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TOPOI – *Towards a Historical Epistemology of Space*

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Aristotle and Ptolemy on Geocentrism: Diverging Argumentative Strategies and Epistemologies

EXCELLENCE CLUSTER TOPOI

TOPOI – Towards a Historical Epistemology of Space

The TOPOI project cluster of excellence brings together researchers who investigate the formation and transformation of space and knowledge in ancient civilizations and their later developments. The present preprint series presents the work of members and fellows of the research group *Historical Epistemology of Space* which is part of the TOPOI cluster. The group is based on a cooperation between the Humboldt University and the Max Planck Institute for the History of Science in Berlin and commenced work in September 2008.

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Chapter 1
Introduction

This paper aims at a comparison of the different argumentative strategies employed by Aristotle and Ptolemy in their approaches to geocentrism through an analysis of their discussion of the centrality of the Earth in *De caelo* II, 13-14 and *Almagest*, I, 3-7. The divergence does not concern only secondary issues but rather the epistemology underlying the theories of these two authors, and this affects also the meaning of theses on which they apparently agree. As we shall argue, this difference potentially entails momentous consequences concerning the justification and the acceptance of fundamental astronomical concepts.

The epistemological distance between the two main "authorities" of classical cosmology was intensively debated in the Middle Ages and Renaissance[1]. It was even crystallized as a disciplinary separation between the academic teaching of "physical" astronomy (that is, the doctrine on the heavens from a natural-philosophical perspective) and "mathematical" astronomy. In twelfth-century Moorish Spain, Ibn Rushd (Latinized Averroes) denounced the discrepancy between the homocentric heavenly mechanism propounded by Aristotle in *De caelo* and *Metaphysics*, XII, on the one hand, and the mathematical devices (epicycles, eccentrics and equants) employed by Ptolemy. He therefore accused Ptolemaic astronomy to be at odds with natural philosophy since it renounced physical tenability for computational convenience. His contemporary al-Bitruji (Latinized Alpetragius) even sought to reform mathematical astronomy in accordance with homocentrism, that is, he reduced all celestial motion to a mechanism of concentric spheres. His book on heavenly motions, translated into Latin by Michael Scot as *De motibus caelorum*, had a great impact in

[1] The standard reference for this issue is Pierre Duhem, *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo* (Chicago and London 1969), although the author's attempt to interpret the history of physics and astronomy from the perspective of twentieth-century epistemology (in particular conventionalism) is completely outdated. For some criticism of Duhem's anachronism see for instance Peter Barker and Bernard R. Goldstein "Realism and Instrumentalism in Sixteenth Century Astronomy: A Reappraisal," *Perspectives on Science* 6/3 (1998), pp. 232–258.

Christian Europe up to the Renaissance. It should be noted that it was republished in 1531 in Venice shortly before analogous works of Paduan Aristotelians appeared: Giovan Battista Amico's *De motibus corporum corporum coelestium iuxta principia peripatetica sine eccentricis et epicyclis (On the Motion of Heavenly Bodies in Accordance with Peripatetic Principles, that is, without Eccentrics and Epicycles*, 1537 and Paris 1540) and Girolamo Fracastoro's *Homocentrica sive de stellis* (*Homocentrics or on Stars*, 1538).

In spite of this well known criticism of Ptolemy's "abstract mathematics", it was commonly assumed that his conceptions could be brought back to an essentially Aristotelian cosmology. As a matter of fact, Aristotle and Ptolemy were in agreement relative to the sphericity of the Earth and its rest at the center of the universe, as well as to the sphericity and the circular motion of the heavens. Hence, the physical considerations of the philosopher and the mathematical arguments of the Alexandrine astronomer could strengthen each other concerning these central issues. What is more, the *Almagest* began with a mention of Aristotle's partition of speculative knowledge into the three disciplines (mathematics, physics and theology) and repeated some (alas misleading) physical theories of Aristotle, as we shall see. In this concordant spirit, Sacrobosco, for one, assumed the essential concordance between Aristotle and Ptolemy and could therefore rely on both authorities in his (very) elementary introduction to spherical astronomy which, in spite of its intrinsic scientific limits, was one of the most successful textbooks ever. Beginning in the thirteenth century, an 'Aristotelian-Ptolemaic cosmology' emerged, bringing together elements from both classical authorities, and this unified geocentric worldview was assumed by most philosophers and theologians.[2] In his narrative of the Copernican revolution, Kuhn therefore felt legitimized to talk about an Aristotelian-Ptolemaic 'paradigm' which Copernicus' *De revolutionibus* was to undermine. By contrast, we will focus on the premisses instead of the conclusions of *De caelo* and *Almagest* regardless of the historical fact that these sources presented close cosmological views on the Earth's position.

These considerations on geocentrism can be indirectly relevant for the birth of mathematical geography.[3] This discipline required, in fact, three

[2] Cf. C. Panti, *Moti, virtù e motori celesti nella cosmologia di Roberto Grossatesta. Studio ed edizione dei trattati "De sphera", "De cometis", "De motu supercelestium"* (Firenze 2001).

[3] On that I. Tupikova, M. Schemmel and K. Geus are preparing a paper: "From Celestial to Terrestrial Mapping: Preconditions and Consequences of Measurements of the Size of the Earth in Antiquity'," in *Spatial Thinking and External Representation.*

historically interconnected cosmological assumptions: the spherical form of the starry heaven (transported in circular motion), the sphericity of the Earth and, last but not least, its centrality. As Szabó and Maula argued[4], the spherical conception of the heavens originated in Greece from technical and geographical premisses, namely the employment of the gnomon at a different latitude than the Babylonians. It was therefore in the Greek and Hellenistic culture that spherical astronomy established itself. Ptolemy benefited from it in his geographical work, as witnessed by the fact that his geographical references (latitudes and longitudes) are projections from the heavens onto the terrestrial surface. In the light of this historical interpretation, geocentrism and heavenly sphericity gains new interest as (at least partly) 'false premisses' which are rich with epistemic consequences.

Before we confront the arguments for geocentricism in Ptolemy and Aristotle, we shall clarify the meaning that we attach to some particularly relevant termini. 'Cosmology' means for us a general theory of the world as a whole. It concerns the dimensions, the structure, the order and the nature of the universe. We will call 'mathematical astronomy' a treatment of the heavenly phenomena based on geometry and arithmetic (thus assuming the traditional Greek perspective). Besides computation, a relevant feature of what we shall call 'mathemaical astronomy' is the geometrical modeling of the celestial phenomena. Moreover, we shall not assume the term 'physics' in the modern sense, but rather in a restricted Aristotelian meaning of a qualitative doctrine of motion based on causal explanation. Within an Aristotelian horizon, it could be regarded as a synonym of 'natural philosophy'. In accordance with this terminology, 'physical astronomy' shall refer to a qualitative doctrine of the heavens providing causal explanations according to philosophical assumptions on motion as well as on the nature of the Earth and the heavens. Moreover, we will call a 'cosmological approach' that treatment of the world which begins with a rational investigation of the whole and makes the theory of motion, in particular the motion on Earth, dependent on this general conception. On the other hand, we will call a 'physical approach" that which begins with consideration of the observable phenomena on Earth relative to motion, gravitation and such, to conclude also about the structure of the world as a whole. As we will argue, this distinction can conveniently

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Towards a Historical Epistemology of Space, ed. M. Schemmel, Max Plank Research Library for the History and Development of Knowledge.

[4]Szabó and Maula, *Enklima. Untersuchungen zur Frühgeschichte der antiken griechischen Astronomie, Geographie und der Sehnentafel* (Athen, 1982).

encapsulate the different approaches of Aristotle and Ptolemy to the issue with which we are presently concerned: geocentricism.

A series of seminars organized by TOPOI and held at the MPIWG-Berlin beginning in 2010 aims at clarifying the emergence and the consolidation of geocentrism and cosmological sphericity as a hegemonic world-view from Antiquity to the Early Modern Period. This paper in particular was conceived during a workshop which took place at the Department I on 25 January 2011.

Chapter 2
Aristotle

Aristotle's considerations on the Earth are presented in the conclusive part of the second book of *De caelo* as was transmitted to us. These chapters (II, 13 and 14) show a strong self-sufficiency and can be regarded as an autonomous treatise on the Earth.

