revolution of the stars. If that is transmitted to the next embedded sphere—to the first sphere carrying the next planet, in this case, to $\text{Jupiter}_{\text{w } \to 1}$—there are going to be several problems. One is that the mover pertaining to this embedded sphere will not cause any additional motion in this sphere: it will be a contradictory entity, a non-moving mover. As the embedded sphere will not perform any additional motion relative to the containing sphere, it will not make sense to settle along what axis the lower sphere is embedded in the containing sphere: any axis will be just as good as any other.[7]

Or rather, any axis will be just as bad as any other, as it will hardly make sense to speak about an axis of rotation around which no rotation takes place. Accordingly, the two spheres might as well be joined to each other along the entirety of the common surface they have. Even then the two spheres will remain distinct: the outer one receives some motion from yet previous spheres, and performs a revolution on its own, under the causal influence of its mover, whereas the internal sphere takes over the entirety of the ensuing motion. The fact that this can happen along the whole of the adjacent peripheries of the two spheres highlights that the causally

[7] That any axis transmits the motion of the outer sphere in its entirety to the inner sphere is a fundamental presupposition of the theory of homocentric spheres. In this theory revolutions are combined by embedding one sphere along an axis not coinciding with the axis of the containing sphere. No matter how the two non-coinciding axes relate to each other, the revolution of the external sphere is transferred to the embedded sphere. Note, however, that the stipulation in the lines above, that the axes of the motions combined do not coincide, will receive further scrutiny in Section 3 below.

relevant entity responsible for the fact that there is not any further component motion performed by the embedded sphere is exceptional: it is a non-moving mover. Clearly, if possible, the introduction of such non-moving movers should be avoided.

As it is, there are at least two ways open for Aristotle to avoid such non-moving movers. One option would be to introduce an additional rewinding sphere for each planet, so that this last sphere rewinds and eliminates the daily motion of the stars.[8] Accordingly, this ultimate rewinding sphere would perform a rewinding motion, which would cancel the motion this sphere receives. This additional sphere, then, would be completely at rest. Attached to this sphere at absolute rest,[9] the first sphere of the next planet—which we now can designate $\text{Jupiter}_{w\ 0\rightarrow 1}$—could perform the daily motion of the stars under the causal influence of its mover.[10]

But there are several problems with this proposal. To begin with, it would be strange that in the celestial domain, which according to Aristotle is in constant motion, there would be spheres which as a result of the combination of their own motion and the motion imparted to them externally, are eternally at absolute rest. Furthermore, the solution would arguably be against the principle of relevance Aristotle formulates at the end of 1074a25-31. That passage says that

> [….] for if everything that moves is for the sake of that which is moved, and every movement belongs to something that is moved, no movement can be for the sake of itself or of another movement, but all movements must be for the sake of the stars. For if a movement is to be for the sake of a movement, this latter also will have to be for the sake of something else; so that since there cannot be an infinite regress, **[Principle of Relevance]** the end of every movement will be one of the divine bodies, which move through the heaven. (Revised Oxford Translation)

The principle formulated in the last two clauses of this passage submits that each and every celestial motion has to contribute to the activity of a planet. Motions which do not contribute to such planetary activity would be superfluous—their presence would contradict the fundamental

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[8] Between the planetary spheres of Saturn and Jupiter this would mean the introduction of the additional sphere, $\text{Saturn}_{rew\ 1\rightarrow 0}$, contributing the component motion $\overline{d}$, contrary to the diurnal motion.

[9] The frame of reference in the Aristotelian cosmos is the stationary Earth at the centre of the celestial spheres. Every region on a stationary celestial sphere would always keep its position relative to the surface of the Earth.

[10] A proposal formulated and set out in detail by Norwood Russell Hanson, *Constellations and conjectures* (Dordrecht—Boston: Reidel 1973), 66-78.

