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A Phylogenetic Study of the Concept of Celestial Orb

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Abstract. This paper presents a phylogenetic study of the concept of orb from its rise to its abandonment. While a heavy load of literature is dedicated to the introduction and abandonment of the concept, there are few systematic studies on the semantic components of this concept in the Islamic tradition of astronomy. We will investigate conceptual articulation among Arab astronomers by distinguishing the astronomical and philosophical understandings of the concept. While the former mainly focuses on the empirical evidence, the latter emphasizes causal and physical role of the concept's referent. Such a distinction enables us to characterize some key conceptual components of the concept of orb. Among other components articulated by the Arab astronomers, the hardness of orbs, led Tycho Brahe and his fellow astronomers to abandon the concept.

Keywords: celestial orb • conceptual change • conceptual components • Islamic astronomy • hardness of orbs

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1. Introduction

Phylogenetic appraisal of scientific concepts is part of a novel approach to the history and philosophy of science in which the history of science goes beyond a mere tool to support philosophical claims, but as a source to locate fundamental philosophical problems (Lennox 2001). A phylogenetic study of scientific concepts can explain how some scientific 'developments going off in different directions… many of which became dead ends' (660). In the meantime, this approach avoids getting Whiggish for the end nodes which do not always end up to the current successful results. Many other philosophers of science and language have followed a similar line of argument (Love 2005; Brigandt 2006; Richard 2019). The historical tree drawn for each scientific concept provides an understanding of current conceptual issues by tracing the focal points of the trajectories that led to the contemporary state of affairs. Such an approach is called 'phylogenetic' for the focus is on the pathway rather than the mechanism; thus, the evolutionary epistemology which concerns the causal mechanisms of such changes is not engaged (Love 2003).

The method we adopted here shall view scientific concepts as forming historical lineages in response to the contingent decisions made in the course of history. Lennox's approach would open up a 'space of theoretical possibilities' to find the foundations of current philosophical problems by 'locating the source of problems' and giving a rational explanation of the theoretical and conceptual 'alternatives' (Lennox 2001). In this paper, we will give a rational explanation for the changes occurred for the concept orb, from its introduction to its rejection,[1] with respect to the scientists' choices. This historical investigation will provide the ground to answer the reason for concept abandonment and the underlying conditions that led to the current scientific status.

We will explore the conceptual development of an already abandoned but central concept of astronomy. The concept of celestial sphere or celestial orb played a crucial role in forming the ancient astronomy, and then paved the way for the advent of novel heliocentric models of the universe. This paper investigates the concept of orb with respect to the main conceptual components upon which the concept was based. If successful, it should become clear why the concept was introduced by the Greeks and not earlier within the Babylonian culture in response to a mathematical study of the celestial motions. An initial form of the concept was born in the Greek culture. This was only a non-elaborated understanding of the overall shape of the universe, containing several ambiguities in terms of observational and philosophical purposes.

Nevertheless, a heavy load of the relevant literature has been dedicated to this period and on whether or not the concept was used for a realistic or instrumental purpose (Duhem 1954; Lloyd 1978; Gardner 1983; Ragep 1990). The emphasis on this period of the concept's life has left the rest of this story unclear. There are very few systematic studies that investigate the importance of the concept orb and how it paved the way for a successful field of science in the Middle Ages. We will trace other pieces of this puzzle back to the Islamic astronomy, where the concept was articulated and associated with an absolutely dynamic understanding. We will show how concept articulation from the eleventh to fourteenth centuries provided the motivation for Arab astronomers[2] to cultivate their non-Ptolemaic models, but at the same time increased the complexity of their models by adding epicycles and deferent spheres. Following this purpose, our main focus remains on the Arabic age of science and for the sake of brevity we keep some significant astronomical discussions of Europeans especially from the 13th to 14th century untouched.

By the end of the fourteenth century, conceptual components such as hardness, uniform motion, and the sphericity of orbs had become rigid in the concept. Concept rigidity, we will argue, is a key sign of a mature scientific concept employed by falsifiable theories. This means that the concept of orb could be a model of a mature scientific concept that did contribute to the advancement of science, although it was abandoned. Rigidified concepts directly mirror on the models and theories. So, we can easily translate our proposal to the point that astronomers increasingly treated the astronomical models as mechanical representations of the actual world.

The rigidified concept of orb remained in use until after Copernicus, who still used the concept with the same semantic components (we will discuss some major components in section 5). The observation of a comet in 1577 by Tycho Brahe persuaded him to attack the supposedly *solid* and *hard* spheres. Although some believe that Brahe assumed hardness as a basic conceptual component of orb for the first time, we will show that this component was assumed earlier by the astronomers of the Islamic age. Brahe's observation, together with the idea to abandon the celestial orb introduced by some of his contemporary astronomers caused the long-lived concept to fall under heavy suspicion. When Kepler proposed his novel laws of planetary motions based on Brahe's observations, the rigidity of the concept of orb caused astronomers to make a crucial decision to ultimately abandon the concept instead of modifying and retaining it.

The phylogenetic approach to the concept of orb, in this paper, should be interesting for philosophers of science for its insights into the understanding of language of science. Unlike concepts of phlogiston or caloric, which were abandoned mainly due to theory change, the concept orb was able to survive in accord with the heliocentric revolution. Above that, the heliocentric revolution could help the concept live longer, for it increased the simplicity of the cosmological models in the sense that was known by Arab astronomers (see Gamini & Sadrforati 2022). Current philosophical and historical accounts cannot explain why this concept did not show an inclusive behavior to survive, as did concepts of gene or atom, in response to the rapid evolutions of their respective scientific fields. The case of gene, among others, is interesting because in the contemporary biology several concepts have been associated with the term 'gene', which without providing sufficient context they fail to fix reference (Brigandt 2010; Weber 2014; Sadrforati 2019). So, it remains to be asked why the concept orb did not survive with the revision on some of its conceptual components. Why did the Ptolemaic astronomy become dead-end and how did it pave the way for later scientific theories? Although a comprehensive response to these issues requires multidisciplinary research, we believe that the current phylogenetic study will shed light on it.

