The Birth of Scientific Controversies, The Dynamics of the Arabic Tradition and its Impact on the Development of Science: Ibn al-Haytham's Challenge of Ptolemy's *Almagest*

Hassan Tahiri

و الواجب على الناظر في كتب العلوم، إذا كان غرضه معرفة الحقائق،
أن يجعل نفسه خصما لكل ما ينظر فيه، و يجيل فكره في متنه و في جميع حواشيه،
ويخصمه من جميع جهاته و نواحيه، و يتهم أيضا نفسه عند خصامه فلا يتحامل عليه و لا يتسمح فيه.
فإنه إذا سلك هذه الطّريقة انكشفت له الحقائق، و ظهر ما عساه وقع في كلام من تقدّمه من التّقصير و الشّبه.

Al Ḥasan ibn al-Haytham
(*Al-Shukūk ʿala Batlamyūs*, p. 4)[1]

Abstract The so-called Copernican revolution is Kuhn's most cherished example in his conception of the non-cumulative development of science. Indeed, in his view not only has the Copernican model introduced a major discontinuity in the history of science but the new paradigm and the old paradigm are incommensurable, i.e. the gap between the two models is so huge that the changes introduced in the new model cannot be understood in terms of the concepts of the old one. The aim of this chapter is to show on the contrary that the study of the Arabic tradition can bridge the gap assumed by Kuhn as a historical fact precisely in the case of Copernicus. The changes involved in the work of Copernicus arise, in our view, as a result of interweaving epistemological and mathematical controversies in the Arabic tradition which challenged the Ptolemaic model. Our main case study is the work of Ibn al-Haytham who devotes a whole book to the task of refuting the implications of the *Almagest* machinery. Ibn al-Haytham's *al-Shukūk* had such an impact that since its disclosure the *Almagest* stopped being seen as the suitable model of the heavenly bodies. Numerous attempts have been made to find new alternative models based on the correct principles of physics following the strong appeal launched by both Ibn al-Haytham and, after him, Ibn Rushd. The work of Ibn al-Shāṭir, based exclusively on the concept of uniform circular motion, represents the climax of the intense

---

H. Tahiri
Université de Lille 3, MSH Nord Pas-d-Calais
e-mail: hassan.tahiri@yahoo.fr

S. Rahman et al. (eds.), *The Unity of Science in the Arabic Tradition*,

theoretical research undertaken during the thirteenth and the fourteenth centuries by the Marāgha School (which owes its name to the observatory of Marāgha in north-western Iran). The connection point, in our view, between the works of Ibn al-Haytham and Ibn al-Shāṭir is that while the *al-Shukūk* gives the elements to build a countermodel to the *Almagest,* the work of Ibn al-Shāṭir offers a model which takes care of the objections triggered by the work of Ibn al-Haytham. Furthermore, not only has the basic identity of the models of Ibn al-Shāṭir and Copernicus been established by recent researches, but it was also found out that Copernicus used the very same mathematical apparatus which was developed by the Marāgha School over at least two centuries. Striking is the fact that Copernicus uses without proof mathematical results already geometrically proven by the Marāgha School three centuries before. Our paper will show that Copernicus was in fact working under the influence of the two streams of the Arabic tradition: the well known more philosophical western stream, known as physical realism, and the newly discovered eastern mathematical stream. The first relates to the idea that astronomy must be based on physics and that physics is about the real nature of things. The second relates to the use of mathematics in the construction of models and countermodels in astronomy as developed by the Marāgha School. The case presented challenges the role of the Arabic tradition assigned by the standard interpretation of the history of science and more generally presents a first step towards a reconsideration of the thesis of discontinuity in the history of science. Our view is that major changes in the development of science might sometimes be non-cumulative, though this is not a case against continuity understood as the result of a constant interweaving of a net of controversies inside and beyond science itself.

1 The Problematic Assessment of the Arabic-Islamic Tradition

No scientific and philosophical tradition has raised such passion and so many heated debates among historians of science than the Arabic-Islamic tradition. The disagreement begins first with the problem of how to label the tradition adequately. Some prefer to call it the Arabic tradition because of the overwhelming dominance of the Arabic language used in scientific and philosophical writings. Others are more inclined to qualify the tradition as Islamic since the majority of those who contribute to the development of science and philosophy are non-Arabs. But this is not the dividing issue. It should be noted though that for the Arabs themselves this is not an issue, and they happily agree to use the more inclusive expression *Arabic-Islamic tradition*. The latter term includes Arabs (whether Moslems, Christians, Jews, Sabeens, and so on), Moslems (Persians, Asians, and so forth), and any other writer who works under the direct influence of Arabic-Islamic thought. For the sake of convenience, Arabic and Islamic are considered in the present paper as interchangeable qualifications. A far more serious question is the assessment of this vast heritage. The never-ending point of controversy is: what is the real contribution of the Arabic tradition in the development of science?

This question sharply divides historians of science into two disjoint classes of historians; the latter one is a recent stream which proposes a new perspective in relation to the role of the Arabic tradition. For the sake convenience, let us give them the two following labels: the *Non-Innovationists* and the *Innovationists* (with regard to the contribution of the Arabic tradition).

1.1 The Non-Innovationists

The underlying methodology of the Non-Innovationists is to try to determine to what extent the resulting novelties, if any, contribute to the emergence of modern science. The conclusion is almost always the same.

Let us begin with the assessment of Arthur Koestler; in his popular and widespread *The Sleepwalkers,* he writes

> But the Arabs had merely been the go-betweens, preservers and transmitters of the heritage. They had little scientific originality and creativeness of their own. During the centuries when they were the sole keepers of the treasure, they did little to put it to use. They improved on calendrical astronomy and made excellent planetary tables; they elaborated both the Aristotelian and the Ptolemaic models of the universe; they imported into Europe the Indian system of numerals based on the symbol zero, the sine function, and the use of algebraic methods, but they did not advance theoretical science (Koestler 1968, p. 105).

Furthermore:

> From the twelfth century onwards, the works, or fragments of works, of Archimedes and Hero of Alexandria, of Euclid, Aristotle, and Ptolemy, came into Christendom like pieces of phosphorescent flotsam. How devious this process of Europe's recovery of its own past heritage was, may be gathered from the fact that some of Aristotle's scientific treatises, including his *Physics*, had been translated from the original Greek into Syriac, from Syriac into Arabic, from Arabic into Hebrew, and finally from Hebrew into medieval Latin. Ptolemy's *Almagest* was known in various Arab translation throughout the Empire of Harun Al Rashid, from the Indus to the Ebro, before Gerardus of Cremona, in 1175, retranslated it from the Arabic into Latin. Euclid's *Elements* were rediscovered for Europe by an English monk, Adelard of Bath, who around 1120, came across an Arabic translation in Cordova (ibid., p. 104–105).