Aristotelian assumption that “nature does nothing in vain.”[11]

Note, however, that this principle of relevance does not mean that the motions of the planets should be produced by the minimum number of celestial spheres and celestial movers. Instead the principle of relevance formulated here requires that any motion of a celestial sphere has to contribute to its end, which is a planet as a beneficiary of the motion. Accordingly, there can be no motions which are not integrated with this interlocking system of revolutions. Moreover, provided the beneficiary of a motion is always the planet coming next in the celestial system, we cannot admit the existence of a motion which is cancelled before contributing to the motion of the lower planet. If such motions, which are cancelled before exerting their influence on a planet, were admissible, the number of spheres, and their movers could proliferate without any limit. One could postulate any number of motions, with suitable further motions, which neutralize their effect. As a corollary to this exclusion principle one can formulate the following rule:

> **Corollary to the Principle of Relevance**: There cannot be any pair of contrary revolutions, one immediately following the other, unless there is a planet on the outer sphere performing the first of these revolutions.

This corollary follows from the principle of relevance, because if there existed such a pair of contrary revolutions, the second would cancel the first one, and as the following planet is not on the first sphere, this first motion cannot contribute to the motion of any of the planets.[12]

Now note, that the proposal, which requires Aristotle to introduce an additional rewinding sphere for each planet, would contravene this Corollary: before the first sphere of the embedded

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[11] Cf. *de Caelo* I.4 277a22-33, where Aristotle refers to the assumption that god and nature do nothing in vain at the end of a passage which intends to show that celestial motions cannot be contrary to one another, because otherwise one would cancel the other, thereby making either or both of them superfluous.

[12] Note that the stipulation that the first sphere in this pair does not carry a planet is not redundant. In Aristotle's interlocking celestial system, in the case of every planet (except for the Moon) the sphere carrying the planet (i.e. Saturn$_{w\ 3\to4,}$, Jupiter$_{w\ 3\to4,}$, Mars$_{w\ 4\to5,}$, Venus$_{w\ 4\to5,}$, Mercury$_{w\ 4\to5}$ and Sun$_{w\ 4\to5,}$) is directly followed by a rewinding sphere (i.e., respectively, Saturn$_{rew\ 4\to3,}$, Jupiter$_{rew\ 4\to3,}$, Mars$_{rew\ 5\to4,}$, Venus$_{rew\ 5\to4}$, Mercury$_{rew\ 5\to4}$ and Sun$_{rew\ 5\to4}$), canceling the motion of the carrying sphere. Nevertheless, the introduction of these two spheres cannot be excluded by the Corollary to the Principle of Relevance, as the motion of the first sphere does contribute to the motion of the planet on this sphere, before it would be cancelled by the following sphere.

planet (e.g. before Jupiter$_{w\ 0\rightarrow 1}$), performing the diurnal revolution of the stars (component *d*), it would introduce another sphere (Saturn$_{rew\ 1\rightarrow 0}$), performing the contrary motion, $\overline{d}$. By Aristotle's principle of relevance this should not then be admissible: the introduction of these additional rewinders is ruled out, because they would not contribute to the motion of a planet. There is no planet attached to them, which they could carry, and the following sphere in the celestial setup immediately cancels the motion they impart, as it moves with a contrary revolution. Hence, contrary to the suggestion, Aristotle's celestial system cannot accommodate an additional rewinding sphere after the rewinding spheres of the planets, unless the import of the principle of relevance enunciated in 1074a30-31, or the principle itself must be readjusted.[13]

2

But if these additional rewinding spheres cannot be introduced, because if introduced, then according to the principle of relevance they would have to be dropped together with the immediately following spheres, which supply the daily revolution of the stars as the component

[13] Needless to say, such a readjustment is not impossible. One could, e.g. submit that the causal efficacy of the rewinding spheres should be considered a negative one. If an embedded sphere is moved by a number of carrying spheres, and then unwound by a number of rewinders, although the overall motion of the sphere is caused by all the movers operative on the moving and rewinding spheres, in a stricter sense we can claim that the overall motion is caused only by those movers the motion of which is not removed by rewinders. If this is so, two spheres performing contrary revolutions can be adjacent to each other not only when the first of these contains a planet, but also if the motion imparted by the first one is not immediately removed by the second one. This is eminently the case on Hanson's proposal: the last rewinding spheres do not *contribute* a motion, rather they *remove* one, and hence their motion will not be removed by the following sphere. (In a similar vein, one could submit, as G.E.R. Lloyd does in his "*Metaphysics* Λ 8," in: Michael Frede and David Charles [eds.], *Aristotle's* Metaphysics *Lambda: Symposium Aristotelicum* [Oxford: Clarendon 2000], 265, that the beneficiary of Jupiter's rewinding spheres is Jupiter, and not Mars, which is next in the celestial order. One way, e.g. the rewinding spheres contribute to Jupiter is that they make it possible for Jupiter to move with the motions it has and at the same time be fully integrated within the overall celestial mechanism.)