2. Before the birth

Although there are limited resources showing *how* the celestial knowledge transferred from Mesopotamia to the Greeks, we certainly know that some major Greek philosophers/astronomers owe to this tradition. Babylonians are known for developing the first systematic mathematical theories to address their observation of the motion of celestial objects. This practice, however, was not a scientific routine or an ordinary knowledge shared among the populace. Only selected observers recorded the celestial and terrestrial events in order to predict the position of celestial bodies for "forecasting the fortunes of the country as well as of the king" (Britton & Walker 1996, p.50). Such an instrumental epistemic goal (to predict) was funded by the ruler and influenced major decisions such as taxation and when to declare war. Babylonian observers were specifically looking for *period relations* by means of the recurring celestial phenomena with supposedly a predicative reoccurrence. In keeping with this rough research agenda, Babylonians were specifically interested in recording the position of the moon, planets, and sun. A 6,585-day cycle for a lunar eclipse, for example, was known to Babylonian observers. They developed mathematical techniques to pursue this predictive interest.[3]

Following such an epistemic goal, Babylonians were particularly interested in the kinematics of celestial objects, rather than the dynamics. Most of the tablets and historical evidence available to us from Mesopotamia contain numerical tables and mathematical functions calculating the period relation of planets and positional status of the moon. Neugebauer argues that the 'central problem' of Babylonian astronomy was to observe and calculate the 'first and last visibility' of the moon or other planets; thus, they were not particularly concerned with the 'planetary motion' or the 'daily motion' of the moon (1954, p.62). In a later paper, he argues for a more radical claim according to which the basis of Babylonian planetary theory was nothing but a 'purely mathematical method', 'free from all philosophical principles' in order to describe only 'the displacement of isolated characteristic phases' (1967, pp.968-972).

Babylonian scientific practice, hence, hardly required a concept reflecting their *causal interests* in the movement of the planets. This adds to the fact that Babylonian culture lacked geometrical tools with which to model their observations. This indicates that the introduction of the concept orb should be looked for in a later era, when epistemic goals took a more causal and dynamic approach.

3. The birth of the orb in Greece

The parallel importance of natural philosophy as well as the geometrical abilities helped Greeks in developing novel theories in astronomy (Jones 1991, p.445). Although later in the history of the concept two different physical and geometrical concepts of orb can be distinguished, the Greek culture used these resources together to support giving birth to the concept. We shall discuss how the Greek interest in natural philosophy backed with geometrical astronomy led to the introduction of the concept. Long before the advent of astronomical planetary models, Greek philosophers were attracted to the heavens. Their goal was not to develop a kinematic science of celestial motions, but to discover the actual shape of the universe and provide a causal understanding of the celestial motions.

One of the earliest known natural philosophers who pondered the geometry of the heavens was Anaximander (610–546 BC). His work *On Nature* postulates a circular or spherical shape for the universe. For him, the universe began to grow from a neutral, but prolific, seed (φυσις). Finding the nature of such substance was in accordance to the original quest of *arché*: the first causal substance of the world. A doxography from Pseudo-Plutarch states that, according to Anaximander this seed contains 'all the opposites' notably 'hot and cold' and 'wet and dry'. The seed then developed into a ball or sphere or umbrella of flames that 'grew round the air about the earth as the bark round a tree', and then this whole shape will be 'torn off and became enclosed in certain circles or rings' (cited by Heath 1991, p.xxii). This interesting passage may suggest that the concept of orb was born by or around the time of Anaximander, but Furely (1987) is reasonably suspicious of this simplistic claim. He argues that this tree-trunk (bark round a tree) image could be interpreted as something roughly 'cylindrical' rather than 'spherical'. He concludes that Anaximander did not attach any 'importance to the overall shape of the cosmos as a whole' (Furley 1987, p.27–8). This conclusion, however, seems in contrast with what Furely himself quoted from Anaximander and from other reports and doxographies delivered to us about him.

One important factor that has been neglected when attempting to understand Anaximander's shape of the universe is the commonsense observational input available to him, like other astronomers in Mesopotamia. A cylindrical shape of the universe has in nature some observational issues that make it very unlikely to hold: (1) planets do not appear bigger or lighter along the paths of their orbits, as expected from a cylinder, and (2) there is no visible hole without stars on the pole of the sky. It is known with certainty that Anaximander provides a circular image of the universe (whether due to observational or philosophical motivations); however, with regard to a three-dimensional model, it is not certain how this shape was imagined. The perceived image of a tree-trunk shape suggests at least a partly spherical shape — for an umbrella has a partly spherical shape. This does not necessarily require having a conception of spherical universe, but provides the means for such a concept.

A doxography received from Hippolytus contains helpful information about Anaximander's conception of the universe. As reported by Hippolytus, the earth is described as having the same distance from πάντων [everything]. If we assume the earth as a mathematical point for Anaximander, then the πάντων reflects a circular concept of the universe because it is only for a circle that all points on the surface have the same distance from the center. But if he had a more sophisticated model of earth in mind (i.e., a three-dimensional model), then the πάντων would be spherical in shape.[4] Thus, it appears that the following passage suggests a primitive concept of orb in ancient Greek:

> τὴν δὲ γῆν εἶναι μετέωρον ὑπὸ μηδενὸς κρατουμένην, μένουσαν δὲ διὰ τὴν ὁμοίαν πάντων ἀπόστασιν.[5] (Graham 2010, p.56)

The above understanding is, at best, a naïve spherical image of the pathway of the planets and the overall structure of the universe, but the importance of such an a priori concept of orb is the significant *physical* understanding attached to its meaning. Such a physical understanding was highly developed by Aristotle (385–322 BC). In *On the Heavens,* Aristotle elaborated his physical understanding by assigning a substance to it. He presented an a priori proof for the existence of a 'bodily substance other than the formations we know", spinning uniformly around the center of the universe (i.e., aether or αἰθήρ) (*On the Heavens* I, 2, 268b, pp.27–29, Trans. Guthrie, 1939). For him, natural elements move naturally either downward (earth and water), upward (air and fire), or in a circular manner (aether) around the center of the universe. He concluded that the last element has an 'unalterable' and 'simple' nature with a natural (voluntary) rotation around the center. In the following sections, we will discuss how later astronomers were more or less affected by such Aristotelian physical principles.