For Koestler, then, the Arabs have added nothing new, their role is simply limited to bringing the Greek scientific and philosophical tradition from the East to the West. In the same spirit we find the following remark:

> Insofar as science is concerned, the first six hundred years of established Christendom were a glacial period with only the pale moon of Neo-Platonism reflected on the icy steppes. The thaw came not by the sudden rise of the sun, but by ways of devious Gulf-stream which wended its way from the Arab peninsula through Mesopotamia, Egypt and Spain: the Moslems. In the seventh and eighth centuries, this stream had picked up the wreckage of Greek science and philosophy in Asia Minor and in Alexandria, and carried in a circumambient and haphazard fashion into Europe (ibid., p. 104).

This and the following are the only passages where the Arabs are mentioned in the work of Koestler. John Dreyer, who at least took care to consult some original sources, devoted more space (one whole chapter) in his *History of the Planetary Systems from Thales to Kepler*[2] to the contribution of the Arabic tradition to the development of astronomy. However, his final verdict is not very different from Koestler's:

> In this rapid view of Arabian astronomers we have only mentioned those whose work we shall have to allude to in the following pages […]. It cannot be denied that they left astronomy pretty much as they found it. They determined several important constants anew, but they did not make a single improvement in the planetary theories (Dreyer 1953, p. 248–249).
>
> Enough has been said to show that when Europeans again began to occupy themselves with science they found astronomy practically in the same state in which Ptolemy had left it in the second century (ibid., p. 279–280).

François Nau reviews the work of Bar Hebraeus and his Arab colleagues of the thirteenth century in the same non-innovationist spirit as the authors mentioned above:

> A l'époque où écrivait Bar Hebraeus, les Arabes s'occupaient d'astronomie depuis près de quatre siècles et notre auteur cite un certain nombre de leurs résultats ; mais ces résultats semblent peu importants ; les auteurs arabes que nous connaissons furent surtout des commentateurs et des astrologues amateurs, on ne les a admirés que faute de connaître les œuvres grecques, leurs modèles. On peut donc considérer le présent *Cours d'astronomie* comme un résumé des œuvres de Ptolémée (avec quelques *adjuncta* dus aux Arabes) (Hebraeus 1899, p. xiv).

Among the Non-Innovationists we even find Thomas Kuhn. Indeed, in his *The Copernican Revolution*, Thomas Kuhn clearly sums up the received view of the contribution of the Islamic tradition:

> The Moslems were seldom radical innovators in scientific theory. Their astronomy, in particular, developed almost exclusively within the technical and the cosmological tradition established in classical antiquity. Therefore, from our present restricted viewpoint, Islamic civilisation is important primarily because it preserved and proliferated the records of ancient Greek science for later European scholars (Kuhn 1957, p. 101).

1.2 The Innovationists

The Innovationists have a more positive view with regard to the contribution of the Arabic tradition. Roshdi Rashed, one of the most eminent members of the group of Innovationists, vehemently opposes the received view and especially the Non-Innovationists' account of the evolution of astronomy.

> Following in the wake of the western doctrine of classical science, he [the historian of science] can view Arabic science as a repository of Hellenic science, a belated Hellenic science as it were … According to this doctrine Arabic science constitutes an excavation site, in which the historian is the archaeologist on the track of Hellenism (Rashed and Morelon 1996, p. x).

Régis Morelon points out that there is a discontinuity in the transmission of the Greek tradition since the composition of the *Almagest* in the second century B.C. Moreover he remarks that the translation of the Greek astronomical writings is not sufficient by itself to establish a genuine, efficient and lasting tradition in the practice of astronomy.

> Cette discipline [i.e. astronomy] n'était plus vivante dans le bassin méditerranéen depuis plusieurs siècles: il n'y a que quelques observations isolées qui aient été enregistrées entre le IIIe et le VIIIe siècle, et les successeurs de Ptolémée ne furent globalement que des commentateurs. Il y avait donc discontinuité dans une tradition. Lorsqu'il s'est agi de la revivifier à Bagdad sous al-Ma'mūn (813–833), les sources écrites de travail étaient évidemment hellénistiques, mais il a fallu retrouver quelle bases et quelles méthodes convenaient pour cette discipline, donc de les recréer (Morelon 2000, p. 104).

One of the main features of the Arabic astronomical tradition, according to Morelon, is the institution of a research programme which can be summed up in the three following points: (i) the importance given to the role of observation which manifests itself in the construction of many observatories. The aim of observatories is to permit the continuous collection of empirical data; (ii) the increasing application of the mathematical apparatus to astronomy due to the development of spherical astronomy; (iii) the sustained conflict between "astronomical physics" (i.e. the research for a physical representation of the universe) and "astronomical mathematics" (dealing with the calculation of the position of the planets).

The studies of Rashed and Morelon strongly suggest that the role of the Arabic tradition is far from being a mere imitation of the Greek tradition. More generally, the Innovationists complain that, in the received view, the Arabic tradition is never examined for its own sake but always in relation to the Greek tradition and as an appendix to the history of Greek science and philosophy. The result is then the expected one: to reduce the role of the Arabic tradition to that of a mere intermediary or transmitter of the Greek heritage. Moreover, it seems that the Non-Innovationists have a peculiar view of the discontinuity of the history of science, which in their view begins with the work of Copernicus. Rashed rejects what he calls the "oblique view of an historical ideology which views classical science as the achievement of European humanity alone" (ibid., p. xii).

But the Non-Innovationists might fight back and take the historical sources as irrelevant for their main argument. The point is not, of course, to compare the results of the Arabic tradition and those of the seventeenth century. The question is rather: why has Arabic astronomy failed to live up to its promises? In other words, the comparison must be between the kind of activities undertaken by the Arabic and medieval European traditions; the latter is rich and profound since it leads to the Copernican revolution, while the former leads nowhere besides the achievements of the Greek science. More generally, the underlying idea is that major achievements of the Renaissance are intrinsically linked to the medieval European tradition and ultimately to the Greek heritage. According to the Non-Innovationists, things suddenly and radically changed when the Europeans of the Middle Ages became acquainted with the Greek works. Koestler claims for example that

> With Euclid, Aristotle, Archimedes, Ptolemy and Galen recovered, science could start again where it had left off a millennium earlier (Koestler 1968, p. 105).