The revision of the import of the principle of relevance does not address the other issue, namely that Hanson's proposal introduces *stationary* celestial spheres before each embedded planetary system.

motion of the planets, one might suggest that Aristotle should not have introduced these first spheres of the embedded planetary systems in the first place. This is so because the last of the rewinding spheres of each planet already performs the diurnal rotation of the stars. This suggestion had been formulated by anonymous interpreters of Aristotle, only to be rejected by Sosigenes and Simplicius.[14] One reason Simplicius quotes for rejecting this suggestion is hardly compelling: he says that if we dropped these spheres, we would not arrive at the number of rewinding spheres specified by Aristotle, unless we counted these spheres twice.[15]

As there is no reason to accept the total Aristotle gives before agreeing upon the existence of the spheres to be counted, Simplicius's objection cannot carry much weight. But more compelling arguments can also be added. These arguments will refer to Aristotle's wording about the task of the last of the rewinding spheres of each planet.

According to this, these spheres `bring back (*apokathistasas*) to the same position the first sphere of the star which in each case is situated below the star in question' (1074a3-4). Sosigenes, in his remarks preserved by Simplicius, stresses several times that this underlines the fact that the rewinding spheres have something more to do than simply to produce the required velocities in the celestial system. By Sosigenes's lights it is just as important that the position of

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[14] Simplicius, *Commentary on* de Caelo, 502.19-25. This suggestion has been endorsed in the literature by J.L.E. Dreyer, *A history of astronomy from Thales to Kepler* (New York: Dover 1953), 113; Thomas Heath, *Aristarchus of Samos: the ancient Copernicus* (New York: Dover 1981), 218-19, and in Ross's comments to 1073b38, quoting Heath's considerations.

[15] `For this happens to them, that they count the same sphere twice as they try to save the figure provided by Aristotle for the rewinding spheres' (502.25-27, cf. 503.35-504.3).

It is a moot point whether Simplicius refers here by the word *anelittousôn* (the rewinding spheres) only to the ones that Aristotle interleaved between the planetary systems, or whether he uses the word in the looser sense, according to which the carrying spheres also can be called rewinders. I am inclined to take Simplicius' objection about rewinders in this latter, looser sense. First, strictly speaking, these interpreters need not exclude any *rewinders* by dropping the first *carrying* sphere in the case of each planetary system. Moreover, if Simplicius actually repeats the same objection in the lines 503.35-504.3, then the term may be used also at 502,25-27 in the more inclusive sense, and the objection can go back to Sosigenes. (Occurrences of the term "rewinder" in this looser sense are collected by Henry Mendell, "The Trouble with Eudoxus," in: Patrick Suppes, Julius Moravcsik and Henry Mendell [eds.], *Ancient and medieval traditions in the exact sciences: Essays in memory of Wilbur Knorr* [Stanford: CSLI Publications 2000], in nn. 40 and 41 on p. 92.)

the embedded first spheres should be adequate.[16] This, as D.R. Dicks submitted, should mean that the first sphere of each planetary system must represent the sphere of the fixed stars exactly. The last of the rewinding spheres is not appropriate for this task, since it has an axis of motion—the one around which it does the rewinding—that is not identical to the axis of the revolution of the fixed stars.[17]

Dicks's point can be further elucidated, as Beere has argued, in that each last rewinding sphere can be described from two vantage points. In so far as its own motion is concerned, it is a rewinding sphere, removing the motion of the planet along the ecliptic. As a result of this rewinding, it will have an overall motion, which is identical to the diurnal revolution of the stars and accordingly in addition to the axis of its own motion, it will have an additional axis of its composite motion, which will be identical to the fixed, North-South axis of celestial revolution.[18] But if the last rewinding sphere, performing the diurnal revolution, were simply to transmit this motion to that sphere which contributes the motion of the embedded planet along the ecliptic (e.g. if $\text{Saturn}_{\text{rew } 2\rightarrow 1}$ were followed immediately by $\text{Jupiter}_{\text{w } 1\rightarrow 2}$, contributing e_{Jupiter}) the diurnal component of the motion of this embedded planet, unlike all the other components it has, would lack a distinct cause of its own.[19]

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[16] This double role is stressed throughout in Sosigenes's account, see most specifically Simplicius, *Commentary on* de Caelo, 498.1-7, 499.7-11 (or 12, depending on whether ll.11f should be bracketed with Aujac, in the Testimonia part of his edition of Autolycus, on p. 170) and 502.11-19.