But it is important here to distinguish a physical and geometrical understanding of the orbs. While for previous Greek philosophers, such as Anaximander, the concept was more associated with physical representations of the universe, the Aristotelian concept moved slightly toward a geometrical understanding. Although his arguments regarding the nature of orbs did not include empirical investigations, Aristotle addressed some observational necessities in geometrical terms. In *Metaphysics*, he reported that two of his contemporary astronomers, Eudoxus (408–355 BC) and Callippus (370–300 BC), proposed models to explain the motion of celestial objects by several same-central spheres (*Meta*, book XII, section 8). Following Aristotle's thoughts, in about the third century BC, appeared the primary forms of a *geometrical* understanding of physical orbs in the sky, and the concept started being used in astronomical theories. When Archimedes of Syracuse (287–212 BC) introduced Aristarchus of Samos' (310–230 BC) understanding of the heliocentric universe in his treatise, he used orb as a well-known concept:

> [. . .] the 'universe' is the name given by most astronomers to the sphere [orb] the center of which is the center of the earth, while its radius is equal to the

> straight line between the center of the sun and the center of the earth. This is the common account (τά γραφόμενα) as you have heard from astronomers [...] (cited and translated by Heath 1991, p.105)

The best-known use of the concept of orb having a highly geometrical understanding appears in Ptolemy's *Almagest* (c. 100–170 AD). It was backed by the Pythagoreans and by Plato and Greek astronomers with a mathematical background. Meton of Athens (fifth century BC) was among the early Greek astronomers who used pure mathematical and geometrical tools to model celestial motions. Plato (428–348 BC), a philosopher with a highly prominent geometrical background, set the guiding problem of astronomy as to demonstrate the anomalies of the planets' motion to serve the overall philosophical background knowledge (Pederson 2011, p.34; Zeinaldin 2017, p.418). For him, the philosophical background appeared in the geometrical language as having a 'uniform' and 'circular' motion or having earth as the 'center of the universe'. The attribution of this guiding problem to Plato was done primarily by Simplicius (*De Cael*, vii. 488, 18-24, Heiberg), but has been frequently discussed in the literature (Knorr 1990).[6]

There is no clear line of figures with which to trace back the exact source of the geometrical understanding of the concept, but it is certain that at least after the age of Aristotle such an understanding was not fully unknown. Following Aristotle, in about the third century BC, the primary forms of a geometrical understanding of celestial motion, free from physical interpretations, appeared. In particular, Hipparchus (c. 190-120 BC) used abstract circles to present a model for celestial motions. Although not declared, a physical understanding of the concept orb is usually coupled with a geometrical understanding. The best-known use of the concept orb having a highly geometrical understanding appears in Ptolemy's *Almagest* (c. 100-170 AD). This is where a heavy load of the relevant literature in the history of science is dedicated to. The literature discusses whether the concept was used for a realistic (physical) or instrumental (geometrical) purpose (Duhem 1954; Lloyd 1978; Gardner 1983; Ragep 1990).

In *Almagest*, Ptolemy frequently used non-physical circular motions to model the planetary motions. For him, the purpose of planetary models was to give a geometrical estimation of the position of the planets at any specific time. Nevertheless, he provided experimental reasoning for the assumption of the sphericity of the universe by his ancestors.[7] In the third part of the first chapter of *Almagest*, Ptolemy explains how the [geometrical] concept of orb was visually introduced by his predecessors. He describes that they were looking at the stars moving from 'east to west along circles' which after a specific 'period of motion' appeared to rise and fall from a 'fixed and the same' center (Toomer 1984, H.10, p.38). After giving such an observational rationale for the introduction of the concept, he clearly states that this observation 'led them to the concept of a sphere'. Ptolemy claims that what made his predecessors come up with a spherical concept rather than, for example, an infinite straight line, is the observational fact that the closer stars get to the pole, the smaller their circles become (Toomer 1984, H.11, p.39). In addition to the astronomical rationale, the sphericity of orbs is supported by a purely geometrical perspective: a sphere is the only shape that provides the means for the planetary models because of its isoperimetric characteristics. In fact, spherical orbs could rotate inside each other to produce the circular motions assumed by other astronomers. For a natural philosopher, a sphere creates the 'smoothest and easiest motion' for the 'small particles' of the 'fine celestial matter' of Aether (Pederson 2011, p.36).

This indicates that the combined intellectual and observational resources of the Greek scholars together backed the creation of the concept orb to reflect the distinct research agenda available to them compared to their fellow Babylonians.

It is now important to distinguish this geometrical concept of orb from a physical concept that generally aims to pick out an external referent. In other words, a pure geometrical concept is an instrument to 'save the phenomena' supported by empirical evidence, while the aim of a purely physical concept is to causally explain the phenomena. For Greek astronomers, the physical and geometrical concepts are tightly intertwined in a way that distinguishing them requires a comprehensive study of each figure in each treatise and for each case of use. It is historically more accurate to attribute an ambiguous physical-geometrical understanding to the concepts used by Greek astronomers.[8]

Thus far, we have shown that the concept of orb was born with two inter-related epistemic interests. Mature astronomers relied upon and reviewed their philosophical assumptions along with their treatises, but sometimes their actual practice reflected clear contradictions with these assumptions. Ptolemy, in particular, is at the center of attention. Evidence exists both for and against his dynamic aim in astronomy. *Almagest* barely provides any realistic clue about his celestial model. Thus, his representations of the planetary motions where the planets rotate on epicycles and their centers revolve around eccentric points do not break with Aristotelian physical principles. Only a physical interpretation of his model can be considered to break with some of those principles. When explaining the rationality of maintaining these hypothetical contradictions, Ptolemy states that:

> The apparent irregularity [anomaly] in their motions is the result of the position and order of those circles in the sphere of each [...] in reality there is in essence nothing alien to their eternal nature in the 'disorder' which the phenomena are supposed to exhibit. (Toomer 1984, H.216, p.141)

Some argue that violating philosophical principles such as 'uniform circular motion' for some of the orbs can be justified by giving no 'significance' or different 'definition' of such rules for Ptolemy (Zainaldin 2017, p.427). This means that the Greek use of the concept orb reached the point that stressing one or another conceptual component could bring about significant implications. To interpret Ptolemy's *Almagest* realistically, for example, the cost is to violate the principle of the uniform rotation of orbs. Although we might be able to historically attribute different conceptual understandings to each Ptolemy's treatise, the overall Greek understanding of orbs remained ambiguous. Ragep reports that long after Ptolemy, some Greek scholars still 'presented [their] theory in a nonphysical way' (Ragep 1996, p.273).