It should be remembered that all extant works of the so-called *corpus Aristotelicum* are the notes of the lectures which the philosopher held at the Lyceum and were later edited by his followers. These writings often resulted from the collection of short treatises, therefore titles are often only labels put on miscellaneous writings on close subjects. This is the case also with *De caelo*. In spite of its title, this work does not exclusively deal with the heavens. It is rather made of several distinct parts: books I (or A) and II (or B) on the universe as a whole and its parts, book III (or Γ) on sublunary elements, and book IV (or Δ) on lightness and heaviness. The chapters 13 and 14 of the second book are apparently a juxtaposition which occurred at the moment of the assemblage of *De caelo* as a unified work. This could be witnessed by the summary at the beginning of book III, a survey on the precedent sections in which the monograph on the Earth is omitted: "We have treated earlier of the first heaven and its parts, and also of the stars which are visible in it, their composition and natural characteristics, and the fact that they are ungenerated and indestructible." Alberto Jori pointed to the relative autonomy of the section on celestial bodies (II, 7–12) and that on the Earth (II, 12–13) in his introduction to *De caelo*. He explained the existence and the insertion of these two monographs by the fact that they complete the treatment of the universe as a whole which is the subject of the first book and of the first part of the second.[1] Paul Moraux already divided the first two books of *De caelo* in three parts: 1. Περὶ τῆς παντὸς φύσεως (on the whole nature, I and II,1-6), 2. Περὶ τῶν καλουμένων ἄστρων (on the so-called celestial bodies, II,

[1] See Alberto Jori, *Introduzione* to Aristotle, *Il cielo* (Santarcangelo di Romagna, 1999), pp. 13–14, riedited as *Erläuterung*, in Aristoteles, *Werke in deutscher Übersetzung*, vol. 12, *Über den Himmel, p. 123.*

6–12) and 3. Περὶ τῆς γῆς (on the Earth, II,12–13). He claimed, however, that the treatise on the Earth is an essential part of Aristotle's books A and B "als ein Ganzes."[2] For our purposes, it is only important to stress that this section has a certain self-sufficiency in order to focus on it and avoid considerations on its relation to *De caelo* as a whole in our analysis.

2.1 Aristotle's confrontation with the cosmologies of his predecessors

In the monograph on the Earth, as we will call *De caelo* II, 13-14, Aristotle faces the issue of the form and the location of the Earth. Chapter 13 is basically an overview of the theses of his predecessors, and chapter 14 is a treatment of his own ones. However, Aristotle presents original considerations also in chapter 13 while discussing and criticizing others' theories. He moreover reports some traditional arguments for geocentrism, although he does not consider them to be cogent. We shall call these "pseudo-arguments":

1. Pseudo-argument from the finiteness of the universe: Aristotle firstly observes that most of those who hold the universe to be finite set the Earth at its center with the exception of the Pythagoreans.[3] The historical relevance of this passage lies in the discussion of the cosmology of the Pythagoreans and the theory of the motion of the Earth with reference also to Plato's *Timaeus*. In the Early Modern Period, several followers of Copernicus would interpret Aristotle's treatment of the Pythagorean cosmology as evidence of the existence of ancient supporters of heliocentrism. For the present matter, this passage is also interesting for Aristotle's report that the Pythagoreans regarded the absence of stellar parallax as insufficient evidence of terrestrial centrality and immobility:[4] "Since the Earth's surface is not in any case the centre, they [the Pythagoreans] do not feel any difficulty

[2] Paul Moraux, *Einige Bemerkungen über den Aufbau von Aristoteles' Schrift De caelo*, in *Museum Helveticum* 6 (1949), pp. 157-165: p. 159: "Wenn wir einige durch Ideenassoziationen eingeleitete Abschweifungen beiseitelassen, so können wir behaupten, daß dieser gut abgewogene Plan die strukturelle Einheit der Bücher A und B beweist. Allem Anschein nach wurden diese Bücher als ein selbständiges Ganzes konzipiert: Ein Zeichen dafür ist, dass die Abhandlung über die Erde (B 13-14) als der letzte Punkt angekündigt wird, der zu besprechen ist, um das vorgesehene Programm abzuschließen."

[3] *De caelo* II,13 293 a 19-21. In the following we will quote from the English translation: Aristotle, *On the Heavens* (Cambridge, Mass. - London, 1986), transl. by W.K.C. Guthrie.

[4] *De caelo*, II,13 293 b 25-30.

in supposing that the phenomena are the same although we do not occupy the centre as they would be if the Earth were in the middle. For even in the current view [that is, geocentrism] there is nothing to show that we are distant from the centre by half the Earth's diameter." As we shall see, Ptolemy did not take into due account these remarks.

2. Argument from the fall of bodies:[5]
   Aristotle argues for the centrality and the rest of the Earth from consideration of the fall of bodies. He assumes that a bigger body falls quicker than a smaller. If the Earth were removed from its central position, it would reach its point of origin very quickly, as a consequence of its huge dimensions. This argument is remarkable for two reasons. First, it seems to be based on a *petitio principii*, that is, it demonstrates geocentrism through a physical theory which assumes geocentrism already as a postulate. Second, it assumes that a body travels downwards the quicker the bigger it is, an assumption which is supported by empirical evidence only under certain circumstances when, for instance, the shape of a falling body and the friction of the medium significantly influence its fall. This argument (which was already questioned in antiquity by atomistic theories of matter and motion) is interesting, however, for its historical meaning, since it waited until the Middle Ages and the Renaissance to abandon the physical theory upon which it relied. It would be the achievement of Renaissance scientist-engineers like Giovan Battista Benedetti and Galileo Galilei to discard this opinion. The Aristotelian passage proposing the argument from the fall of bodies is also relevant because it contains an epistemological claim concerning the path that one should follow to demonstrate the centrality of the Earth:[6] "I mean that we must decide from the very beginning whether bodies have a natural motion or not, or whether, not having a natural motion, they have an enforced one. And since our decisions on these points have already been made, so far as our available means allowed, we must use them as data." Accordingly, considerations on motion or rather on terrestrial motion, should precede considerations on the structure of the whole universe. Therefore, Aristotle does not admit discussion on why the Earth and its elements are stable, since this is the factual presupposition and nothing to be demonstrated.

[5] *De caelo* II,13 294 a 11 ff.
[6] *De caelo*, II,13 294 b 32 - 295 a 2.

We could say that, in his treatment, terrestrial physics, in particular his theory of the natural places of the elements (and of natural and violent motion), is the presupposition of his conception of the cosmos[7]. Aristotle adds to his argument that, if the Earth moved from its place, a falling body would fall ad infinitum, since it would encounter no firm bottom to arrest its downward motion. This consideration, according to Aristotle, elicited discussions among thinkers on the foundation upon which the elements are placed:[8] "Consider too that if one removed the Earth from the path of one of its particles before it had fallen, it would travel downwards so long as there was nothing to oppose it. This question, then, has become, as one might expect, a subject of general inquiry." Such inquiry, however, is not worth being conducted in Aristotle's eyes. Terrestrial immobility has an epistemological (and ontological) priority over speculations depending on cosmic order in general.

3. Pseudo-argument from creation:[9] Aristotle remarks that those who held that the cosmos had an origin also believe that the Earth agglomerated at its center. Not only does Aristotle disagree on the assumption of a "creation" or "origin" of the world (an issue on which he does not expand here), but he also rejects the argument. If one assumed with Empedocles that the parts of the Earth were brought together by a vortex, one would neglect that up and down have an ontological and epistemological priority over motion. In other words space determinations should precede spacial displacements:[10] "Nor, again, are heavy and light defined by the vortex: rather, heavy and light things existed first, and then the motion caused them to go either to the centre or the surface. Light and heavy, then, were there before the vortex arose (...). In an infinite space there can be no up and down, yet it is these that distinguish heavy and light."

[7]Cf. Paul Moraux, 'La méthode d'Aristote dans l'étude du ciel *De Caelo* I 1 – II,12" in *Aristote et les problémes de méthode* (Paris-Louvain, 1961), pp. 173-194: p. 182, n. 10: "Il serait trop long de relever tous les cas où, dans l'étude de l'univers et du ciel, il est fait état des principes de la physique terrestre. Voici pourtant quelques exemples intéressants. Théorie des quatre éléments, des mouvements et des lieux naturels (...). Théorie de la pesanteur et lois mécaniques de la chute des corps (...). Théorie de la génération et de la corruption. Opposition du "selon nature" et "contre nature" ou "par violence". Hylémorphisme (...). Existence de détérminations telles que devant-derriére, droite-gauche, etc., chez les animaux (...)."

[8]*De caelo*, I,13 294 a 17-19.

[9]*De caelo* II,13 295 a 13 ff.

[10]*De caelo*, II,13 295 b 3-9.

Hence, spacial determinations (up and down) come first, then the determinations of lightness and heaviness and, eventually, motion. In general terms, one can remark that the argument from creation is not valid for Aristotle because the centrality and the immobility of the Earth do not need to be demonstrated from a cosmological perspective but are already given as sensible evidence.

4. Argument from lightness and heaviness:[11] The priority of the theory of natural places over cosmological considerations is reassessed by Aristotle also relative to the rest of the Earth at center. According to Anaximander and others, the reason for that is "indifference."' The Earth is equidistant from all extremes, therefore it maintains its central position and is at rest. In Aristotle's eyes, this argument is ingenious but not true. In fact, he remarks, not only the centrality of the Earth and its natural tendency toward the center should be taken into account, but also the upward tendency of fire. The entire theory of elementary motions should be considered, since only the Earth falls to the center and not the other elements:[12] "The reason is not impartial relation to the extremes, but motion towards the centre is peculiar to the Earth." As a conclusion, Aristotle repeats that only the theory of motion, in particular the consideration of the "light-heavy" and "up-down" determinations, bears decisive and valid arguments relative to geocentricism (see Fig. 2.1.)