Koestler adds: "As soon as it was reincorporated into Latin civilization, it bore immediate and abundant fruit" (ibid.). And without the slightest hesitation, he concludes: “The heritage of Greece was obviously of no benefit to anybody without some specific receptiveness for it” (ibid.). Carra de Vaux, another Non-Innovationist, finds sharper words to qualify the contribution of the Arabic tradition. Carra de Vaux undertook the translation, at the end of the nineteenth century, of what appears to be the most original chapter of al-Ṭūsī’s *Tadhkira* (or *Memoir of Astronomy*). The purpose of the translator is very clear: to explicitly refute the following statement made by an Arab biobibliographer (quoted by de Vaux): “N. E. Attūsī met le sceau à l’interprétation de l’*Almageste*, mais il est si bref et il ajoute des gloses si profondes que les esprits les plus perspicaces en restent étonnés” (Carra de Vaux 1893, p. 341). The translated chapter, included as an appendix in Paul Tannery’s extremely influential historical book *Recherches sur l’histoire de l’astronomie ancienne*, is preceded by an introduction in which de Vaux gives this overall assessment:

> Le chapitre dont nous allons donner la traduction suffira peut-être à faire sentir ce que la science musulmane avait de faiblesse, de mesquinerie, quand elle voulait être originale. N. E. Attūsī est un des hommes qui l’ont le plus illustrée (Carra de Vaux 1893, p. 338).

And why this lack of originality? “Elle [Arabic science] a manqué d’un élément non moins nécessaire que la liberté : la force du génie” (ibid.). It looks as if there is something intrinsic to Arabic-Islamic thought which makes it incapable of any creativity. “Le génie” is not something that can be shared by all human beings or that can be acquired, through hard labour, by human nature, it is endowed to only one restricted class of human beings; that is why western science will never leave its natural soil since it is the making of the Europeans and will remain so. And de Vaux presents his translation as objective evidence of his claim since he concludes

> La portée de ce chapitre n’est donc pas très grande; il mérite néanmoins d’être lu à titre de curiosité. […] Arrivé à ce point, nous n’avons plus à intervenir ni comme historien ni comme critique ; nous nous faisons simple interprète, et nous souhaitons d’être fidèle (ibid., p. 347).

Kuhn further explains how the indirect discovery of the Greek heritage through third languages gave the medieval Europeans a strong desire to go back to the authentic texts:

> Peuerbach, for example, began his career in astronomy by working from second-hand translations of the *Almagest* transmitted via Islam. From them he was able to reconstruct a more adequate and complete account of Ptolemy’s system than any known before. But his work only convinced him that a truly adequate astronomy could not be derived from Arabic sources. Astronomers, he felt, would have to work from Greek originals, and he was about to depart for Italy to examine manuscripts available there when he died in 1461 (Kuhn 1957, p. 125).

The cultural and social conditions are then favourable for a man with a mission to make his appearance:

> Copernicus is among that small group of Europeans who first revived the full Hellenistic tradition of technical mathematical astronomy which in antiquity had culminated in the work of Ptolemy. […] With Copernicus we return for the first time to the sort of technical astronomical problem (ibid., p. 135).

Faced with what the Non-Innovationists declare as being hard evidence, the Innovationists seem to be more on the defensive, seeming to have no choice but to accept the conclusions of their opponents. After expressing, like the previous historians, his astonishment as to the lack of creativity in the Arabic tradition, Koestler asserts that the problem is no longer of philosophical or epistemological consideration but of the history of civilisations and closes herewith any further discussion on the issue.

> It is a curious fact that the Arab-Judaic tenure of this vast body of knowledge, which lasted two or three centuries, remained barren. […] How this readiness to rediscover its own past, and be fertilized by it as it were, arose in Europe is a question that belongs to the field of general history (Koestler 1968, p. 105).

The discovery from 1957 onwards of the writings of a series of astronomers of the Marāgha School of the thirteenth century (which owes its name to the observatory of Marāgha in north-western Iran) dramatically changes the situation of the dispute between Innovationists and Non-Innovationists. George Saliba, one of the scholars who studies these works closely, describes the sensation caused by the discovery:

> Research conducted in the History of Arabic astronomy, within the last three decades, has brought to light a group of texts, that were hitherto unknown, and which radically altered our conception of the originality and scope of Arabic astronomy. The works of astronomers such as Mu'ayyad al-Dīn al-ʿUrḍī (d. 1266), Naṣīr al-Dīn al-Ṭūsī (d. 1274), Quṭb al-Dīn al-Shīrāzī (d. 1311), and Ibn al-Shāṭir (d. 1375), to name just a few were barely known in the nineteenth century or in the early part of the present [twentieth] century. Only Ṭūsī was mentioned in nineteenth-century literature (Saliba 1996, p. 245).

The work of the Marāgha astronomers was motivated by the same aim: to find alternative models to the Ptolemaic system. Their results have far-reaching consequences on our understanding of the history of astronomy.

> First, the Marāgha results were, from the very beginning, deemed extremely important on account of their relationship to the works of Copernicus. But one should say that this relationship did not touch upon the Copernican notion of heliocentricity. That feature of Copernican astronomy entails the transformation of geocentric mathematical models into heliocentric ones by the reversal of the vector connecting the sun to the earth, while leaving the rest of the mathematical models intact. It is rather the similarity of the Copernican geocentric versions of those models to those of the Marāgha astronomers that invited curiosity (ibid., pp. 265–267).

The sensation in these new findings is not so much the identity of the Copernicus models with those developed by the Marāgha astronomers three centuries earlier, since it is perfectly conceivable that Copernicus could have developed his own models independently. The existing links between Copernicus and the Marāgha School became more and more evident when it was found that Copernicus used the same technical apparatus as that developed by the Arabic astronomers during the thirteenth and fourteenth centuries (for more detail see Saliba 1996, p. 269). Moreover, Saliba explains what is at stake on the historical level as far as the development of astronomy is concerned.

> What is clear is that the equivalent model of Ibn al-Shāṭir seems to have a well established history within the results reached by earlier Muslim astronomers, and could therefore be historically explained as a natural and gradual development that had started some three centuries earlier. The same could not be said of the Copernican model (Saliba 1994, p. 304; also Saliba 1996, p. 113).