4. Articulation of the concept in the Early Arabic Astronomy

Ptolemy's works served as the basis of astronomy in the age of Islamic civilization. Arab astronomers were primarily influenced by Ptolemy's *Almagest*. A great shift in this period, however, took place when the focus shifted to Ptolemy's later treatise, *Planetary Hypothesis* (known as *Kitāb al-Iqtiṣāṣ* or *Kitāb al-Manshūrāt* in Arabic). While it is hard to argue whether Greek astronomers, particularly Ptolemy in *Almagest*, were aiming for a dynamic or kinematic explanation of celestial motions, the *Planetary Hypothesis* explicitly aims for a dynamic and realistic model of the cosmos. At the forefront of this treatise, Ptolemy explicitly describes his aim to develop a comprehensible model for astronomers and 'mechanical methods' for 'instrument-makers' (Murschel 1995, p.33). The concept orb used in this treatise is the three-dimensional and physical representation of the *Almagest*'s circles. Yet, Ptolemy instantiated orb in two forms: filled and fully spherical orbs (epicycles) and thick spherical shells (deferents). Ptolemy asserts that orbs are not necessarily spherical, but could be three-dimensional whorls or tambourine-shaped (Figure 1). That is why, among Arab astronomers, this treatise is called *al-Manshūrāt*, which means 'coin-like disks' (Murschel 1995).

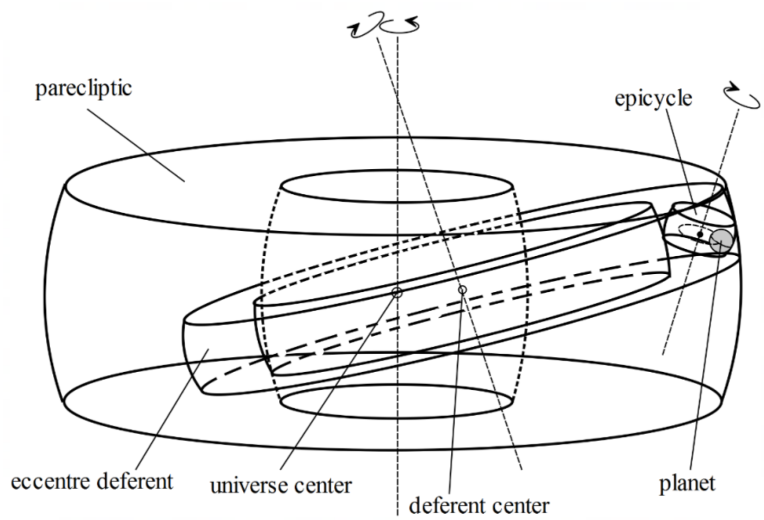

Figure 1:

Arab astronomers borrowed a rich concept of orb from this treatise, which combines the philosophical aims with the astronomical principles. Unlike his earlier work, Ptolemy criticized the Aristotelian view that the movements of inner spheres are caused by the outer spheres and held that each celestial body is moving per its own soul (ibid, 39). Commitment to the astronomical requirements is more clearly reflected in this form of the concept of orb. For example, to save the astronomical observations in the geometrical models, the movement of Ptolemy's orbs creates incomplete spherical shapes like the 'sawn-off pieces' of a sphere sliced by the eccentric sphere inside it, causing the outer spheres to appear as two crescents (Figure 2). Such a sophisticated concept of orb also undermines basic Aristotelian principles of a central sphere. This means that the concept borrowed by the Islamic culture had the physical aims, but was open to changing its components in response to astronomical necessities.

Arab astronomers, as well as some medieval Europeans, borrowed such an eclectic concept of orb. It is not certain how and when this occurred, but we know that some early Arab astronomers had access to the *Planetary Hypothesis*. Ibn al-Haytham (965–1040), for example, published a critical treatise on Ptolemy's later physical model and elaborated on the flaws of the Ptolemaic system, stressing the physical aspects of a planetary model. He argued that 'natural analogy' leads to the fact that any celestial motion requires a 'naturally

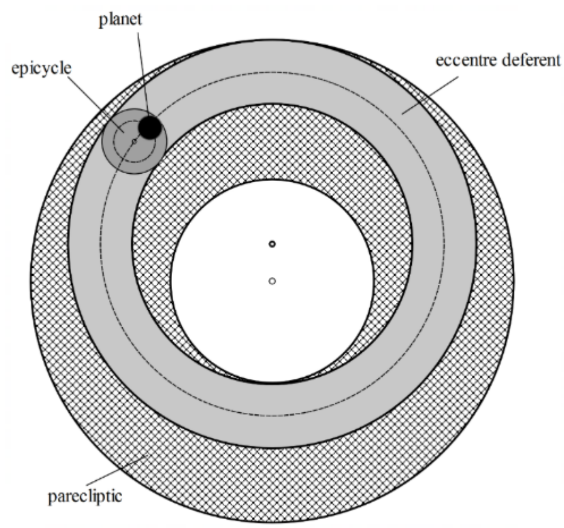

Figure 2:

solid orb' as its mover (Ibn al-Haytham 1971, p.45). Although some of Ptolemaic key terms such as 'equant' have a clear non-physical nature, he explicitly sets the epistemic goal of such an astronomical practice to come up with 'real', 'sound' and 'general' models with no 'philosophical contradiction' (Ibn al-Haytham 1971, p.63). By 'philosophical' he did not mean an orthodox commitment to all Aristotelian principles, but an excerpt of them selected according to the observational and geometrical requirements of his astronomical project. For example, he keeps the principle of uniform circular motion of celestial objects, which had been violated by Ptolemy's equant point, but leaves the principle that all orbs must spin around the center of universe, as well as the sphericity of orbs. Ibn al-Haytham's selective approach to the conceptual components could be explained by the 'lack of fit between a mathematical theory of the planets and a [physical] cosmology' inherited from the serious epistemic aim difference between *Almagest* and *Planetary Hypothesis* (Rashed 2014, p.14).