2.2 Aristotle's presentation of his own views

Chapter II,14 deals essentially with Aristotle's own views. It begins with considerations concerning terrestrial immobility:[13] "For ourselves, let us first state whether it [the Earth] is in motion or at rest". In fact, some thinkers believed that the Earth is a celestial body among others and other philosophers held that it is at the center but spins about its own axis. As Aristotle already remarked, the former theory belonged to the Pythagoreans whereas the latter to Plato. In *De caelo*, he questions the views of these predecessors but, as we shall see, he treats the problem beginning with his theory of motion rather than from a general cosmological perspective.

[11] *De caelo* II,13 295 b 10 ff.
[12] *De caelo*, II,13 295 b 23-25.
[13] *De caelo*, II,14 296 a 24-25.

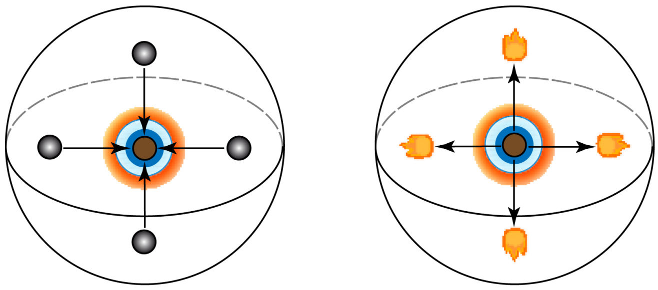

Figure 2.1: Left: the center of the sublunary world as "gravitational" center. Right: sublunary world as symmetry center.

1. Argument from the categorization of motion:[14] Aristotle objects to the geokinetic theories of the Pythagoreans and Plato that these are not compatible with the theory of motion or rather with "his" theory of motion. A metaphysical premiss is also at stake: the order of the world is eternal. The reasons for this assumption should be sought elsewhere. Aristotle assumes also that a "natural motion" is such that a whole and its parts share the same tendency. As for the Earth as an element its tendency is "toward the center", as everyday experience witnesses. Hence, the hypothetic motion of the Earth like other planets would be a "violent" or "enforced" motion but, since a violent motion cannot be eternal, the geokinetik theory would violate the eternal regularity of nature.

2. Argument from the rise and setting of stars:[15] Aristotle remarks that the terrestrial motion would affect celestial appearances, in particular the fixed stars. This argument is in striking conflict with Aristotle's previous observation that the Pythagoreans did not accept the argument from stellar parallax as a proper objection against their planetary conception of the Earth, since its validity depends on the dimensions of the cosmos. Aristotle's argument seems to be rather confused:[16] "Secondly, all the bodies which move with the circular movement are observed to lag behind and to move with

[14] *De caelo* II,14 296 a 25 ff.
[15] *De caelo* II,14 296 a 34 ff.
[16] *De caelo*, II,14 296 a 35 - 296 b 6.

more than one motion, with the exception of the primary sphere: the Earth therefore must have a similar double motion, whether it moves around the centre or is situated at it. But if this were so, there would have to be passing and turnings of the fixed stars. Yet these are not observed to take place: the same stars always rise and set at the same places on the Earth." It seems plausible that the double motion of planets to which Aristotle here refers concerns the daily and the periodical rotations, one along the equator and one along the ecliptic. It is, however, unclear why the spinning of the Earth at the center of the world should have more than one motion, if not for a priori reasons forcing the analogy between the Earth and the other planets. It is curious that Copernicus's pupil Rheticus would turn this argument against Aristotle as he would argue in his *Narratio prima* that Copernicus's threefold terrestrial motion (daily, annual and "of declination") agrees with Aristotle's remark that a planet must have more than one motion:[17]

> Following Plato and the Pythagoreans, the greatest mathematicians of that divine age, my teacher thought that in order to determine the causes of the phenomena circular motions must be ascribed to the spehrical Earth. He saw (as Aristotle also points out) that when one motion is assigned to the Earth, it may properly have other motions, by analogy with the planets. He therefore decided to begin with the assumption that the Earth has three motions, by far the most important of all.

To sum up, the general meaning of Aristotle's argument from the rise and setting of the stars is clear, but not its details. It should be additionally noted that this argument is not based on terrestrial physics, as usual, but rather on astronomical considerations.

3. Argument from the identity of gravitational and cosmological center:[18] Aristotle remarks that the cosmological and gravitational center of the terrestrial element coincide:[19] "[...] that the Earth and the Universe have the same centre [...] we see that weights moving toward the Earth do not move in parallel lines but always at the same angles to it [...]." This argument presupposes of course

[17] Georg Joachim Rheticus, *Narratio prima*, in Erward Rosen, *Three Copernican Treatises* (New York, 1959), pp. 147-148
[18] *De caelo* II,14 296 b 6 ff.
[19] *De caelo*, II,14 296 b 15-16.

the sphericity of the Earth. This reasoning is therefore not based on commonsense and intuitive observations, as Aristotle presents it, but lies in theoretical assumptions (arguments for the spherical form of the Earth can be found elsewhere, for instance in *De caelo* II, 14 298 a 7-10). An observer who already knows that the Earth is spherical and notices that heavy bodies fall vertically to the ground at all latitudes will conclude that heavy bodies fall straightforwardly to the center of the Earth. Still, Aristotle remarks that they fall to the center of the Earth only incidentally. Their tendency is, in fact, toward the cosmological center. What counts is "place". Earth goes to the center like fire to the periphery of the central region of the universe. Accordingly, the coincidence of terrestrial and cosmological center is accidental. In other words, symmetry has an ontological and epistemological priority over gravitation. Be that as it may, the conclusion is that the Earth "must be at the center and immobile" (see Fig. 2.2).

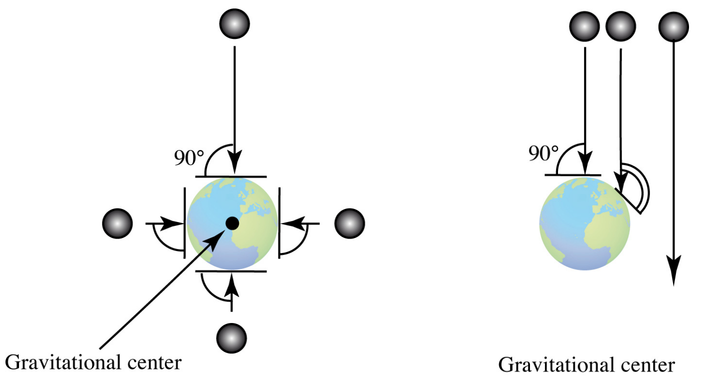

Figure 2.2: Right: Earth as a gravitational center. Falling bodies hit the Earth's surface at the same angle (90°). Left: gravitational center is outside the Earth. For a gravitational center lying at a very remote distance, the falling bodies should hit the earth surface at parallel lines.

4. Argument from objects thrown upwards: Aristotle adds a remark concerning objects thrown upwards. They will always come back to

the ground in a straight line:[20] “To our previous reasons we may add that heavy objects, if thrown forcibly upwards in a straight line, come back to their starting-place, even if the force hurls them to an unlimited distance”.

5. Argument from the simplicity of motion:[21] This is a reworking of considerations from natural places. A simple body, as an element, can have only one motion and cannot simultaneously move toward and ”away” from the center, as would be the case if the Earth moves. In that case, in fact, the body’s motion would have a vertical as well as a horizontal component. Additionally, the whole must be in the place which its parts tend to reach. Since no force can force the Earth as a whole to abandon its natural place, it must be at rest at the center.

6. Confirmation from mathematical astronomy: Mathematical astronomy receives very little acknowledgment from Aristotle. Its role is merely to confirm his views based on mainly physical arguments. As he writes in the conclusion of his defense of the centrality and immobility of the Earth:[22] “This belief finds further support in the assertions of mathematicians about astronomy: that is, the observed phenomena – the shifting of the figure by which the arrangement of the stars is defined – are consistent with the hypothesis that the Earth lies at the centre. This may conclude our account of the situation and the rest or motion of the Earth.” This argument will be later specified by Ptolemy for the case of possible displacement of the Earth along the east-west direction. What Aristotle means here is that the angular distances among stars within certain ‘arrangements’ such as constellations remain constant (see Fig. 2.3).

[20] *De caelo*, II,14 296 b 22-25.
[21] *De caelo* II,14 b 25 ff.
[22] *De caelo* II,14 297 a 2-8.

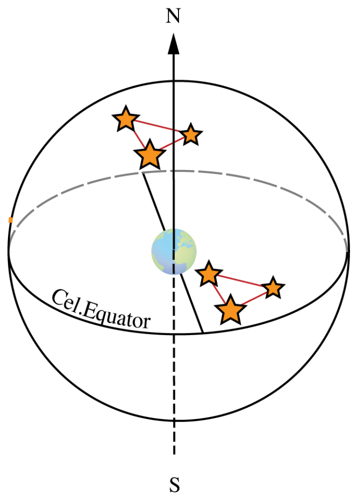

Figure 2.3: Argument from mathematical astronomy. The angular distances between the stars in the same concetellation remain constant.