And he concludes that Copernican astronomy cannot be very well understood, on the mathematical and technical level, without careful study of the achievements of the earlier Marāgha astronomers. This explains why de Vaux failed to understand the originality of the translated chapter in which al-Ṭūsī proves an important theorem, establishing the generation of rectilinear motion from two circular motions, which is then systematically used by his successors including Copernicus. The time is now ready for the historians of science and its evolution through successive civilisations to step in to respond to Koestler's invitation. The distinguished historian Otto Neugebauer, who has closely studied the development of astronomy from its beginning with the Babylonian civilisation up to the Renaissance, has this to say:

> The recovery of the planetary theory of the astronomers of the Marāgha School […] is not only of great interest in itself, but has also demonstrated that much of what had been taken for Copernicus's own planetary theory is actually of medieval Arabic origin, and was transmitted to western Europe by an unknown route, perhaps by way of late Byzantine sources, to Italy at some time in the fifteenth century (Neugebauer and Swerdlow 1984, p. 290).

Neugebauer adds "the question therefore is not whether but when, where, and in what form, he [Copernicus] learned of Marāgha theory" (ibid., p. 47). It looks as if the history of science is about to be rewritten. The status of Copernicus seems to be hanging in the balance more than ever, thus blurring the sharp distinction which he is traditionally associated with. The Non-Innovationists find in the *De Revolutionibus* a clear-cut between the medieval European era and the Renaissance, since it contains some significant results which make his author the starting point of a revolution. According to Kuhn, for example, Copernicus' aim in *De Revolutionibus* is to solve the problem of the planets which he felt Ptolemy and his successors had left unresolved.

> None of the "Ptolemaic" systems which Copernicus knew gave results that quite coincided with good naked-eye observations. They were no worse than Ptolemy's results, but they were also no better. After thirteen centuries of fruitless research a perceptive astronomer might well wonder, as Ptolemy could not have, whether further attempts within the same tradition could conceivably be successful (Kuhn 1957, p. 139).

Furthermore, in Kuhn's view, the nature of Copernicus's revolution is more technical than conceptual in the sense that it is the use of mathematics which distinguishes him from his predecessors:

> In recognizing the need for and in developing these new techniques, Copernicus made his single original contribution to the Revolution that bears his name. […] Copernicus' mathematics distinguishes him from his predecessors, and it was in part because of the mathematics that his work inaugurated a revolution as theirs had not (ibid., p. 143).

Since, as already mentioned, the technical novelties essential to the development of the Copernican system have been shown to have their origin in the Marāgha School, we might say, using Kuhn's own paradigm, that the Copernican revolution is in fact the Marāgha School revolution. Far more significant is the fact that Copernicus appears to be working under the influence of both the traditionally well known Arabic western realist tradition and the newly discovered Arabic eastern tradition. This paper will show in what way the *De Revolutionibus* can be seen as a synthesis of both these traditions. The first relates to the idea that astronomy must be based on physics and that physics is about the real nature of things; the second relates to the use of mathematics in the construction of models and countermodels in astronomy as developed by the Marāgha School.

The availability of the works of the Marāgha astronomers gives more sophisticated ammunition to counterbalance the Non-Innovationists' strong weaponry: hard facts. Armed with these new findings, the Innovationists go on the offensive in the dispute. In the face of this new evidence, it seems that the received view on the periodisation of science, already challenged by Duhem, needs to be revised as suggested by the following statement of Neugebauer: "in a very real sense, Copernicus can be looked upon, as if not the last, surely the most noted follower of the Marāgha School" (Neugebauer and Swerdlow 1984, p. 47). Saliba for his part calls for the abandonment of the following periodisation paradigm underlying the Non-Innovationist reading of the Arabic tradition.

> The prevailing periodization could be summarized along the following stages: (1) the translation stage, when Greek astronomy passed into Arabic, and that seems to have been understood as *just* a translation stage; (2) a stage of additional minor commentaries of a type that Nau called *adjuncta* to Greek astronomy; and finally (3) a stage of general decline in Arabic scientific creativity, which must have started sometime during the twelfth century just as Europe was in the process of acquiring the Greek heritage, especially the astronomical and the mathematical one, through the translation from Arabic into Latin. From then on, there was no longer any need to pay attention to the Arabic tradition, for Europe was developing science on its own (Saliba 1994, p. 247).

Like Saliba, Rashed identifies the problem in the dogmatic periodisation of the history of science by the Non-Innovationists. Their way of looking at the history of science, not as a process but as a jump from ancient to modern science, creates a paradox: heavily underestimated, the Arabic tradition ends up denying its existence in its own right, while at the same time the working historian of science cannot afford to ignore the hard facts he is confronted with in his practical studies. Rashed invokes Duhem's major historical work as "merely the expression of a profound [historical] necessity" (Rashed and Morelon 1996, p. x) of the role of the Arabic tradition, without which the medieval scientific and philosophical writings could not be understood. And he concludes that the Non-Innovationists' account creates a gap so huge between ancient and modern science that it makes it impossible to bridge.

> Presented as a postulate, and in the absence of authentic knowledge of the works of the School of Marāgha and of its predecessors in astronomy – of al-Khayyām and of Sharaf al-Dīn al-Ṭūsī in algebra and algebraic geometry, of the Arabic infinitesimalists from Ibn Qurra to Ibn al-Haytham – this absolute pre-eminence has naturally created a vacuum prior to the works of the seventeenth century, and has resulted in a model of Arabic science that flattens its most remarkable peaks of achievement (ibid., p. x).

As a result of this stark contrast introduced in the periodisation of the history of science, there is not only one science but two wholly different kinds of science.