[17] D.R. Dicks, *Early Greek astronomy to Aristotle* (Ithaca, New York: Cornell University Press 1970), 202.

[18] This is brought out in my notation by the number 1 on the right-hand side of the index of e.g. $\text{Saturn}_{\text{rew } 2\rightarrow 1}$.

[19] Note that it is a mistake to claim, as Beere does, that `[o]ne could not say that the sphere of the fixed stars itself is responsible for this [i.e. for the diurnal revolution around the North-South axis, as the motion imparted to the first sphere of Jupiter by the last rewinding sphere of Saturn], since its motion has been filtered out by unwinding spheres.' (Beere, "Counting the Unmoved Movers," 13) On the contrary, the motion imparted by the mover of the first sphere of Saturn is not cancelled by a rewinding sphere. Hence this mover would impart the diurnal rotation to all the spheres of Saturn, and so, on this setup, it would be causally responsible for the diurnal rotational component of all the ensuing spheres, and with them, of every single planet. Hence one could claim that the own motion of the last rewinding sphere of Saturn—$\overline{e}_{\text{Saturn}}$, along the plane of the ecliptic, in an opposite sense to the motion of Saturn's second sphere—is caused by its own mover, whereas the resulting revolution, *d*, around the North-South axis of the universe is causally dependent on the unmoved mover of the first sphere. What this

As a result, it would not be on a par with the other planetary component motions in terms of explanation and causation. Hence, Aristotle cannot drop the first moving sphere of each planet, performing the diurnal revolution of the stars, unless he is willing to revise the basic principle at work in setting out the details of his celestial theory of interlocking planetary systems, that each eternal planetary component motion should have a mover of its own.[20]

3

The third option to save Aristotle from the charges of an erroneous celestial theory, is to suggest, as Jonathan Beere does, that the way an enveloping sphere transmits motion to an embedded sphere is by carrying the axis of the embedded sphere on a path, which may be simple or complex. If, as in the case of the interaction of the last rewinding sphere of a planet, and the first sphere of the planetary system of the following planet, the axis of the embedded sphere is

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explanation does not provide, is a distinct cause for each planet, which would be exclusively responsible for the component of diurnal rotation of the spheres of this planetary system only.

[20] Again, such a revision is not impossible, all one needs to grant is that the status of the diurnal revolution is unique in the celestial realm, and accordingly the first moving sphere of Saturn—or indeed, the sphere of the fixed stars—imparts the diurnal revolution to each and every celestial sphere.

Note, however, that even if we adopted this suggestion, this still does not imply that one should accept the more radical proposal of Ido Yavetz, "On the Homocentric Spheres of Eudoxus," *Archive for the History of Exact Sciences* 51 (1998), 237 n. 16, that, from a purely geometrical standpoint, after the elimination of the first spheres of the planetary systems, the last rewinders of the upper planet, performing a rotation along the plane of the ecliptic (e.g. Saturn$_{\text{rew } 2\rightarrow 1}$), and the now adjacent second spheres of the planetary system of the next planet (e.g. Jupiter$_{\text{w } 1\rightarrow 2}$), also performing a rotation along this plane, but in an opposite sense, could be replaced by a single sphere, performing the rotation along the plane of the ecliptic combined from these two ecliptical rotations. On this suggestion, the cause of the ecliptical motion of Jupiter would be the cause effecting the ecliptical motion of Saturn, combined with an additional mover, which is responsible for the increase in speed along the same orbit. (This sphere could be designated Jupiter$_{\text{w } 2\rightarrow 2'}$.) Similarly, as we proceed inwards in the cosmos—with the exception of Venus, Mercury and the Sun, which have the same ecliptical revolution—these motions will be adding up in a linear fashion. In general, then, the cause of the ecliptical motion of an inner planet would be the combination of all the preceding ecliptical movers there are in the celestial system. This would be in breach of the rule that every eternal component motion needs to be produced by the operation of a *single* cause.