Chapter 3
Ptolemy

The first book of the *Almagest* starts by mentioning Aristotle's division of theoretical philosophy into three primary categories, theology, physics and mathematics. In the following discussion, Ptolemy makes his point clear:[1]

> ...the first two divisions of theoretical philosophy should rather be called guesswork than knowledge, theology because of its completely invisible and ungraspable nature, physics because of the unstable and unclear nature of matter; hence there is no hope that philosophers will ever be agreed about them; and that only mathematics can provide sure and unshakeable knowledge to its devotees, provided one approaches it rigorously.

Ptolemy organizes his discussion of mathematical constructs modeling cosmic order along this line of thought. His basic principles – geocentrism, sphericity of the Earth and of the sky – should be verified by means of mathematical astronomy. As a professional astronomer he tries to "provide proofs in all of these topics by using as starting-points and foundations, as it were, for our search the obvious phenomena, and those observations made by the ancients and in our own times which are reliable."[2]

Ptolemy's thorough discussion is organized according to the following scheme (*Almagest*, I 3 – 8):

1. that the heavens move like a sphere;

2. that the Earth, taken as a whole, is also sensibly spherical;

3. that the Earth is in the middle of the heavens;

4. that the Earth has the ratio of a point to the heavens;

[1] *Almagest* I H6, p. 36. Here and in the following we will quote from the English translation: Toomer, G. J. *Ptolemy's Almagest* London: Duckworth, 1984.
[2] *Almagest* I H9, p. 38.

5. that the Earth does not have any motion from place to place;

6. that there are two different primary motions in the heavens.

In the following we will discuss the argumentation used by Ptolemy relative to the first five points. The last point distinguishes between the daily rotation of the celestial sphere “which carries everything from east to west” (first primary motion) and the motion of Sun, Moon and planets in the opposite direction relative to the axis, which, in turn, is inclined relative to the rotational motion of the first motion (second primary motion). The trajectory of the Sun due to this motion (relative to the sphere of the fixed stars) defines the ecliptic plane inclined relative to the equator of the celestial sphere. Ptolemy added to this list a third ‘celestial motion’, that is, the precession first found by Hipparchus and confirmed by Ptolemy himself. This kind of motion was not yet known in Aristotle’s time.

3.1 The heavens move like a sphere

Let us emphasize that the statement that “the heavens move like a sphere” was considered by Ptolemy to be logically equivalent to the statement that “the stars’ trajectories are circular in shape” and vice versa, only because for him the stars were thought to be fixed on the celestial sphere.[3] The arguments proposed in the *Almagest* I,3 for the sphericity of the heavens can be roughly classified as observational, ‘physical’ and ‘mathematical’. Ptolemy suggests that ‘the ancients’ came to the concept of the celestial sphere first from the following kind of observations:[4]

> They saw that the Sun, Moon and other stars were carried from east to west along circles which were always parallel to each other, that they began to rise up from below the Earth itself, as it were, gradually got up high, then kept on going round in similar fashion and getting lower, until, falling to Earth, so to speak, they vanished completely, then after remaining invisible for some time, again rose afresh and set; and [they saw] that the periods of these [motions], and also the places of rising and settings, were, on the whole, fixed and the same.

[3]In the second book of his later treatise, *Planetary hypotheses*, where Ptolemy extends the mathematical models of the *Almagest* to the physical realm, stars are thought to be fixed not **on** the spherical shell, but rather **between** nested spherical shells.

[4]*Almagest* I H10, p. 38.

Ptolemy further qualifies the observational evidences for the revolution of ever-visible stars and the motion of partly invisible stars. The observational arguments concerning the former, that is that

- their motion is circular and always takes place about one and the same center;
- that point becomes the pole of the heavenly sphere for observers;
- and those stars which are closer to the pole revolve on smaller circles;

and concerning the latter that:

- those stars that are near the ever-visible stars remain invisible for a short time;
- and those further away remain invisible for a long time in proportion to their distance,

are visualized in Fig. 3.1. Obviously, these arguments are of 'local' geo-

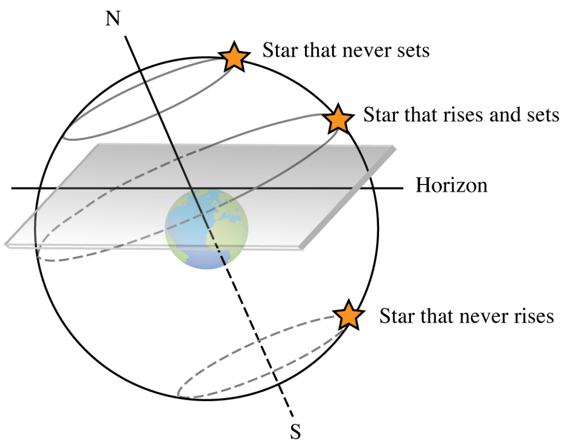

Figure 3.1: Ever-visible stars and stars that rise and set at a given geographical position. Here and in the following we will depict the horizon plane drawn at an observer's position through a grey shadowed surface.

graphical character: they can be put forward just after two-night observations, without comparison to observational data from different places.[5] Stars can be observable at some localities and invisible at other places; they can belong to ever-visible stars at a certain geographical latitude and to stars that rise and set at other places. The position of the great circle on the sky which separates these two classes of stars is different at different latitudes. This fact was possibly not known to Homer (his mention of 'arctic circle' did not imply any geographical dependancy) but was already widely accepted in Aristotle's time. That is why Aristotle sounds anachronistic when he says that some direction "nearly corresponds to the ever-visible circle" in his famous wind orientation scheme[6] – this can be attributed to the fact that Aristotle was not a professional astronomer.

Discussing the consequences of these observational facts on astronomical knowledge, Ptolemy stresses that "absolutely all phenomena are in contradiction to the alternative notions which have been propounded."[7] It is interesting to note how deeply the paradigm of the sphericity of the cosmos has indeed prejudiced his mathematical speculations: in fact, he oversaw another mathematically equivalent explanation – in a cylindrical world (see Fig. 3.2) the observational effects would hardly be distinguished from those observed in a spherical cosmos.[8]

The other possible mathematical solution overseen by Ptolemy is a rotational three-axis ellipsoid. For the special sort of such ellipsoid with two equal axes rotating about the remaining axis, the observational effects will be the same as in the spherical universe (see Fig. 3.3).

As alternative hypotheses accounting for the visible paths of the stars, Ptolemy mentions only the untenable opinion (perhaps held by Xenophanes)[9] that stellar motions might occur in a straight line towards infinity. It is clear that such motion can be ascribed only to stars that rise and set, and not to those which are ever-visible and move in circular paths. In fact, to rule out this hypothesis the above mentioned arguments are sufficient. Nevertheless, Ptolemy proposes[10] some other objections:

[5]Although being intuitively clear, these arguments really need some mathematical justification, namely that the intersection between a plane and a sphere is always a circle.

[6]*Meteorologica*, II, VI, 363 b.

[7]*Almagest* I H11, p. 38.

[8]The authors use the opportunity to thank H. Mendell for a thorough discussion on the cylindric model in relation to Anaximander.

[9]Aetius II 24.9: "The same philosopher [Xenophanes] maintains that the Sun goes forward ad infinitum, and that it only appears to revolve in a circle owing to its distance".

[10]*Almagest* I H11, pp. 38–39.

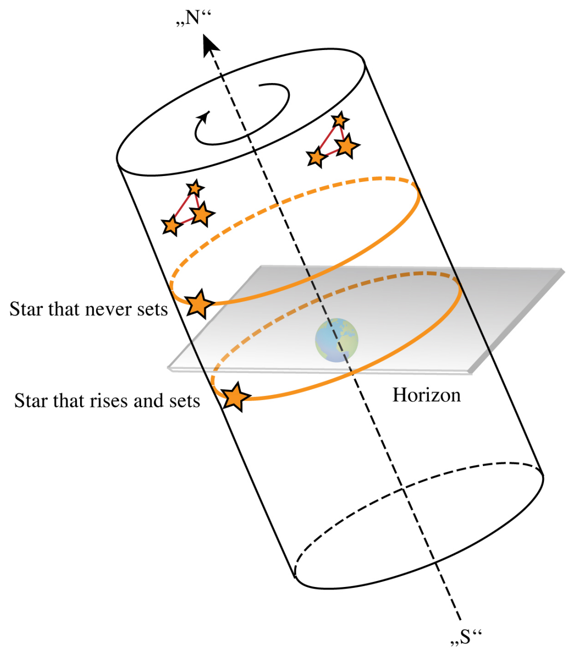

Figure 3.2: Observational effects in the “cylindrical universe”. The stars’ visible trajectories are concentric circles; the local horizon defines the different sets of ever-visible stars and stars that rise and set. The mutual distances between stars remain constant. One needs astronomical observations arranged in a special way to distinguish between a spherical and a cylindrical world.