According to the Non-Innovationists' view, a new kind of science emerges whenever a major upheaval occurs in the fundamental concepts of science. Rashed's underlying objection has far-reaching consequences: (i) what is science seems to be a more problematic question than ever, and as a result there is no way to distinguish science (since there is no such thing as a science) from other forms of theories and beliefs; (ii) the rigid periodisation of the evolution of science, which leads to the fragmentation not only of the various scientific disciplines but also of the multiple scientific theories in each scientific branch, leaves no room for talking about the unity of science or at least understanding how the so-called modern science and its rapid ramifications are brought about. The fact of the matter is that our awareness of the deep interdependence between the various scientific disciplines is getting stronger as more scientific branches are linked together through the rapid exchanges of scientific writings and our understanding of the evolution of science increases as more records are made available. The full significance of Duhem's enterprise can now be seen in a new light, since his systematic analysis of all the available scientific and philosophical documents shows how this task can be achieved. Driven by another motivation, Duhem wants to make the following point: the way in which the major achievements of the Renaissance can be seen as the necessary evolution of the scientific research framework developed during the Scholastic period. The nineteenth century historian's attempt (the first eminent historian to challenge the received view) is at odds with the prevailing paradigmatic periodisation of modern historians of science according to which the seventeenth century is the beginning of the era of modern science. To defend his claim and his faith, the strongly religious physician has to innovate. This explains why he devotes eight out of ten volumes of his *Le Système du Monde* to the analysis of the so-called sterilised medieval European writings. The result: a lively and dynamic account in which he describes science in the making by systematically exposing the various controversies leading to the formation of modern scientific concepts. By presenting newly discovered material (Ibn al-Haytham's *Al-Shukūk 'ala Batlamyus*), our contribution is designed to update *Le Système du Monde* and to fill the gap in our understanding of Duhem's exposition of the evolution of science in general and of the emergence of modern science in particular. Our aim is to show how our fruitful and dynamic interpretation of the progress of science can be a way out of this long and bitter dispute between the Non-Innovationists and the Innovationists. One last remark: the general lines of this interpretation are based on Shahid Rahman's research project "La science et ses contextes" (MSH-Nord-pas de Calais), already suggested in Rahman/Symons 2004, (pp. 3–16) and developed in my thesis in relation to the history of mathematics, where the gap between the history and philosophy of mathematics is closed by the systematic study of scientific controversies.

2 Plato's Astronomical Doctrine

According to Duhem, if we want to find the first clear definition of the subject matter of astronomy, we have to go back to the teachings of Plato as reported by Simplicius in his *Commentary*

> Plato assumes in principle the motion of celestial bodies is uniform circular and perfectly regular [i.e. constantly in the same direction]; he then poses to the mathematicians the following problem: What uniform circular motions are convenient to be taken as hypotheses in order to save the appearances presented in the wandering planets? (Duhem 1913, volume I p. 103).

The task of the astronomer is clearly defined: (i) he may only use uniform circular motion; (ii) he has to account for any other kind of motion by the combination of uniform circular motions such that the resulting motion resembles the motion of the star; (iii) he has to choose further hypotheses in such a way that the resulting motion is in conformity with the observed motion of the heavenly bodies. These are the principles which guided the works of Eudoxus and Kallipsus. The latter's homocentric system does not succeed in saving the appearances due to the complexity of the motion of the wandering planets. Successor astronomers such as Apollonius and Hipparchus succeeded in giving a satisfactory response to Plato's problem. Strictly following Plato's principle, they retained uniform circular motion as the principle of motion, but they introduced some hypotheses which gave rise to the famous theory of circular motions eccentric to the earth and the deferent-epicycle theory. These two models, which turn out to be equivalent, have been used successfully to account for the motion of the sun (Fig. 1).

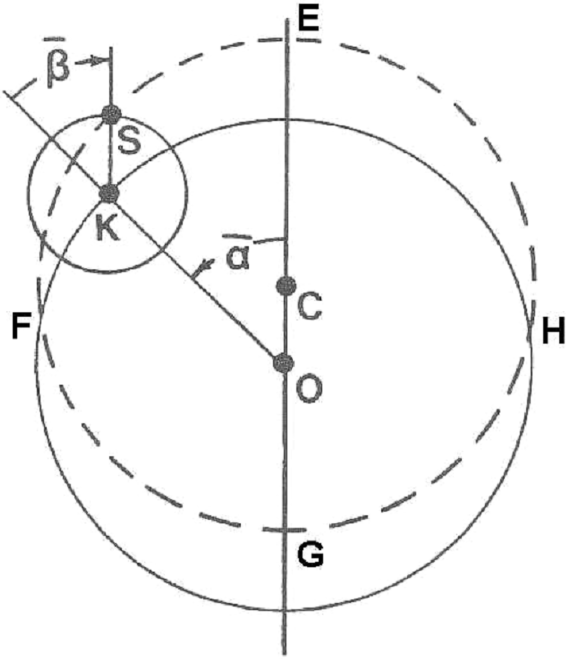

Fig. 1 $\bar{\alpha}$ and $\bar{\beta}$ are called the mean anomaly since they measure the angular distance of the mean sun from the apogee. The two models are mathematically equivalent if *SK* = *OC* and $\bar{\alpha} = \bar{\beta}$

In the eccentric model (*EFGH* circle), the sun moves with uniform speed along *EFGH*, but the centre of the circle is no longer assumed to coincide with that of the earth. The sun *S* is at its greatest distance from the earth at apogee *E* and at its closest to the earth at its perigee *G*. This model allows the sun to travel at constant speed describing equal arcs at equal times but it appears to an observer supposed to be at *O* to travel more quickly when in the lower half of the eccentric *FGH* and more slowly when in the upper half *HEF* (its slowest point being of course at apogee *E*), because of its varying distance from the earth. It happens that an entirely different model will produce the same result if the sun is assumed to be moving on an epicycle with centre *K* in the direction contrary to the order of the signs (i.e. clockwise as indicated by the arrow). Point *K* is assumed to be moved on a circle centred on the earth *O* called the deferent (unbroken circle) in an equal and contrary motion to that of the epicycle. The deferent circle is said to be concentric to the earth. The equivalence of the eccentric and the deferent-epicycle models, and therefore the resulting motions, was first proved by Apollonius and is reproduced by Ptolemy in the *Almagest* Book III Chapter 3.

3 Shift in the Theory of Astronomy: Ptolemy's *Almagest*

To account for the more complex motion of the wandering planets, Ptolemy uses further hypotheses which introduce a major shift in the evolution of astronomy. His description of the motion of Venus illustrates the importance of these changes (Fig. 2).