A contemporary of Ibn al-Haytham, Abu Rayhān al-Bīrūnī (973–1050) was at the center of the dispute between the philosophical and astronomical understandings of concept orb. It has been argued that al-Bīrūnī was clearly aware of the *Planetary Hypothesis* and referred to it in his works (Hartner 1964). What distinguishes his works from those of others is an explicit distinction he made between physical and geometrical understandings of orb. He held that "*circle* and *orb* (*falak*) are two terms that denote the same thing and are interchangeable, but sometimes orb refers to the sphere (*kurah*), in particular when it is [causally] moveable (*mutaḥarrik*)" (*Masudic Canon* 1954, p.54). This insight indicates the importance of al-Bīrūnī for later astronomers of the Islamic age to the articulation of the concept orb. In other words, Arabic astronomy inherited the ambiguity of a physical and geometrical understanding of the concept until at least the tenth century and it is only about that time that roughly deliberate use of the solid and three-dimensional concept of orb appeared.[9] A purely physical language of the Arab astronomers, well-known among historians of science, appeared only after they could articulate their key scientific concepts.

Al-Bīrūnī was hesitant to accept philosophical principles without careful inspections. This tendency was not limited to the concept of orb and his overall astronomical project, but extended to all his works. For example, al-Bīrūnī found it possible to have a void outside the last orb, which is in clear contrast to the Aristotelian philosophy (Hullmeine 2019, p.130). This non-Aristotelian tendency is more notable in the long correspondence between al-Bīrūnī and Avicenna (*Al-As'ilah wa-l-Ajwibah*), where al-Bīrūnī poses some serious reservations about the Aristotelian foundations. Among all eighteen questions exchanged between al-Bīrūnī and Avicenna, the first eight directly present tensions over Aristotelian natural philosophy. In particular, al-Bīrūnī raised doubts about the Aristotelian reasons for the 'levity or density' of celestial orbs (Nasr 2010, p.73). Of course, al-Bīrūnī could not reject Aristotelian philosophy altogether, but broached intellectual reservations in order to highlight the importance of empirical over a priori knowledge. In one critical part of this correspondence (question three of eighteen), al-Bīrūnī asked Avicenna about the theoretical reasons [provided by Aristotle] behind having only six directions in space, although, for example, we can imagine twenty-seven cubes around a three-dimensional object. This question turns out to be more serious when he extended the dimensions to the spherical shapes[10], where there are no specific directions at all (Nasr 2010, p.85). Avicenna (980-1037), a great Aristotelian scientist and philosopher, responded by restating basic Aristotelian rules he had learned from *Physics (Kitāb al-Samā' al-Ṭabī'ī)*. However, his real answer lies in the realization of a sphere (*kurah*) as an object. According to Avicenna, as long as a sphere is an object, it has length, width and depth and, having two extremes for each side, creates six dimensions (Nasr 2010, p.87). The importance of this exchange is how al-Bīrūnī was able to provoke Avicenna into thinking about a bodily spherical orb and articulate his concept of a celestial orb.

The correspondence between al-Bīrūnī and Avicenna narrowed down when it came to the sixth question. Al-Bīrūnī raised doubts about the spherical shape of celestial orbs. He argued that, according to simple geometrical imagination, if an oval rotates on the major axis and the lenticular rotates on the minor axis, then they may make circular paths in the Ptolemaic models and fill space without creating any void (*makān khāl*), rotating without collision (Nasr 2010, p.99). Then, in an interesting move, al-Bīrūnī compares this movement with the motion of objects in celestial orbs, immediately adding that he is not arguing against the sphericity of celestial orbs, but that this is merely hypothetical speculation. Avicenna, in response to this strong objection, steps back and begins to distance himself from Aristotle by arguing that, on some points, it is required to "adopt philosopher's points to the best available ways" meaning that one should interpret philosophical views to best fit astronomical certainties (Nasr 2010, p.100). However, he did not abandon the sphericity of celestial orbs, for he states that this key point has 'natural and geometrical reasons' behind it. Here, the discussion clearly focuses on the dynamics of orbs. One could legitimately argue that al-Bīrūnī's provocative reservations could not discredit the strong Aristotelian tendency of the time; however, what attracts our attention is how the physical (solid) understanding of an orb as a new conceptual component has gradually articulated the previously less-articulated form of the concept.

5. The rigid concept

Al-Haytham and al-Bīrūnī were members of a dominant branch of Islamic astronomy, who took the lead in articulating astronomical theories and concepts. In general, they added several modifications to the Aristotelian philosophical foundations to fit them with empirical evidence. On the western side of Islamic civilization, however, some philosophers/astronomers were insisting on a purely Aristotelian understanding of celestial models. The Andalusian astronomers, such as al-Biṭrūjī (died c. 1204) and Averroes tried to propose an astronomical model strictly adherent to the Aristotelian foundations (Sabra 1998, p.319). For example, they aimed for astronomical models with orbs rotating around *one* center, which is the center of universe. This radical alternative, though with several innovations, was neglected by the majority of Arab astronomers who claimed against it.

Despite such an orthodox understanding of the Aristotelian foundations, Arab astronomers developed a physical and causally active understanding of celestial orb.[11] The eleventh to the fourteenth century was a critical period where Arab astronomers, implicitly or explicitly, customized philosophical principles associated with the concept to the advantage of their astronomical projects. This long process of concept articulation led to rigid conceptual components, such as *hardness* and *sphericity*. We have categorized some of the conceptual components that were shaped during hot philosophical conflicts.

5.1. Natural motion of orbs

In his first book, *On the Heavens*, Aristotle puts forward an account of natural motion in which *water* and *earth* naturally move downward, *air* and *fire* move upward, and the heavens naturally move circularly about the center (*On the Heavens* I, 2, 268b, p.27–29, Trans. Guthrie 1939). However, in his second book, Aristotle advances another perspective according to which stars enjoy 'life and action' and hence their motions are caused by their free will, like for animals. Wolfson (1962, p.72–75) explains how commentators of Aristotle used this opportunity to attribute free-will motion to celestial orbs. In particular, Avicenna attributes a soul to each celestial orb and assumed animated motion for them (2000, p.617). He argued that circular motion cannot be conceived as natural, because it does not have any destination and the object moves with no rest.