stationary—this is so, because the enveloping sphere performs a rotation as its composite motion exactly around the axis of the embedded sphere—the rotation of the enveloping sphere is not transmitted along the stationary axis to the embedded sphere. For the next sphere to have the same rotation, this sphere, too, will need a motion, and a corresponding mover, of its own.[21]

We should note that this suggestion does not lead to a proliferation of celestial motions and movers. Even though in principle no purely astronomical consideration would exclude that any number of spheres aligned on the same axis should follow one another, each of them performing some rotation under the causal influence of its unmoved mover, and only the last contributing the diurnal revolution of the stars to the planet, the principle of relevance, quoted from 1074a30-31 forecloses the introduction of any such spheres. The putative intermediate spheres would not contribute to the motion of any planet, and hence they can be definitively excluded from the celestial realm.

Nevertheless, the suggestion has some unexpected consequences. Most notably, we should ask whether the principle that rotations are transmitted only by the translation of axes, and never by the rotation of the axes themselves, is operative only in case the axes in question are stationary. Answering this question in the affirmative will mean that a major presupposition of the theory of homocentric spheres is overruled in this instance. This major presupposition submits that the way the revolutions of two consecutive homocentric spheres are combined does not depend on external factors. The combined motion of the two spheres is simply superadded to any motion the external sphere may receive from the outside.

But rejecting this presupposition will have counter-intuitive consequences. Most notably, if there are two spheres, one embedded in the other, both performing the very same rotation, say *b*, both of them will need a mover to effect this revolution. Even so, as soon as the outer sphere will in turn be embedded in yet a further enveloping sphere, with a motion around a different axis, say *a*, the whole system will behave differently. The outer sphere will now perform a composite motion, combined from the revolution of the outermost embedding sphere, *a* and from its own revolution *b*. The innermost sphere, however, will perform a different motion. We have just stipulated that once the axis of rotation is not stationary, the rotation around this axis gets

[21] On this setup, again, we can designate this embedded sphere e.g. Jupiter$_{w\,0\rightarrow1}$, indicating that it does not receive a motion from the spheres preceding it.

transmitted to the embedded sphere, and hence the motion of the innermost sphere, performed under the causal influence of the mover of its own, will be added to the composite motion of the preceding sphere, producing the motion combined from *a* and twice the component motion *b*.

The upshot of this thought experiment is that if we restrict the applicability of Beere's suggestion, and would stipulate that rotations around an axis are transmitted through the axis if it is not stationary, we will need to ask what is the causal explanation for the vastly different behaviour of stationary axes, as opposed to the ones which perform some motion. Such a causal explanation might take many forms. Aristotle may be thought to employ tacitly some such causal explanation when formulating his interlocking celestial system, but up until the point one has been formulated along the lines of Aristotle's overall considerations about celestial theory, the restriction of the claim to stationary axes will have to remain a special pleading and hence suspect.

On the other hand, if embedded spheres receive the motion of the enveloping ones only as a result of the fact that their axes are carried along a trajectory by the enveloping sphere, the status of the movers of the rewinding spheres will be in jeopardy. In each of the cases where a rewinding sphere is operative, the motion of the sphere in which this rewinder is embedded can be divided into two aspects. First there is that revolution which the rewinding sphere will remove by a contrary revolution, but there is also the additional, possibly composite motion which is not affected by the operation of the rewinding sphere. E.g., the rewinder designated here as $\text{Saturn}_{\text{rew } 4\rightarrow 3}$[22] is embedded in a sphere—$\text{Saturn}_{\text{w } 3\rightarrow 4}$—which performs four motions. The rewinder is introduced by Aristotle to remove one of these four motions, notably g_{Saturn}, whereas both the rewinder and the sphere in which it is embedded will perform the combination of motions *d,* e_{Saturn} and f_{Saturn}.