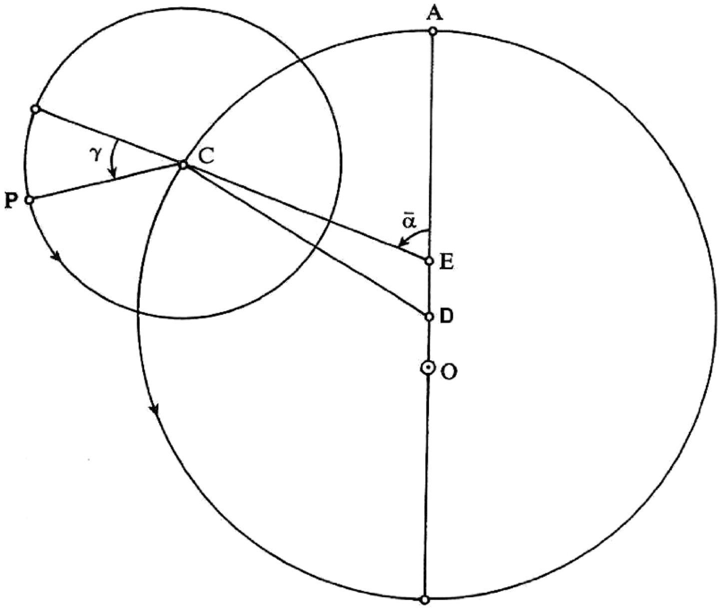

Fig. 2 P denotes a planet; C is the centre of the epicycle; D is the centre of the deferent; E is the point around which the epicycle is assumed to move uniformly, i.e. the equant point

To account for the double anomaly for each planet ((i) an anomaly which varies according to the planet's position in the ecliptic, and (ii) which varies according to its position relative to the sun), Ptolemy assumes that the planet *P* is carried by the epicycle in its backward motion at uniform speed measured by anomaly γ, while the centre of the epicycle is moved by the deferent around its centre *D*.

Now, according to the principle of uniform circular motion, point *C* must move uniformly around the deferent and the planet *P* must also move uniformly around the epicycle; i.e. the line *CP* must describe equal arcs in equal times and the epicycle, which carries the planet, is invariably linked to the vector *CE* describing equal arcs in equal times around *D*. In the case of Venus, Ptolemy declares: "but since it is not clear whether the uniform motion takes place around *D* …" (Ptolemy, p. 473). Ptolemy assumes instead that point *C*, the centre of the epicycle, describes equal arcs in equal times not around the centre of the deferent *D* as it should but around a point *E* such that $ED = OD$; *E* is called the equant point. In other words the deferent is assumed to move uniformly around a point different from its centre.

His account of the motion of the moon confirms this trend (Fig. 3).

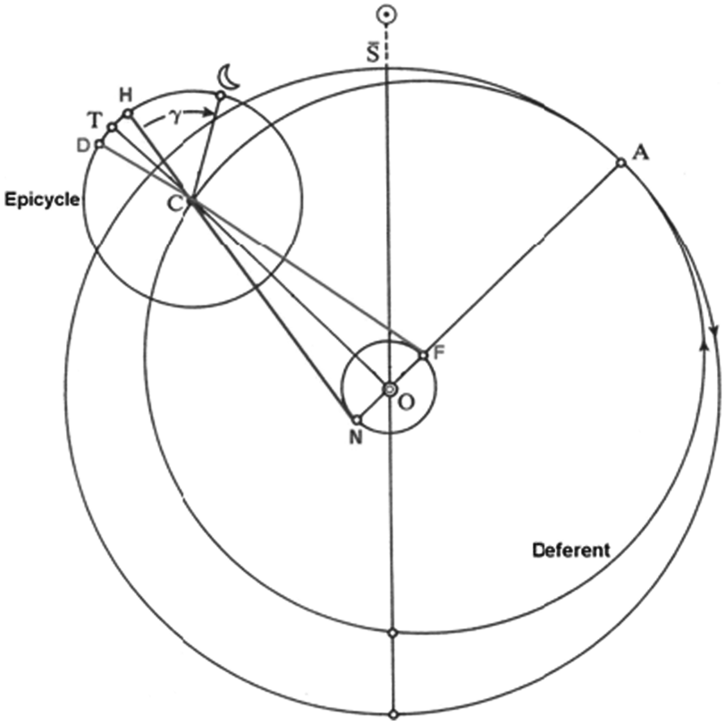

Fig. 3 $\bar{S}$ is the mean apogee (i.e. a fictitious body that moves uniformly around the earth *O*); *F* is the centre of the deferent; *C* is the centre of the epicycle on which the moon moves uniformly; *T*, the apogee seen from *O*, is called the true apogee; *H*, the point from which the mean anomaly is measured, is called the mean apogee; *N* is the prosneusis point

This description of the motion of the moon consists of the following features:

(i) the deferent moves around its centre F such that $\overline{S}\,OA$ and $\overline{S}\,OC$ are equal and opposite, i.e. like the motion of Venus, we have here a deferent moving uniformly around a point O other than its centre;

(ii) instead of counting the anomaly γ which determines the distance of the moon M on the epicycle from the apogee D, it had to be measured from point H (called the mean apogee for this reason) such that the radius HC has a direction towards a point N which is always located diametrically opposite to point F.

It should be noted that H is a variable apogee since N, called the prosneusis point, has to be constantly in motion to remain opposite to the moving point F. The difference between the equant and the prosneusis is thus that the description of the motion of the moon starts from a non-stable point. The motion of Mercury is accounted for by more complicated motions since Ptolemy uses a combination of the equant and prosneusis features.

The admission of the equant and prosneusis hypotheses signals a significant departure from both Plato's astronomical tradition and Aristotle's physical principles, since we have in both cases a uniform motion which takes place around an axis that does not pass through the centre of the sphere generating it. This is what Ptolemy calls παρὰ τὸν λόγον translated by Toomer as "not in strict accordance with [ancient] theory" (Ptolemy 1984, p. 422), in effect rejecting the conception of his predecessors. The *Almagest* is to show here that astronomy needs new principles and a new way of reasoning: (i) Plato's astronomical doctrine should be modified by abandoning uniform circular motion; (ii) the Aristotelian physical principles should be restricted to the sublunar phenomena.

One of the major consequences of Ptolemy's work is that it puts an end to the unclear relationship between mathematics and physics. His decision is to subordinate the latter to the former; this philosophical approach involves a particular conception of science which has, as one of its severe side effects, widened the gap between mathematics and physics. It remains to be seen whether it is the right approach. These difficult questions are not raised by the author of the *Almagest.* Given Ptolemy's exposition of his theory, the reader should not expect the mathematician-astronomer to discuss its philosophical and epistemological implications. A controversy is needed to challenge its underlying assumptions and to bring to the forefront these foundational issues.