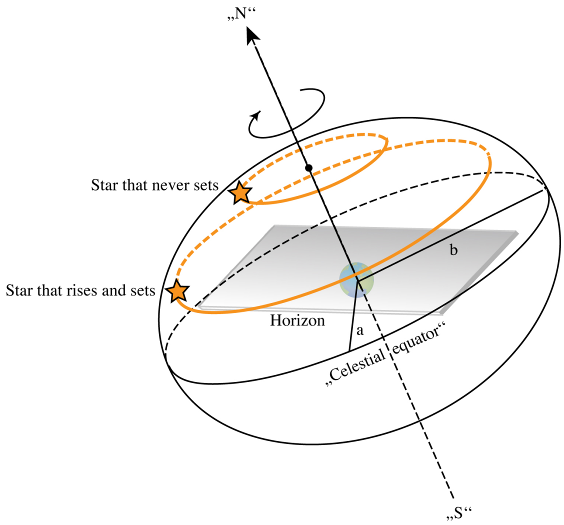

Figure 3.3: Observational effects in the “ellipsoidal universe”. Fixed stars lie on the surface of an ellipsoid with two equal axes ($a = b$) rotating about an axis perpendicular to the plane defined by these axes. The stars’ visible trajectories are concentric circles; the local horizon defines the different sets of ever-visible stars and stars that rise and set. The mutual distances between stars remain constant.

- "...What device could one conceive which would cause each of them [stars] to appear to begin their motion from the same starting-point every day?"
- "How could the stars turn back if their motion is towards infinity?"
- "...If they did turn back, how could this not be obvious?"
- In this case "...they must gradually diminish in size until they disappear, whereas, on the contrary, they are seen to be greater at the very moment of their disappearance ..."

The first three counter-arguments have a touch of 'common sense' reasoning or a purely rhetoric character. The last argument is totally forged: Ptolemy himself refers to this phenomenon a couple of lines later as being caused "by the exhalations of moisture surrounding the Earth being interposed between the place from which we observe and the heavenly bodies".[11]

Additionally, Ptolemy refers to another hypothesis which he regards as "completely absurd," namely, that "the stars are kindled as they rise out of the Earth and are extinguished again as they fall to Earth."[12] Nevertheless, he discusses this issue thoroughly.[13] Not only the necessity of cosmic order should rule this hypothesis out – because otherwise "the strict order in their size and number, their intervals, positions and periods could be restored by such a random and chance process" (in fact, the process need not necessarily be "random") – but also some other objections of special interest are proposed. Ptolemy mentions that, if this were the case, then

- "...One whole area of the Earth has a kindling nature, and another an extinguishing one, or rather that the same part [of the Earth] kindles for one set of observers and extinguishes for another set; and that the same stars are already kindled or extinguished for some observers, while they are not yet for others..."
- For the stars which are ever-visible in certain regions and are partly-visible at others, one should admit "that stars which are kindled and

[11] This explanation is actualy incorrect; in his later work (*Optics*, III 60) this phenomenon, now known as a Ponzo-illusion, is correctly explained as a pure psychological effect.

[12] Aetius II I3, I4, III 2.II: "According to Xenophanes the stars are made of clouds set on fire; they are extinguished each day and are kindled at night like coals, and these happenings constitute their settings and rising respectively."

[13] *Almagest*, I 3 H12, p. 39.

> extinguished for some observers never undergo this process for other observers."

These counter-arguments are really of 'global' geographical character: they can be put forward only through comparison of observational information gained at different geographical localities. Ptolemy also presents some arguments[14] which can be roughly classified as 'mathematical':

- "...If one assumes any motion whatever, except spherical, for the heavenly bodies, it necessarily follows that their distances, measured from the Earth upwards, must vary, wherever and however one supposes the Earth itself to be situated. Hence the sizes and mutual distances of the stars must appear to vary for the same observers during the course of each revolution, since at one time they must be at a greater distance, at another at a lesser. Yet we see that no such variations occur."

- "...Since of different shapes having an equal boundary those with more angles are greater [in area or volume], the circle is greater than [all other] surfaces, and the sphere greater than [all other] solids[15], [likewise] the heavens are greater than all other bodies."

- "No other hypothesis can explain how sundial constructions produce correct results..."

In fact, the first argument refers to the constancy of the stars' mutual distances and spacial relations. Once more, Ptolemy does not mention here that the mutual distances between stars would remain intact not only in a 'cylindrical' world but also in a cosmos in the form of an ellipsoid (see above).

The second counter-argument is of a curiously mixed nature: a correct mathematical result interbred with a yet naive interpretation of an extremal principle – a future tradition which survived until G. Leibnitz.

How basic the concept of celestial sphere was for sundial constructions is widely discussed[16] in the literature: astronomical calculations with

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[14] *Almagest* I H13, pp. 39–40.

[15] Due to Toomer (*Almagest*, p. 41), these propositions were proved in a work by Zenodorus, early second century BC.

[16] See, for example, D. R. Dicks *Early Greek Astronomy to Aristotle*, p. 166: "The data are very inaccurate for the latitude of Babylon (particularly the equinoctial and winter solstitial figures), which is not surprising since the underlying assumption seems to be that the length of the shadow increases in arithmetical progression with the hight of the Sun... Moreover, the results are set out according to a predetermined scheme

gnomons make sense only in the geocentric world and the apex of a gnomon symbolizes the Earth in the center of the spherical universe. The very visualization of the concept of the celestial sphere with gnomons and its usage in sundials can be traced back to the *analemma* construction as discussed in Vitruvius (see Fig. 3.4).

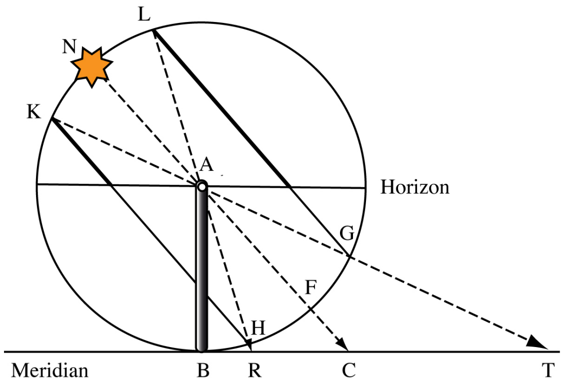

Figure 3.4: The gnomon AB is placed perpendicular to the horizon plane. Point R marks the end of the shadow at summer solstice; point T marks the winter solstice. Cutting the arc HG into halves and marking this point with F one gets the point of equinox C at the prolongation of the line AF. Obliquity of the ecliptic is depicted by the angle RAC.

For completeness and to show the very way of Ptolemy's argumentation, we will list the arguments which he himself classifies as 'physical':

- "...The motion of the heavenly bodies is the most unhampered and free of all motions; and freest motion belongs among plane figures to the circle and among solid shapes to the sphere [...]"
- "...The aether is, of all bodies, the one with constituent parts which are finest and most like each other; now bodies with parts like each other have surfaces with parts like each other; but the only surfaces with parts like each other are the circular, among planes, and the spherical, among three-dimensional surfaces. And since the aether

whereby the solstices and equinoxes are placed arbitrarily on the 15th day of the first, fourth, seventh, and tenth months of a schematic year of twelve months and thirty days each."

is not plane, but three-dimensional, it follows that it is spherical in shape."

- "...Nature formed all earthly and corruptible bodies out of shapes which are round but of unlike parts, but all aetherical and divine bodies out of shapes which are of like parts and spherical. For if they were flat or shaped like a discus they would not always display a circular shape to all those observing them simultaneously from different places on Earth. For this reason it is plausible that the aether surrounding them, too, being of the same nature, is spherical, and because of the likeness of its parts moves in a circular and uniform fashion."

It is easy to see that the first of the 'mathematical' and the last of the 'physical' arguments presumes that stars as objects have some perceptible size – this misapprehension would survive until the early modern times.

3.2 The Earth, taken as a whole, is sensibly spherical

The arguments aimed at demonstrating the sphericity of the Earth were widely known in Antiquity and are repeated by Ptolemy; the specification "taken as a whole" should indicate that one ignores the local irregularities of the Earth's surface. For the sake of completeness, Ptolemy also considers some other possible forms for the Earth (concave, plane, of polygonal shape, cylindrical) and shows which astronomical evidence would rule out these cases.

3.3 The Earth is in the middle of the heavens

Ptolemy deals with geocentrism and enlists a series of astronomical arguments in favour of this thesis in *Alamagest* I,5. Ptolemy tries to consider all other possible cosmological arrangements with an eccentric Earth and rules them out on the basis of pure observations. The alternatives are the following:

1. that the Earth is not on the axis [of the universe] but equidistant from both poles,

2. it is on the axis but removed towards one of the poles,

3. it is neither on the axis nor equidistant from both poles.

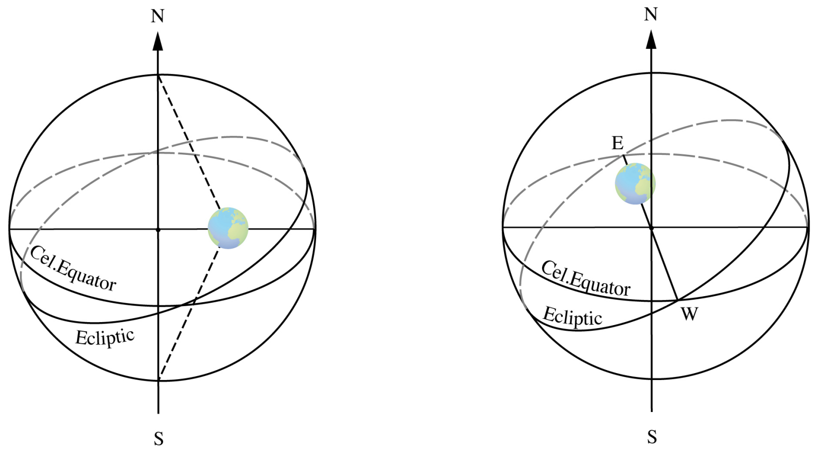

Figure 3.5: First case: the Earth is equidistant from both poles – two possible locations.