One should note that these two aspects are distributed over the axis of the rewinding sphere. The possibly composite motion which is taken over by the rewinding sphere is exactly the motion imparted by the enveloping sphere as a result of moving the axis of the rewinding sphere

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[22] Note that we need to use this more circumspect formulation, that this sphere is *designated here* as $\text{Saturn}_{\text{rew } 4\rightarrow 3}$, because strictly speaking this designation will not be accurate on this account. Here the suggestion is that the inner sphere turns out to be attached to the preceding sphere through an axis which does not transmit the last, fourth component motion of $\text{Saturn}_{\text{w } 3\rightarrow 4}$.

along a trajectory, whereas the rotation which has to be removed by the rewinding sphere is a revolution around the axis of the rewinding sphere. In this case, however, provided revolutions are not transmitted along axes, Aristotle would need to give an account that is somewhat different from the one he gives here. He should avoid saying what he says at 1074a17-24, that both the carrying and the rewinding spheres perform rotations. Instead, he should formulate the role of these rewinders in terms of their being set into their enveloping sphere exactly along the axis of the rotation which is to be cancelled at that point, so that as a result of this exact orientation they do not take over that component of the composite motion of the enveloping sphere, without themselves performing any motion of their own at all.[23]

On this account not only will the role of the rewinding spheres turn out to be different from the role of the carrying spheres, their mover will also have a rather peculiar status. Recall that our original problem was that the first spheres of the planetary systems, if they receive the diurnal revolution from the sphere into which they are embedded, will not perform any further additional rotation, and hence the unmoved movers which are causally responsible for their behaviour will turn out to be unmoved and non-moving movers. Once we follow Beere's suggestion, that revolutions are not communicated through the spinning of embedded axes, and do not restrict it to cases where the axes of rotation are stationary, the movers of the rewinding spheres will have a similar paradoxical status. They will not impart motion, hence they will still have to be described by the self-contradictory label `non-moving movers.' Nevertheless, depending on what we take to be causally responsible for setting the axes of the embedded spheres, they might be causally efficacious in an important way. If the embedded sphere were attached to the enveloping sphere along any other axis than the actual one, it would take over the entire composite motion of the enveloping sphere, and would not filter out the rotation the rewinding sphere was introduced to filter out in the first place. Accordingly, provided that the

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[23] We have precious little evidence about the rewinding spheres in Theophrastus. That he also included such spheres is clear from the testimony of Simplicius (*Commentary on* de Caelo, 504.7-8), that he called these spheres *antanapherousai*, back bringers, because they bring back the poles of the spheres beneath them. This terminological point, however, is not conclusive as to whether these spheres perform the motion of their own, or perform their back-bringing function by not taking over some component motions. In the case of Sosigenes (and Simplicius), however, it is clear that the rewinding spheres do the rewinding by performing a motion of their own, see Simplicius, *Commentary on* de Caelo, 502.2-6, 7-9, 11-15.

axes of the embedded spheres are set by the material setup of these spheres—say, by one sphere being joined to the next literally by axels or pegs, around which the motion of the embedded sphere is performed—these spheres do not require a mover for performing the task of rewinding.

One, however, may insist that setting an axis of rotation is part of the task of the mover which causes the revolution about this axis. On this view, the mover of a rewinder is causally responsible for setting the axis of the rewinding sphere along which the sphere does not receive the rotational component of the enveloping sphere. In this case, the most precise description of these "movers" would be that they are degenerate cases of unmoved movers. They perform only half the task of a normal unmoved mover. They set the axis of rotation, around which the sphere could move, but they do not impart a component rotation around this axis: they are unmoved axis setters.[24]

4

Now it should be plain that each of the suggestion in the literature about the problem of interaction between the last rewinding sphere of a planet, and the first sphere of the following planetary system involves some significant difficulty. In a way this fact can be used to Aristotle's advantage. Even if the traditional understanding of the option he propounds in 1073b38-1074a14 remains problematic, the fact that the other available options are no less problematic suggests that this interpretation cannot be rejected outright. Even if the actual celestial system Aristotle propounds on this interpretation might be the result of a simple mistake in the introduction of the rewinding spheres, the considerations above suggest that this mistake could not be localized and eliminated in a trivial manner, because from among the available options this is one which satisfies several requirements of the utmost importance at the same time. First, each and every one of the celestial spheres is in motion, none of them is at rest. Moreover, Aristotle's celestial system is causally articulated and perspicuous. It creates the closest match between the components of planetary motions and the spheres involved in the celestial system, in just the way Eudoxus and Callippus provided a one-to-one correspondence between the components of

[24] I am indebted for clarification on this issue to Gábor Betegh and Henry Mendell.

planetary motions and the component spheres of their non-interlocking planetary systems. No component motion—not even the diurnal rotation, which every single sphere performs in the celestial system—is an exception. The diurnal rotation of each planet requires the additional motion of a separate sphere, with its dedicated unmoved mover, in each of the planetary systems.