4 The Beginning of the Controversy over the Foundations of Astronomy: Ibn al-Haytham's *Doubts Against Ptolemy's Almagest*

The composition of the *Almagest* represents the climax of Greek astronomy. It was Ptolemy who brought the Greek planetary theory to its final and definitive form. The original name of *Almagest,* which according to Toomer is originally derived from a Greek form μεγίστη meaning the "great [treatise]", is μαθηματική σύνταξις *Mathematical Systematic Treatise* (Ptolemy 1984, p. 1); by this Ptolemy means to give a comprehensive mathematical account for the motion of heavenly bodies. Beside some important results of his own, Ptolemy includes practically all astronomical achievements of his predecessors which could be reached with the mathematical methods of antiquity. Ptolemy's work reigns supreme over the cosmological scene for many centuries. His *Almagest* is to astronomy what Euclid's *Elements* is to geometry. But surprisingly, *Almagest*'s life is much shorter than that of the *Elements*, since it was the first important Greek scientific work to be successfully disputed. By the eleventh century, we begin to notice a serious shift in the astronomical field, a shift which has far-reaching consequences for the development of philosophy and science as a whole. The starting point of this shift is the relentless and systematic attack levelled against Ptolemy's approach to science. The domination of *Almagest* was strongly challenged for the first time by an eminent Arabic scientist, al-Ḥasan ibn al-Haytham, in his famous book entitled *al-Shukūk 'ala Batlamyus* (or *Doubts about Ptolemy*) in which the author raises serious doubts about Ptolemy's claims concerning the nature of astronomical theory. Ibn al-Haytham does not seem to be impressed at all by the *Great Mathematical Treatise*, since what interests him is not so much the formal account for the motion of heavenly bodies, successful though it may appear, but rather the justification of the geometric constructions underlying the *Almagest* machinery.

Our analysis of the controversy between Ibn al-Haytham and Ptolemy is largely based on *al-Shukūk*, whose argumentative presentation will be followed closely, and its impact on the history of astronomy will be clearly exposed by taking as our guide Duhem's interesting dynamic approach to the history of science which underlies his monumental work *Le Système du Monde*. The structure of Ibn al-Haytham exposition of the controversy follows the style of what later has been formalised as disputations or obligations by presenting Ptolemy as a proponent while he plays the role of an opponent or a challenger. This original dialogical method of exposition adopted by Ibn al-Haytham in his *al-Shukūk* which can be characterised as a dispute based-approach not only inaugurates a new way of arguing in the history of science and philosophy, to be followed later by his successors, aimed at putting to the test Ptolemy's fundamental claims but captures the nature of scientific and philosophical practice. It should be noted that the object of the controversy concerns the motion of the planets, which is by far the main controversial issue raised by *al-Shukūk*; that does not mean that the other issues discussed are devoid of any interest.

4.1 The Controversy over the Structure of a Planetary Theory

4.1.1 The Refutation of the Prosneusis Hypothesis

The first point raised in this respect by Ibn al-Haytham is that concerning the movement of the moon in which Ptolemy uses the prosneusis hypothesis. He begins his discussion by presenting a concise formulation of Ptolemy's argument.[3]

> [Ptolemy] says in Book V, chapter 5, which is on the inclination of the diameter of the moon's epicycle, that the diameter of the moon's epicycle, whose extremity is the epicycle apogee, always inclines towards a point below the centre of the world, a point whose distance from the centre of the world is as the distance of the centre of the world from the eccentric centre. But since the eccentric sphere moves the epicycle, the epicycle's diameter, whose extremity is the apogee when the epicycle is at the eccentric apogee, will always point to the eccentric's centre. [For] when the eccentric deferent moves, thereby moving the epicycle, there will move, together with the epicycle, the eccentric's diameter that passes through the epicycle apogee. This diameter cannot therefore be directed at any time to a point other than the eccentric's centre unless it moved and changed its position so as to be oriented towards another point (p. 15).

Ibn al-Haytham stresses here that Ptolemy's account presupposes that the diameter of the epicycle which carries the moon moves to a point other than its natural one. And from this assumption, he concludes: "now the epicycle's diameter is an imagined line." This assertion seems to do no harm to Ptolemy's theory since he claims that some concepts such as the prosneusis point could be considered so. Indeed, Duhem, as we shall see, articulates a sophisticated theory which could be used as a justification of the conceptual apparatus underlying the *Almagest.* But Ibn al-Haytham replies with a surprise counterargument, since he continues

> And an imagined line does not move by itself with a sensible movement that produces something existing in the world. Similarly, the plane of the epicycle is an imaginary plane; and an imaginary plane does not have a sensible motion. Nor does anything move with a sensible movement that produces something in the world unless it be a body that exists in the world. From this it follows that it is the body of the epicycle that moves, thereby giving rise to the change of position of the epicycle's diameter in such a way as to be directed towards a point other than that towards which it would [otherwise] be directed (p. 15).

This is a devastating attack against Ptolemy's theory. Furthermore, Ibn al-Haytham rejects Duhem's interpretation of Ptolemy's approach according to which the whole theory should be considered as pure fiction because a planetary theory could by no means be homogeneous.

> Ptolemy had gathered all the motions that he could verify from his own observations and from the observations of those who had preceded him. Then he sought a configuration of real existing bodies that exhibit such motions, but could not realise it. He then resorted to *an imaginary configuration based on imaginary circles and lines,* although *some* of these motions could *possibly exist in real bodies*. But if one imagines a line to be moving in a certain fashion according to his own imagination, it does not follow that there would be a line in the heavens similar to the one he had imagined moving in a similar motion. Nor is it true that if one imagined a circle in the heaven, and then imagined the planet to move along that circle, that the [real] planet would indeed move along that circle (p. 41, my emphasis).

Ibn al-Haytham considers *Almagest* as a mixed theory because motion, which is a physical notion, divides its concepts into two classes: (i) physical entities which possess a uniform circular motion. These are abstract entities since they can be associated with real existing bodies; (ii) imaginary entities which are, by contrast, not capable of acquiring the property of motion. By distinguishing entities according to the motion criterion, Ibn al-Haytham rejects Ptolemy's attempt to blur the two kinds of entities. As for imaginary entities in particular, Ibn al-Haytham is not opposed at all to the introduction in a physical theory of entities to which no physical reality corresponds—we have to bear in mind that he is also a mathematician. But what the Arabic physician denies to the Greek mathematician is the attribution to imaginary entities by the latter of properties which are of a purely physical character. It is like attributing to *i* the property of a real number although everybody knows that there is no real number whose square is equal to –1. For Ibn al-Haytham to assume thus the existence of imaginary objects in motion is an absurdity: a conclusion he draws from his discussion of the motion of the inferior planets in latitude.