Let us consider the first case. Two possible positions for the Earth are given in Fig. 3.5.

In order to understand Ptolemy's arguments, it is useful to recall that only if the Earth is in the center of the celestial sphere will the Sun rise for any observer exactly in the eastpoint and set in the westpoint only twice a year, namely at equinoctials.[17] The equinox is defined as a day when the Sun's declination $\delta = 0$, that is, the Sun's trajectory lies on the celestial equator, and the length of the day is equal to the length of the night (see Fig. 3.6). Ptolemy argues:[18]

> If the image [the Earth] removed towards the zenith or the nadir of some observer[19], then, if he were at *sphaera recta*, he would never experience equinox, since the horizon would always divide the heavens into two unequal parts, one above

[17] Strictly speaking, the eastern and western directions are defined locally for every observer relative to the local northern direction; for further considerations, we will use also a global coordinate system with a northern direction defined through the rotational axis of the cosmos and eastern-western direction coinciding with the intersection line between the ecliptic and equatorial plane.

[18] *Almagest* I H17, p. 41.

[19] Here, Ptolemy explicitly implies that the Earth's size is negligible in comparison to the distance to the stars; otherwise, the Earth would not be equidistant from both poles.

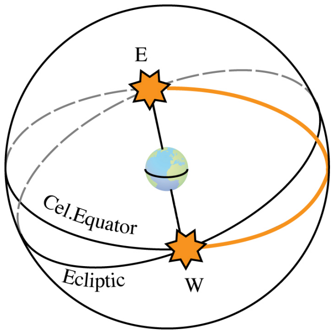

Figure 3.6: Equinox: the Sun's declination $\delta = 0$ and the visible path of the Sun coincides with the celestial equator. The Sun rises directly in the east and sets directly in the west direction for every observer on the Earth's surface. Here and in the following, we will depict the visible path of the Sun above the horizon plane with a yellow line.

> and one below the Earth; if he were at *sphaera obliqua*, either, again, equinox would never occur at all, or [if it did occur], it would not be at a position halfway between summer and winter solstices, since these intervals would necessarily be unequal, because the equator, which is the greatest of all parallel circles drawn about the poles of the [dayly] motion, would no longer be bisected by the horizon; instead [the horizon would bisect] one of the circles parallel to the equator, either to the north or to the south of it. Yet absolutely everyone agrees that these intervals are equal everywhere on Earth, since [everywhere] the increment of the longest day over the equinoctial day at the summer solstice is equal to the decrement of the shortest day from the equinoctial day at the winter solstice.

Ptolemy considers separately two possible positions of observation, one at the equator (*sphaera recta*) and another at an arbitrary latitude (*sphaera obliqua*). He concludes, in fact, that in both cases one would never experience equinox, since the horizon would always divide the heavens into two unequal parts. The argumentation is visualized in Fig. 3.7. The completeness of Ptolemy's analysis of the astronomical consequences of this case can be seen from his notice that it can nevertheless happen that one observes the same lengths of day and night at *sphaera obliqua*. But in

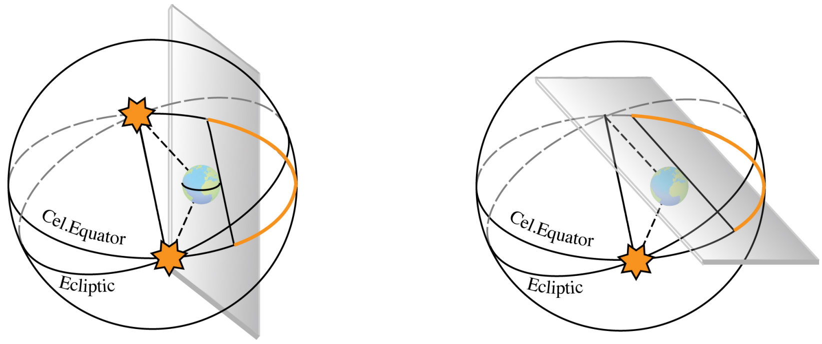

Figure 3.7: The Sun's declination $\delta = 0$. Observational situation at *sphaera recta* (left) and at *sphaera obliqua* (right).

this case that will happen not at the true equinoctial date when the solar declination $\delta = 0$ but at some other date (see Fig. 3.8)!

The next step in Ptolemy's analysis is to consider the observational consequences of the Earth's displacement along the east-west direction. He proposes the following counter-arguments:[20]

- The sizes and distances of the stars in this case would not remain constant and unchanged at eastern and western horizons.
- The time-interval from rising to culmination would not be equal to the interval from culmination to setting.

Having considered and ruled out the possible symmetrical displacement of the Earth from the rotational axis of the universe, Ptolemy begins to consider the astronomical consequences of the possible displacement of the Earth along the north-south direction *along the rotational axis*. He concludes[21] that in this case:

- The plane of the horizon would divide the heavens into unequal parts, different for different latitudes.
- The plane of the ecliptic would be divided by the plane of the horizon also into unequal parts; instead the six zodiacal signs are visible above the Earth at all times and places, while the remaining six are invisible.

[20] *Almagest* I H18, p. 42.
[21] *Almagest* I H18–19, p. 42.

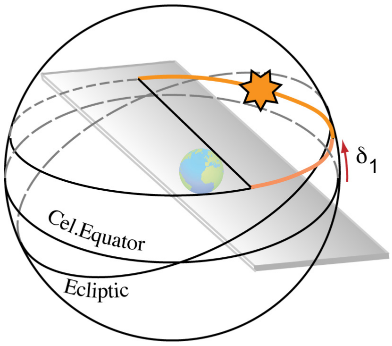

Figure 3.8: "False equinox": the Earth is not on the rotational axis of the universe but equidistant from both poles. One can possibly observe the same length of day and night not at the true equinoctial date $\delta = 0$ but at some other date with some other Sun's declination δ_1.

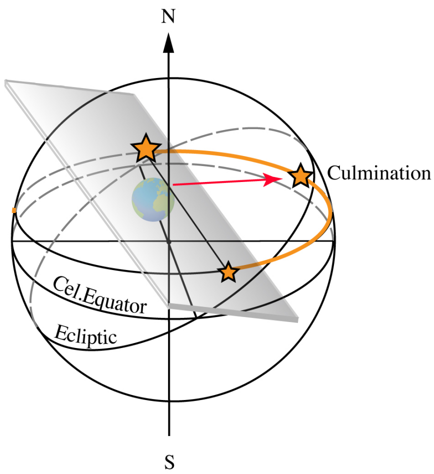

Figure 3.9: Displacement in the east direction. Stars appear to be bigger in east direction and smaller in west direction. The moment of culmination did not lie in the middle of the time-interval between the rising and setting of stars.

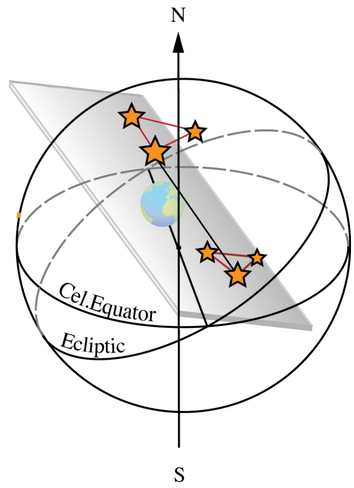

Figure 3.10: Displacement in the east direction. The angular distances between the stars in the same constellation appear to be bigger in east direction and smaller in west direction.

- Only at *sphaera recta* could the horizon bisect the celestial sphere.
- The shadow of the gnomon at equinoxes at sunrise would no longer form a straight line with its shadow at sunset in a plane parallel to the horizon, not even sensibly.

The first and third arguments can be easily understood with the help of Fig. 3.11 and 3.12. The last (fourth) argument in the list is of special interest:

> [...] if the Earth were not situated exactly below the [celestial] equator, but were removed towards the north or south in the direction of one of the poles, the result would be that at the equinoxes the shadow of the gnomon at sunrise would no longer form a straight line with its shadow at sunset in a plane parallel to the horizon, not even sensibly.

Actually, this is an old 'evidence' for geocentricism, which was used as a proof also by Pliny in his *Natural History*:[22]

[22]Pliny, *Natural History* I, chapt. 70.