Furthermore, Aristotle intended to arrive at a causally perspicuous system, which also unifies the different planetary motions into a single overarching system, with a unified account of the integration of the motions of different planetary systems. This is necessary, as he puts it `if all the spheres combined are to explain the phenomena. [….] for only this way can they all carry out the motion of the planets' (1073b38-1074a1 and 1074a4-5, Revised Oxford Translation, slightly modified),[25] even though—as should be clear from the considerations above—there was no trivial

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[25] Note that something went seriously wrong in the paraphrase cum translation Beere gives of Sosigenes's remarks on Theophrastus's description of the rewinding spheres as *antanapherousai*, back bringers at Simplicius, *Commentary on* de Caelo, 504.4-15 (Beere, "Counting the Unmoved Movers," n.26, on pp. 14-15). The concluding claims in this passage should be rendered as stating that it is the task of the compensatory effect of these additional back-bringers that `the poles of the lower spheres have to fall on the same perpendicular as the poles of the similar upper ones [….] for only this way, he says, can they all carry out the motion of the fixed stars.' Already the similar wording of *Metaphysics* XII.8 1074a4-5 makes it certain that in the last clause the embedded object of the accusative cum infinitive construction is not the pronoun *hapanta*, as Beere's translation has it, but rather the nominal phrase *tên tôn aplanôn phorân*.

The important difference between the Aristotelian passage and this clause in Simplicius is that in the *Metaphysics* the motion which is carried out by all is the motion of the planets (as if that were one single motion, or at least as if the several planetary motions could be lumped together and be designated collectively as *the* motion of the planets, which the entirety of the planetary entities carry out collectively), whereas in the clause in Simplicius the motion which they all carry out is the motion of the fixed stars. But the difference might as well be just the result of some error in the tradition: Around the end of this paragraph—which started out by calling attention to a terminological point about Theophrastus's usage—Simplicius indicates, by interjecting "he says" twice into his text (*Commentary on* de Caelo, 504.12 and 14), that he renders somebody else's words. The first sentence he flags with this tag is a slightly paraphrased version of *Metaphysics* XII.8 1074a3-4, whereas the second sentence is identical with 1074a4-5, but for the use of *houtôs* instead of *houtô*, and the fact that the *Metaphysics* speaks about the motion of the planets (*planêtôn*) whereas the sentence in Simplicius mentions the motion of the fixed stars (*aplanôn*). One could still maintain that Theophrastus reformulated Aristotle's claims, in almost the same words, making only some minor stylistic and doctrinal changes, and Simplicus, through the testimony of Sosigenes, is referring to him. But this is excluded by the final flourish Simplicius closes his sentence with, when he adds that what the author—be it Aristotle or Theophrastus—says is `as we have already way to pursue these different objectives at the same time, *Metaphysics* XII.8, then, on this understanding, is a chapter where Aristotle set the outlines of such a celestial system, but he did not appreciate the internal tensions involved and did not work out all the ramifications of the principles operative in his celestial system.[26] [*]

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said, said appropriately.' As up until this point Simplicius has only endorsed Aristotle's (and not Theophrastus's) doctrines, he clearly is thinking he renders Aristotle's lines and points out that Theophrastus's terminology, that the rewinding spheres are *antanapherousai,* back bringers, spells out the very feature that Aristotle expressed in 1074a3-4.

If this is so, one should also ask whether the discrepancy between the text of the *Metaphysics* and of Simplicius's *Commentary on* de Caelo is due to scribal error after Simplicius, and as such should be emended away (as Aujac does, in the Testimonia part of his edition of Autolycus, on p. 179), or whether Simplicius is quoting here Aristotle from memory or through the intermediary of Sosigenes, who had a slightly altered text. In this case the text of the *Commentary on* de Caelo should not be tampered with (as Fortenbaugh *et al*. decide in their edition and translation of Theophrastus 165D FHSG). The second alternative cannot be ruled out, but it needs to be stressed that even if Simplicius is quoting a different version of the Aristotelian passage from Sosigenes, he is apparently not aware of the textual differences.