5.2. Uniform motion of orbs

Aristotle explicitly asserted that orbs and planets move in a uniform circular path with no 'acceleration', 'retardation' or 'irregular motion' (*On the Heavens* II, 6, Trans. Guthrie 1939). This philosophical axiom created significant issues for later astronomical projects, because actual observation opposes it. In fact, Ibn al-Haytham and members of the Marāgha school opposed Ptolemy for assuming non-uniform motion of deferent orbs. They called it the 'equant problem'. Although Ibn al-Haytham, in his critical treatise, claimed that the physical models in *Planetary Hypothesis* are not consistent with this axiom, he did not propose an alternative for these models (1990, p.24). Later, members of the Marāgha school proposed new physico-geometrical models, including orbs exhibiting uniform motion, while keeping the equant point, which was observationally necessary.

5.3. Centers of orbs

As stated, Aristotle assumed that celestial motions are around the center of the universe; however, this axiom could not be upheld by any satisfactory planetary model. Surprisingly, many authors of *hay'a* books in the Islamic age endorsed this axiom in their introductory chapters but, when proposing their models, neglected it altogether and used epicycles and deferent (al-Haytham 1990, p.10; [al-Tūsi's manuscript translated in:] Ragep 1993, p.101). Only a few Arab astronomers carefully embraced this conflict and attempted to fix it[12]. Al-Shīrāzī (1236–1311), for example, explicitly mentioned in his introductory chapter that orbs are moved by their souls, meaning that they use 'free will' to 'rotate uniformly around their own centers' (al-Shīrāzī, §15).

5.4. Sphericity of orbs

The sphericity of an orb is not only philosophical (for the a priori advantages of a round shape), but conceptual, because non-spherical spheres are (logically) contradictory. In fact, when one orb moves within another that has a different center, the former will create crescent shapes above and below the latter (Figure 2). Nonetheless Arab astronomers neglected this conflict and assumed eccentric orbs.

5.5. Hardness of orbs

Aristotle's verdict on the qualities of orbs is open to interpretation. While the heavens are composed of aether, which is free from terrestrial qualities such as hard/soft and hot/cold, there is clear evidence that Aristotle perceived aether to be corporeal and physical (*On the Heavens* II, 12, Trans. Guthrie 1939). These points appear to be contradictory, for one rejects the physicality of orbs and the other signifies its physical nature. Regarding this complication, early Arab astronomers remained mostly silent while implicitly assuming the quality of *hardness* for their postulated physical orbs. This is because they did not seek to distance themselves from the Aristotelian philosophy by attributing a single quality to orbs, but the hardness of orbs was an important consequence of their explicit beliefs. We need to explore this critical conceptual property, because it plays a central role in the abandonment of the concept.

Let's begin with the notion of 'tearing and mending' [*khargh wa iltiyām*]. Avicenna argues that an object with a circular motion, meaning orbs, would not find any acceleration in their speed, for change of speed is the property of objects in the linear move. Since orbs move only circular, they cannot undergo any 'tearing or mending' (Avicenna 1984 [1026], p.26). It seems that an object with no tearing and mending is to be *hard*. The philosophical justification for the link between the motion of orbs and their natural hardness seems missing, but the connection between 'tearing and mending' and the hardness of orbs is more than clear. Avicenna continues by arguing that orbs are not 'humid or dry' [*raṭb wa yābis*] by means of getting ripped easily or laboriously (1984 [1026]). According to this text, Avicenna is implicitly endorsing the hardness of orbs, but it is important to note that he is more of a philosopher than an astronomer.[13] This text, in particular, is stated in a philosophical context using an Aristotelian foundation. We will show how such an understanding is taken by later astronomers.

Around two centuries later, in the introduction of *al-Tadhkirah*, al-Tūsī argues for the same nature of orbs, but this time in an astronomical context. He claims that objects with the circular motion do not undergo any kind of change, including no 'tear or mend', 'grow nor diminish' and 'expand nor contract' (Ragep 1993, p.100). Here again the motion and nature of orbs are linked together, but al-Tūsī is straightforward in assuming a hard nature for the orbs. Ragep (2001) argues that al-Tūsī is among few Arab astronomers who believed that 'certain physical and metaphysical principles need to be imported from natural philosophy' (p.57). This means that the transformation of orbs' hardness from the philosophical context to the astronomical context makes sense for him. The same kind of argument, relating the nature of orbs to their motion, can be found in Avicenna's responses to al-Bīrūnī (Nasr 2010). Later astronomers of the Marāgha School, such as al-Shīrāzī, were hesitant about the relation between philosophy and astronomy, but took this conceptual component of orbs for granted.

6. Abandoning the concept

So far, we have argued that since the early eleventh century the concept of orb was gradually articulated. The concept orb was developed consequently to fit into a physical model of the universe where celestial objects move in accordance with the rule of cause and effect. In other words, hard orbs are firmly attached to the planets causing them to move in the same direction and at the same speed of themselves. Astronomers of the Marāgha School, in particular, were clearly recognizing the physical and geometrical aspects of the concept orb. For them, the hard orbs were real objects of the external world that actively contribute to the motion of heavenly objects. The same concept was borrowed by the Middle age astronomers of the Western culture. Roughly the same understanding of orbs remained the key astronomical concept at least until the sixteenth century. Indeed, the physical interpretations of orbs frequently appear in al-Haytham's works identically transferred to Georg Peuerbach's (1423-1461) treatises, and were certainly available to Copernicus and Kepler (Hartner 1955, p.122; Swerdlow 1976, p.425).