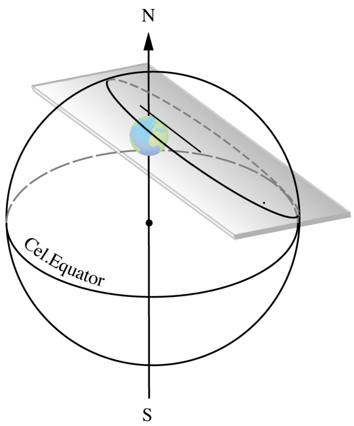

Figure 3.11: Displacement of the Earth along the rotational axis of the universe: the plane of the horizon would divide the heavens into unequal parts, different for different latitudes.

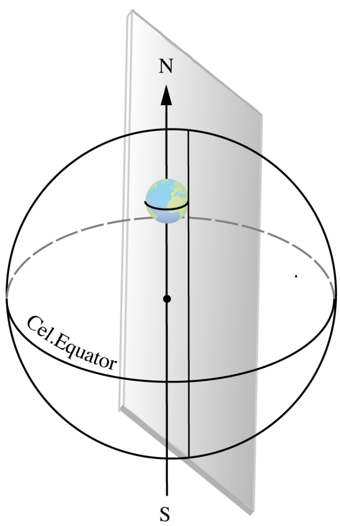

Figure 3.12: Displacement of the Earth along the rotational axis of the universe: Only at *sphaera recta* could the horizon bisect the celestial sphere.

> It is demonstrated by dioptra, which affords the most decisive confirmation of the fact, that unless the Earth was in the middle, the days and nights could not be equal; for, at the time of the equinox, the rising and setting of the Sun, are seen on the same line, and the rising of the Sun, at the summer solstice, is on the same line with its setting at the winter solstice; but this could not happen if the the Earth was not situated in the centre.

A visualization of the above mentioned argument for the case of the equinox in Pliny is given in Fig. 3.13.

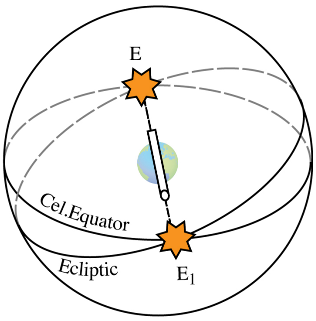

Figure 3.13: Pliny's argument: at equinoxes the sunrise and sunset points can be observed along the same line with a dioptra; therefore, the observer is located at the intersection of two great circles, that is one is placed in the middle of the universe.

A similar line of argumentation can be found in Euclid:[23]

> Let Cancer, at point Γ in the east, be observed through a dioptra placed at point Δ, and then through the same dioptra Capricorn will be observed in the west at point A. Since points $A\Delta\Gamma$ are all observed through the dioptra, the line $A\Delta\Gamma$ is straight.

It should be noted that Cancer and Capricorn as zodiacal signs are not *observable* as points on the celestial sphere; on the other hand, the position of the Sun at summer solstice is marked by its entrance in the tropic of Cancer and the longitudinal difference between the two signs is equal to

[23] Euclid, *Phaenomena*, I.

180 degrees. That means that Pliny's argument can be just a reformulation of the 'mental observation'[24] illustrated by Euclid. It is remarkable that Ptolemy uses this statement only as a counter-argument.
Ptolemy rounded up his argumentation for the third case (the Earth is neither on the rotational axis nor equidistant from both poles) by concluding that it is impossible because "the sorts of objection which we made to the first [two] will both arise in that case."[25]

The last reason for the central position of the Earth comes from the observation of the Moon's eclipses:[26]

> Furthermore, eclipses of the Moon would not be restricted to situations where the moon is diametrically opposite the Sun (whatever part of the heaven [the luminaries are in])[27], since the Earth would often come between them when they are not diametrically opposite, but at intervals of less than a semicircle.

Ptolemy does not discuss this argument in detail: in fact, it presupposes that both the Sun and Moon have a circular motion around the center of the cosmos – this is certainly not the case for the lunar and solar theories developed in the *Almagest*.

3.4 The Earth has the ratio of a point to the heavens

One should emphasize that Ptolemy's statements considered above are practically all valid only if one neglects the Earth's size in comparison to the size of the universe. His continuous repetition of the word *sensibly* clearly indicates that he himself was aware of the intrinsic precision of his 'proofs'. The arguments presented in this section should in fact give the necessary justification of the approximation used in the 'proofs' of the previous sections. The following arguments are proposed:[28]

- "the sizes and the distances of the stars, at any given time, appear equal and the same from all parts of the Earth everywhere, as observations of the same [celestial] objects from different latitudes are found to have not the least discrepancy from each other";

[24] To our knowledge, this kind of observation was in fact never made: not only the atmospheric refraction but also a final size of the Sun would make the precision of such 'proofs' mathematically invalid.
[25] *Almagest* I H19, p. 42.
[26] *Almagest* I H19, p. 42.
[27] That is, at opposition, at full Moons.
[28] *Almagest* I H21, p. 43.

- “the gnomons set up in any part of the Earth [...] and likewise the centers of armillary spheres, operate like the real center of the Earth; that is, the lines of sight [to heavenly bodies] and the paths of shadows caused by them agree as closely with the [mathematical] hypotheses explaining the phenomena as if they actually passed through the real center-point of the Earth”;
- “the planes drawn through the observer’s lines of sight at any point, which we call ‘horizons’, always bisect the whole heavenly sphere”.

The very nature of astronomical observations, however, limits the precision of these arguments to a perceptible level – a fact which was not lost on Ptolemy. Once more, he has to repeat that “the Earth has, **to the senses**, the ratio of a point to the distance of the sphere of the so-called fixed stars”.[29] What is now missing are the arguments which could rule out the displacement relative to the center of the universe which were of the Earth’s size. Such displacement would not be observable with the precision of naked-eye astronomy but could be monitored in frames of Aristotle’s physics through terrestrial observation.

3.5 The Earth does not have any motion from place to place

As we have seen, Ptolemy thinks that geocentrism can be sufficiently demonstrated through astronomical considerations based on geometry and observation up to a *perceptible level*.

Nevertheless, he does not use the physical arguments against the motion of the Earth in *Almagest* I, 7 to rule out the possiblity of a tiny central displacement of the Earth. Unlike Aristotle, he seems to regard these arguments as irrelevant for demonstration of the centrality of the Earth. Ptolemy argues that the fall of bodies can be regarded as a corollary of geocentrism instead of an argument for it:[30]

> One can show by the same arguments [provided in support of the centrality of the Earth] that the Earth cannot have any motion in the aforementioned directions, or even move at all from its position at the center. [...] Hence I think it is idle to seek for causes for the motion of objects toward the center, once

[29] We can only agree here with the comment of Toomer that the classification ‘so-called’ used for the fixed stars means that for Ptolemy the stars did in fact have a motion – that is, precession.

[30] *Almagest*, I,7 p. 43.

> it has been so clearly established from the actual phenomena that the Earth occupies the middle place in the universe, and that the heavy objects are carried toward the Earth.

Ptolemy, exactly like Aristotle (see Fig. 2.2, right) observes that the fall of heavy bodies toward the center is evident since[31] "the direction and path of the motion [...] of all bodies possessing weight is always and everywhere at right angles to the rigid plane drawn tangent to the point of impact." Additionally, Ptolemy reviews a series of physical considerations which he could derive from *De caelo*, although his opinions diverge from Aristotle's. Firstly, he discusses the fact that the Earth is not supported by anything in its position at the center of the universe. Unlike Aristotle[32], he reassesses the "argument of equilibrium for indifference" ascribed to Anaximander in *De caelo*. In fact, as one reads, "that which is relatively smallest should be overpowered from and pressed in equally from all directions to a position of equilibrium."[33] Additionally, he affirms that there is no up and down in the universe, since directions depend on the observer. This statement is at odds with Aristotelian cosmology. In *De caelo* II,2 one reads that the heavens have an up and down, a right and a left, a back and forth. This idea is supported by an analogy between the heavens and animals which are beings capable of moving themselves. In spite of his independence from Aristotle, Ptolemy assumes[34] along with him that a body falls down faster the bigger it is. This is also according to him an argument against the displacement of the Earth from its center, toward which it has a natural tendency. Moreover [35], "living things and individual heavy objects would be left behind, riding on the air, and the Earth itself would very soon have fallen completely out of the heavens. But such things are utterly ridiculous merely to think of". Although physical arguments are not essential to demonstrate the centrality of the Earth, according to Ptolemy they are decisive for rejecting the axial rotation of the Earth, an issue which he explicitly tackles:[36]

> ...although there is perhaps nothing in the celestial phenomena which would count against that hypothesis, at least from simpler considerations, nevertheless from what would occur here

[31] *Almagest*, I, 7 p. 43.
[32] *De caelo*, II, 13.
[33] *Almagest*, I, 7 p. 43.
[34] *Almagest*, I, 7 p. 44.
[35] Ibid.
[36] *Almagest*, H25, p. 45.

> on Earth and in the air, one can see that such a notion is quite ridiculous.

As we have seen, Aristotle ascribes the same argumentation to Plato.[37]

Ptolemy's arguments against the axial rotation of the Earth (and terrestrial motion in general) became famous after Copernicus's refutation in the first book of his major work. They are basically derived from the excessive velocity of the terrestrial spinning and the supposition that flying and thrown objects would be left behind by the terrestrial motion.