26 Such considerations could be used to suggest that *Metaphysics* XII.8 was composed late in Aristotle's life: otherwise, it might be claimed, Aristotle would have removed what apparently is a computational slip at 1074a12-14 and could settle one way or another the problems I have been canvassing here. I should stress that I do not subscribe to this inference. The fact that Aristotle, as far as we are aware of this through the Aristotelian corpus and through the testimonies of his commentators, did not revisit these issues elsewhere, does not imply that he must have been dead soon after the composition of *Metaphysics* XII.8. A host of other considerations could have kept Aristotle from revising his position on these issues.

* I have been working on issues of Aristotle's celestial theory for quite some time. Nevertheless, it should be clear from the paper how much my approach is indebted now to Jonathan Beere's article.

This paper is a revised version of part of my talk at the first congress of the Gesellschaft für Antike Philosophie, held in Berlin in October 2004. I am grateful for comments and objections to my audience and to my host, Christof Rapp. I am especially grateful for encouragement and suggestions to Victor Caston, for part of the clarification at the end of Section 3 above to Gábor Betegh, for ample written comments and extended discussions to Henry Mendell. I am also grateful to Jim Hankinson for a number of important suggestions.

Appendix

The winding spheres, constituting the planetary system of Saturn, and the attached rewinding spheres can be referred to as follows:

Sphere	Motion contributed by this sphere	
$\text{Saturn}_{\text{w}\ \to 1}$	d_{Saturn}	(the diurnal motion)
$\text{Saturn}_{\text{w}\ 1\to 2}$	e_{Saturn}	(the ecliptical motion of Saturn)
$\text{Saturn}_{\text{w}\ 2\to 3}$	f_{Saturn}	
$\text{Saturn}_{\text{w}\ 3\to 4}$	g_{Saturn}	
$\text{Saturn}_{\text{rew}\ 4\to 3}$	$\overline{g}_{\text{Saturn}}$	(contrary of g_{Saturn})
$\text{Saturn}_{\text{rew}\ 3\to 2}$	$\overline{f}_{\text{Saturn}}$	(contrary of f_{Saturn})
$\text{Saturn}_{\text{rew}\ 2\to 1}$	$\overline{e}_{\text{Saturn}}$	(contrary of e_{Saturn})

Read: Saturn's winder to one motion, Saturn's winder from one to two motions, etc. and then Saturn's rewinder from four to three motions, Saturn's rewinder from three to two motions, etc.

The last rewinding sphere of this group is followed immediately by the first sphere of Jupiter, $\text{Jupiter}_{\text{w}\ \to 1}$ performing *d*, the diurnal motion. (Subscripts after component motions *d* can be dropped, as the diurnal component of the motion of the different planets is identical.)

The subscripts of each winding or rewinding sphere indicate how many component motions are communicated to the sphere, and then, as a result of its winding or rewinding, how many motions this sphere performs. Each winding sphere adds a further component motion, each rewinding sphere removes one. The contribution of a winding sphere is eliminated by the rewinder which has the same subscripts, in reverse order (e.g. $\text{Saturn}_{\text{w}\ 2\to 3}$—contributing f_{Saturn}— is rewound by $\text{Saturn}_{\text{rew}\ 3\to 2}$—contributing motion $\overline{f}_{\text{Saturn}}$). The left-hand subscripts of the first spheres of the planets are left blank in order to leave open what motion these spheres take over from the ones immediately preceding them. (This may also apply to $\text{Saturn}_{\text{w}\ \to 1}$, as the sphere of the fixed stars may well be different from this sphere.)

Jupiter has four winding and three rewinding spheres, like Saturn. In the case of Mars, Venus, Mercury and the Sun yet another pair of winding and rewinding spheres is added, e.g. between $\text{Venus}_{\text{w}\ 3\to 4}$ and $\text{Venus}_{\text{rew}\ 4\to 3}$, there is $\text{Venus}_{\text{w}\ 4\to 5}$, contributing the additional component, h_{Venus}, followed by the rewinder $\text{Venus}_{\text{rew}\ 5\to 4}$, contributing component $\overline{h}_{\text{Venus}}$. The Moon has five winding spheres only, their motions are not eliminated by rewinding spheres.

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