There is a common consensus among historians of science that it was Tycho Brahe (1546–1601) or some of his fellow astronomers such as Christoph Rothmann (1560–1600) who first initiated the dissolution of the celestial spheres. Among Brahe's prominent astronomical observations, he observed a comet in 1577 moving across the sky through the assumed orbs. More importantly, he measured the precise distance of Mars to earth during its period relation and realized that this planet can be closer or more distant than the sun to the earth. These crucial observations imply that the comet and Mars can tear and mend the previously assumed hard orb of the sun. Brahe then concluded that "these orbs do not exist corporeally in heaven" (cited by Rosen 1985, p. 19). Although it is almost certain that he borrowed the idea of the elimination of 'solid', 'crystalline' and 'impenetrable' orbs from his fellow Christoph Rothmann in 1585–6 (Rosen 1985; Lerner 1996; Granada 2006), what is important for us is that by the end of the sixteenth century some great astronomers[14] had endorsed the *dissolution* of the spherical orbs altogether. Brahe was more prominent than the others, probably because of his accurate and precise astronomical measurements; however, his provocative claim required further endorsement. The attribution and distribution of Brahe's claim have been accredited by the authority of Johannes Kepler (1571–1630) in his 1618 book, *Epitome*

Astronomiae Copernicanae: “Tycho eliminated solid orbs” (cited by Granada 2006, p.125).

In addition to his endorsement, Kepler realized that it is hardly possible to explain his laws of planetary motion by employing spherical orbs. In the absence of a well-defined physico-geometrical concept that plays the causal role in planetary models, concepts such as Kepler’s *Sun-Rays* or Descartes’ *Flux* were not adequate to fill the gap. Nevertheless, the advent of these novel concepts should be seen as the beginning of a major case of *conceptual change*. Kepler described his project as “the unexpected transfer of the whole of astronomy from fictitious circles to natural causes, which were the most profound to investigate, difficult to explain, and difficult to calculate, since mine was the first attempt” (cited by Gingerich 1973, p.304).

What we have from the history of the scientific concept orb owes largely to some major scholars in the late twentieth century including Edward Rosen and Edward Grant. Rosen wisely distinguishes a philosophical and astronomical realm of discourse and argues that for Ptolemy, orbs are not “obstructive, but conducive to permitting each planet’s natural motions and ... Hence, all the bodies can penetrate and shine through absolutely all the fluid media” (cited in Rosen 1985, p.15). This astronomical reasoning, according to Rosen, has less definite indication. In other words, Aristotle was less sharp in specifying the qualities of heavenly objects. But in the second part of his paper, Rosen jumps from Greek astronomy to the late sixteenth century where the idea of ‘hard sphere(s) was drummed into the head of Tycho Brahe’ (p.19). This long jump, which is not restricted only to Rosen’s works, reflects how the Islamic age of science and even the Middle Ages of the European astronomy where the Greek astronomy flourished were neglected. The interesting part is that Brahe’s explicit mention of al-Haytham (Alhazen) and Witelo is simply neglected or poorly addressed. Hartner (1955) argues that during the Middle Ages Alhazen’s (Ibn al-Haytham’s) writings had an ‘enormous reputation’ and ‘the dependency of early Renaissance astronomers’ on his writings ‘is beyond doubt’ (p.124). Rosen admits that Brahe had access to a book including Ibn al-Haytham’s *Optics* as well as Witelo’s *Perspectiva*, but he holds that Brahe ‘erroneously imputed’ or ‘misattributed’ the hardness of orbs to them (p.22). Then, he keeps investigating what happened in the late sixteenth century and comes up with the idea that ‘Rothmann, rather than, Brahe, is to be credited with dissolving the solid celestial spheres’ (p.31). In other words, Rosen resolves a puzzle with the pieces of another.

Edward Grant wrote more about this issue, with even less theoretical wisdom (1987; 1994). In his first paper on the subject matter, the focus is on the Latin Middle Ages’ theologians, rather than astronomers or philosophers with more natural tendencies in their studies. His rationale for focusing on theologians is the ‘profound inter-relationship’ between Greek thought and Christianity. This made him persuaded to strongly link the scientific concept of celestial orbs to the concept of heavens employed in the holy texts (1987, p.159). His thorough study of the relationship between the sacred texts and the theologians of the Middle Ages, including Vincent of Beauvais (1184–1264), Thomas Aquinas (1225–1274), Henry of Hesse (1244–1308), and Nicole Oresme (1325–1382), clearly shows that the concept orb should be interpreted as fluid, and the hardness is implicitly or explicitly rejected. The reason is that the holy texts refer to the heavens as the ‘aqueous’, ‘crystalline’ or ‘airy’ (1987, p. 159–161). When he discusses the John of Sacrobosco (1195–1256), which is a prominent astronomer of the Middle Ages, he adds another text from Michael Scot (1175–1232), the scholar famous for his translation of the Aristotelian philosophy and Averroes’s, to prove his intention. Likewise, in the case of Campanus of Novara (1220–1296), the Italian astronomer who mentions the incorruptibility of the heavens, Grant is not sharp enough in his claim: "Nowhere, however, does [he] associate[s] solidity or hardness with the term" (1987, p.167). Grant gives less attention to the central mathematicians such as Georg von Peuerbach (1423–1461) and Regiomontanus (1436–1476), who were both under the influence of ibn al-Haytham. While the hardness of orbs is clear at least in Peuerbach's and al-Haytham's works, Grants claims that "I have examined both treatises and have found only the usual silence on the issue of hardness or softness" (1987, p.173). The reason he could not find the hardness in those treatises and more importantly during the whole Islamic works, we think, is that he simply looked for an exact term 'hardness'; instead of engaging with the texts and the consequence of each term in the whole cosmological worldview.

In fact, the stance of main Middle Age astronomers and more importantly Islamic age astronomers is clear on the hardness of orbs. Contrary to Grant who thinks that the hardness of orbs was unknown until Copernicus, Swerdlow (1976) argues that Copernicus 'like every other astronomer of his time, envisioned planetary models to be composed of nonintersecting, rigid sphere' and this understanding of orbs was introduced to the western astronomers through the translations of ibn Haytham's *On the Shape of the Universe* (p.108, p.117). In fact, the treatise of ibn al-Haytham was widely translated and distributed among western astronomers. On the other hand, Grant is right that philosophers, theologians and probably some astronomers of the Middle Ages who were influenced by the biblical texts and the translation of Aristotle and Averroes considered orbs as solid and fluid substances (which may sound contradictory). But what Grant is missing is the distinction between astronomers, philosophers, and theologians' understanding of key scientific concepts.