[37] We will not take into account here the inaccurate comparison between Aristotle's and Ptolemy's physics in Olaf Pedersen, *A Survey of the Almagest* (Odense, 1974), 43-45. On the one hand, Pedersen uncritically assumes the Aristotelian background of Ptolemy. On the other hand, he interprets *Almagest* I, 7 anachronistically and extrinsically, using meaningless expressions like "an immense pressure of the ether molecules". On top of this, Pederson erroneusly equates the theory of the central Earth spinning on its axis with heliocentrism.

Chapter 4
Conclusions and perspectives

In the *Almagest*, Ptolemy's argumentative strategy in favor of geocentrism is clearly the reverse of that employed by Aristotle in *De caelo*, II, 13-14. Whereas the natural philosopher derived the centrality (and immobility) of the Earth from his theory of the elements, that is, form "physical" observations and assumptions, the Hellenistic astronomer derived similar conclusions from geometrical-astronomical considerations. Aristotle explicitly regarded mathematical astronomical or rather cosmological arguments as secondary. In his opinion, they merely corroborated his natural demonstration. In a certain sense, one can say that he built his cosmology on the basis of theories concerning terrestrial physics (the theory of the elements). Ptolemy reversed, at least in the relevant passages of the *Almagest*, Aristotle's perspective as he considered physical arguments to be secondary: "Hence I think it is idle to seek for causes for the motion of objects towards the centre, once it has been so clearly established from the actual [astronomical] phenomena that the Earth occupies the middle place in the universe".[1] According to him, physics descends from cosmology and not the other way round. As we have seen, elementary observational phenomena, like the fall of bodies, do not require further explanation once the spherical form of the heavens and the centrality of the Earth have been demonstrated. It is precisely the inverse of Aristotle, for whom the theory of the elements comes first.[2]

Still, to account for this divergent approach to geocentricism, the classical distinction between mathematical and physical astronomy is not sufficient. Averroes and scholastic philosophers criticized several aspects of Ptolemaic astronomy from a natural or "physcal" perspective. The geometrical models for planetary motions seemed to be at odds with basic assumptions of Aristotle like the uniform circularity of celestial motions or the concentricity of heavenly spheres. Ptolemy was therefore ac-

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[1] *Almagest*, I, 7.

[2] We leave a treatment of Ptolemy's physics and physical premisses as a prospect for further research based on *Planetary hypotheses* and *Tetrabiblos*.

cused of neglecting natural philosophy and his mathematical models were deemed unable to explain the real nature of the universe. Accordingly, it became usual to distinguish mathematics and physics, description and explanation. This separation was still at work in the homocentric cosmologies of the early sixteenth century, as was the case with the Italian Aristotelians Amico and Fracastoro. In the framework of the Copernican debate, there were several attempts to distinguish mathematical and physical astronomy, in order to avoid a conflict between Copernican tables and Aristotelian physics. Mathematical astronomy should only provide useful models for celestial computation, whereas philosophy should deal with natural causes. Theologians were particularly severe in maintaining this distinction which entailed also a hierarchic understanding of the levels of knowledge: mathematical, philosophical and, at top, revealed. Notably, this position was stubbornly supported by the Lutheran theologian Andreas Osiander, author of the conventionalist anonymous introduction to *De revolutionibus*, and later by the Catholic Inquisitor Roberto Bellarmino, who played a decisive role in the trials of Bruno and of the heliocentric theory. Both limited mathematical astronomy to computation or, as Duhem put it, to "save the phenomena" (*sozein ta phainomena*).From our analysis it has become clear, however, that Ptolemy's and Aristotle's arguments for geocentrism cannot be traced back to the separation between abstract mathematical models and real physical causes (Averroes and scholastic) nor to the separation of computation and explanation (Osiander and Bellarmino). In fact, they show a more general divergence in the treatment of nature. This is an ontological and an epistemological difference at the same time. On the one hand, Aristotle tackles geocentricism from the perspective of a qualitative philosophy of nature, especially his theory of elementary motion. On the other hand, Ptolemy relies on a mathematical understanding of the cosmos as a whole. The former derives cosmology from terrestrial physics, whereas the latter proceeds in the opposite direction. It should be remarked that, in this respect, Copernicus would follow in Ptolemy's footsteps, claiming in book one of *De revolutionibus* that terrestrial physics should be corrected to agree with his general cosmological assumptions, beginning with the Earth's motion. The divergence between Aristotle and Ptolemy is that between a qualitative and a mathematical approach to nature as well as that between a terrestrial and a heavenly perspective.

Concerning Ptolemy's epistemology – one could say, his 'mathematical epistemology' – an enlightening introduction to it is the first chapter of the first book of the *Almagest*, which contains interesting philosophical considerations and claims. Ptolemy mentions the Aristotelian idea that there are three speculative disciplines, physics, mathematics and theology, possibly relying on *Metaphysics* V,1 or similar passages. However, he alters Aristotle's perspective, since he exploits this quotation to extoll firstly the nobility of mathematics and to hint, in the following, even at the superiority of mathematics over the other two speculative disciplines. This superiority concerns at least the certainty of its demonstrations. Whilst philosophers will never reach an agreement in their speculations as a consequence of the profound uncertainty of their discipline, "mathematics can provide sure and unshakable knowledge to its devotees, provided one approaches it rigorously. For its kind of proof proceeds by indisputable methods, namely arithmetic and geometry."[3] In a very Platonic mood, Ptolemy surmises that mathematics gives access to divine things, because its objects occupy a position between the sensible and the intelligible, between the changing reality given to our perceptions and the eternal, unchanging realm of divinity.[4] With a fruitful intuition, Ptolemy adds that mathematics helps also physics "for almost every peculiar attribute of material nature becomes apparent from the peculiarities of its motion from place to place."[5] Needless to say, both the idea of a mathematical theology and that of a mathematical theory of motions are in contrast with Aristotle's metaphysics and his hylomorphic physics. Ptolemy adds some considerations on the providential design underlying nature, which owes much to Pythagoreanism and Platonism:[6]

> With regard to virtuous conduct in practical actions and character, this science, above all things, could make men see clearly; from the constancy, order, symmetry and calm which are associated with the divine, it makes its followers lovers of this divine beauty, accustoming them and reforming their natures, as it were, to a similar spiritual state.

A cosmological perspective like that of Ptolemy virtually entails a reinvestment of Aristotelian physics once the arguments for terrestrial centrality are demonstrated to be invalid from an astronomical perspective, as Copernius did in the first book of *De revolutionibus*. Copernicus's planetary system challenged physics from a cosmological perspective but not Ptolemaic epistemology, on which his method precisely relied.

[3] *Almagest* p. 36.
[4] *Almagest* p. 36.
[5] *Almagest* p. 36.
[6] *Almagest* pp. 36-37.

The "Aristotelian-Ptolemaic system" is a medieval and early modern product. The convergence of the general cosmological conclusions of *De caelo* and of *Almagest*, in spite of their different approaches, led to a unified geocentric cosmology based on arguments derived from both sources, as Sacrobosco witnesses. From the twelfth to the seventeenth century, university students learning the basics of spherical astronomy from Sacrobosco's *De sphaera* would receive the impression of a profound unity between the two principal sources of ancient cosmology, Aristotle and Ptolemy, relative to the essential features of the cosmos and the reasons they brought forward. Sacrobosco traced his general cosmological views back to the authority of these two sources, although he had only limited or indirect access to the original texts. As a matter of fact, he skipped, shortened or oversimplified the arguments of Aristotle and Ptolemy, and tended to present their shared opinions as part of the same conception. Although the commentators of Aristotle, especially through Averroes, became aware of the contrast between the homocentric planetary model propounded by their "master" and the epicyclic-eccentric geometrical devices of Ptolemy, the image of an Aristotelian-Ptolemaic worldview as a unity was not abandoned and later was even strengthened as an effect of the post-Copernican debate. This fundamental agreement became almost commonplace. According to Galilei's renowned *Dialogo*, for instance, the chief world systems were only two: the Ptolemaic and the Copernican, the first one coinciding with the Aristotelian. Kuhn's account of the "Copernican revolution" owes much to this interpretative schema. By contrast, this paper has pointed out the different, if not opposite, approaches in Aristotle's and Ptolemy's treatment of a fundamental cosmological issue on which regard they are usually mentioned together: geocentricism. A new attention to epistemological tensions between the two main classics of cosmology pertaining to methodology and philosophy of knowledge helps us understand that there is no "traditional", "ancient" or "Greek" cosmology. This suggests that the ancient world experienced a theoretical, philosophical and cultural variety that can be easily overlooked from the modern perspective. In fact, not only have we often received a crystallized image of Greek knowledge, but also dispose of works which are themselves great syntheses that overshadow and hide previous debates and multiplicity. Just as Aristotle's *De caelo* superseded previous cosmologies, Ptolemy's *Almagest* superseded previous mathematical astronomy. The work of the historian of ancient cosmology shall therefore be to highlight argumentative tensions, deconstruct the alleged unity of the views of singular authors or epochs, and seek to obtain an insight into the cultural pluralism of debates that history and tradition has veiled.

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