In his later book, Grant (1994) presents more details of his claim. In this book, Grant considers more figures and texts and comes up with a developed idea. He cites Giovanni Riccioli's (1598–1671) quote in which the ideas of 'solid' and 'fluid' orbs are compared, concluding that "it is much more probable that the heaven of the fixed stars is solid" (cited by Grant 1994, p.264). Later he implicitly distinguishes the theological and astronomical understandings of heavens and orbs. Some key characteristics of orbs are attributed to the 'secular and astronomical context, having no connection with theology' (Grant 1994, p.322). However, Grant still holds his previous stance with few references to the key Islamic astronomers such as ibn al-Haytham or al-Tūsī. When it comes to the hardness of orbs, Grant re-writes what he claimed in his (1987) paper: "Although terms like 'crystalline' and 'icy solidity' seem to imply hardness, they could be interpreted otherwise" (p.333). He returns to the accounts of Vincent of Beauvais, Saint Augustine, Saint Bonaventure, Saint Basil and other theologians with regards to their understandings of the holy firmament and heavenly objects. While in the first paper, he claimed that the hardness of orbs appeared somewhere between Copernicus and Brahe, here he softens the claim and admits that at least after the thirteenth century the hard orbs 'emerged as an opposition hypothesis' (p.338). Yet, he insists that it is only after Tycho's assertion that 'the firm connection' between the solidity and hardness of orbs was made (p.347).

Contrary to Grant, our phylogenetic study shows that abandoning the concept orb was not due to an unsupported conceptual mistake of Brahe or his contemporaries. The concept was articulated and, based on the major components mentioned above, including the hardness of orbs (§5,5), transferred to the European culture. We believe that we have provided enough reasons to show that Brahe did not pull the idea out of his hat. In fact, there is evidence showing that in January 1587 Brahe wrote a letter to Rothmann and admitted that for Alhazen (Ibn al-Haytham) and Witelo the heavens are solid (Goldstein and Barker 1995, p.395). It seems that the hardness of orbs was a common idea for Rothmann and Brahe, but a mention to Alhazen and Witelo reminds us that there should be a deeper root in the history of the concept of orb. Our approach to the history of the concept made it clear that some semantic components were rigidified during the Islamic age. We believe that no problematic conceptualization did occur in the sixteenth century, but the concept was articulated earlier by Arab astronomers.

7. Conclusion

A phylogenetic approach to scientific concepts makes it possible to give a rational explanation of the introduction, change and dissolution of a concept. In this paper, we studied the concept orb focusing on its birth in ancient Greek and its articulation in the Islamic age. The point we draw from this long history was how the concept was articulated and rigidified in the Islamic age, which ultimately led to its dissolution. We argued that for Greek astronomers and philosophers the concept was semantically ambiguous since there was no consistent semantic use. This we explained by a lack of distinction between the physical and geometrical understandings of the concept. This concept of ambiguity was articulated by Arab astronomers in the Islamic age of astronomy between the tenth to the fourteenth century. In this period, some conceptual components such as the sphericity and hardness of orbs centralized in conceptual understandings. This implies that concept identity is strictly tied to the preservation of these conceptual components. Missing this key historical insight has led some scholars to think that Tycho Brahe abandoned the concept based on a conceptual misunderstanding. We have argued that Tycho Brahe and his fellow astronomers correctly borrowed the articulated concept from Arab astronomers and abandoned the concept exactly because of this conceptual misconduct. In fact, the development of astronomy in the Islamic age led Arab astronomers to articulate the concept of orb in a way that ultimately marked its dissolution.

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Notes

[1]Lennox (2013) defines conceptual change as consisting both the introduction and rejection of a concept (p.113–114).

[2]By "Arab astronomers" we mean the astronomers who wrote in Arabic originated from various ethnos and cultures lived in Islamicate societies between the ninth to fifteenth centuries.

[3]Among their mathematical techniques is the well-known linear zigzag function, where the maximum and minimum amounts of a variable return to its value after a constant period of time. Recent archeological research shows that, in his tablet XIV, Enuma Anu Enlil calculated the ideal time for the lunar month as being 30 days.

[4]Kahn (1960, 56) mentions a similar point about the word στρογγυλός (round) that can be understood as a sphere or a flat disk.

[5]The earth is suspended, supported by nothing, and stays where it is because it maintains an equal distance from everything (Graham 2010, 57).

[6]Some historians argue against this attribution because planetary anomalies were not known before the second century BC (Knorr 1990). However, what is important for us is that, by the second century AD, it was accepted as a research agenda by some major astronomers and scientists in Greece.

[7]Based on the above narration of the phylogeny of the concept of sphere, Ptolemy's use of 'ancestor' probably refers to astronomers in the third or second century BC.

[8]There is a hot dispute among historians of science whether Greek astronomers were instrumentalists or realists. Among the famous proponents of the former is Duhem (1954) who interpreted Ptolemy and Geminos, among others, as trying merely to *save* the phenomena. Lloyd (1978) argued that Duhem's strong claim is based on misinterpretations of the evidence, but it is clear that, at least for some earlier Greek astronomers, saving the phenomena was the aim.

[9]This attribution applies only to the authors of an astronomical genre called *hay"at al-aflāk* (the configuration of orbs). This genre was later standardized by Naṣīr al-Dīn Ṭūsī (1201–1274) in the thirteenth century.

[10]It is important to bear in mind the difference between sphere as a geometrical shape (*kurah*) and the celestial orb as the physical concept in Greek and Islamic astronomy (*falak*). Here, the discussion is about the former, but it has clear consequences for the latter and both of them were aware of this.

[11]Naṣīr al-Dīn al-Tūsī, a major astronomer and philosopher of the 13^{th} century, explicitly endorses the reality of spheres in *al-Tdhkira fī al-Hay'a* (*Memoire in the Science of Configuration of Orbs*) (1990, p.67).

[12]Contrary to eastern Muslims who tended to resolve these issues in favor of their astronomical aims, western Muslims like al-Biṭrūjī and Ibn-Rushd tried to keep up with Aristotelian foundations.

[13]Ibn al-Haytham describes this property by explaining that orbs do not accept 'passivity' [*infial*]. By denying this property, al-Haytham means that orbs do not easily tear or mend, which became an orthodox notion across the Islamic science and philosophy.

[14]Granada (2006, p.126) provides a list of at least five scholars who more or less rejected the existence of celestial spheres by the end of the sixteenth century.