> This is an absurd impossibility, in direct contradiction with his earlier statement about the heavenly motions — being continuous, uniform and perpetual — because this motion has to belong to a body that moves in this manner, since there is no perceptible motion except that which belongs to an existing body (p. 36).

Now how could the motion of the lunar diameter be justified? It should be noted that the diameter is moved by the body of the epicycle. But for the position of the diameter to be changed, the epicycle must move in such a way that the diameter's position should always be directed towards the prosneusis point. Ibn al-Haytham examines an assumption made by Ptolemy in his *Planetary Hypotheses* in which he introduces a body (a sphere or a disc) that moves the epicycle. But he points out that this body moves uniformly, and consequently the diameter moves with uniform circular motion around the centre of the epicycle, and he concludes:

> Therefore if this diameter always points, as he [Ptolemy] assumed, to one and the same point, while the body of the epicycle moves with a circular, uniform and continuous movement, then this diameter needs another mover which always orients it towards the assumed point (p. 16).

In other words the prosneusis hypothesis requires a body other than that introduced by Ptolemy, and he continues:

> Ptolemy, however, does not assume in the *Planetary Hypotheses* a body that brings about this movement. Moreover, if, for the sake of this movement, a body is assumed to move the epicycle, then this body must need to possess two opposite movements. (p. 17)

He then shows by reductio ad absurdum that the assumed existence of such a body leads to a contradiction. Below is a brief summary of how he arrives at this conclusion. I think using a slightly modified version of Sabra's figure (Sabra 1994, XIV p. 125) makes it easier for the reader to follow Ibn al-Haytham's abstract argument.

For the lunar diameter to be always directed towards *O*, the assumed body *B* must move in two opposite movements: (i) from *A*, where the centre of the epicycle coincides with the eccentric apogee, to *C*, where the lunar diameter is perpendicular to *OA* (the world diameter that passes through all the centres), *B* must move contrary to the epicycle movement in order to maintain the diameter directed towards *O*. At this position, the angle *OCD* reaches its maximum. (ii) As the epicycle continues its movement, the angle becomes smaller and smaller and at the perigee of the eccentric *P*, the prosneusis line *OC* coincides with the world's diameter *OA*. To move the diameter *OC* towards the perigee, *B* must move in the opposite direction to its previous movement, i.e. in the same direction as that of

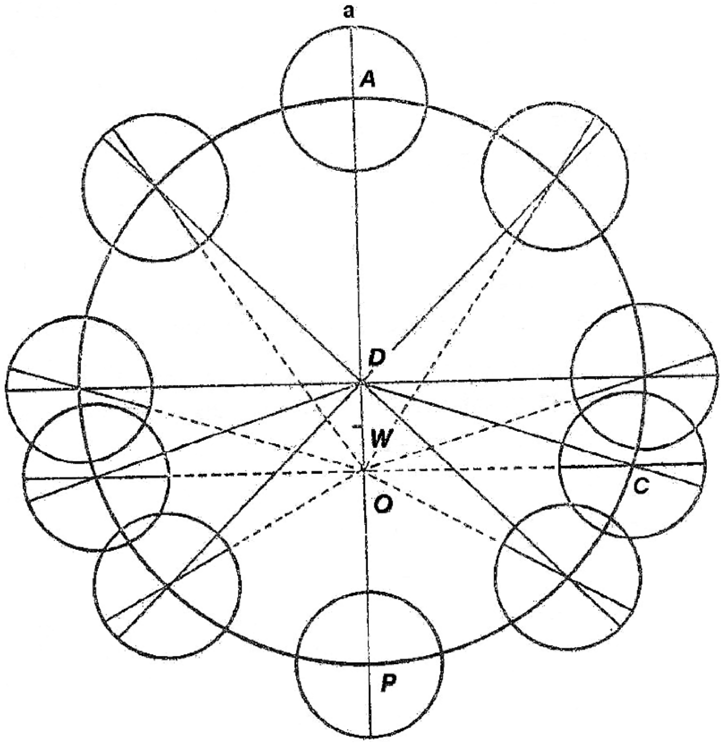

Fig. 4 a: apogee of epicycle, *A*: apogee of deferent, *D*: deferent centre, *W*: world centre, *O*: proneusis point, *P*: perigee of deferent.

the epicycle. Within a period of half a lunar month, the assumed body *B* has thus to perform two opposite movements. The same can be shown for the other half of the lunar month.

Ibn al-Haytham thus shows that the prosneusis hypothesis needs another assumption itself: an entity which can perform not only two kinds of motion, but two motions which are required to occur in opposite directions. What is the status now of what can be called an assumption of second-order? Can this assumption be accepted by assuming that the denoted object is by no means a physical reality but rather an imaginary one? We have already mentioned that Ibn al-Haytham rejects the idea of assuming motion in an imaginary entity. But the second-order assumption is worse, since it attributes to an entity the capacity of performing two contrary motions. Can we accept it nevertheless on the grounds that the object which performs two contrary motions is a more imaginary entity than the object which moves uniformly around a point other than its centre? In short, the second-order assumption is a property of second-order entities. It appears then that the imaginary status not only further widens the gap between mathematics and physics but seems to give an absolutely free hand to the mathematician-astronomer to assert whatever he imagines suitable for his calculations. Is there no restraint whatsoever on the kind of assumptions he may make or on the conditions they should satisfy? If this is the case, this means that to account for the empirical phenomena, the mathematician-astronomer does not seek to make the right assumptions since there is no such idea of right assumptions, that is, there is no formal criterion on which he has to base his assumptions. But since he declares that his assumptions are, accordingly, not necessarily about the actual world, how can we thus determine whether his language machinery makes sense or not? It is in this context that we have to understand why the most virulent attack ever launched by Ibn al-Haytham against Ptolemy's arguments is the one involving the second-order assumption.

> Now this is an absurd impossibility: I mean that one and the same body should possess two opposite, natural and permanent motions. And if it is said that the two motions are voluntary, it will follow that one part of the heaven makes two opposite choices and therefore its substance must consist of two opposite substances or of a multitude of opposite substances. And this is regarded as impossible by *all philosophers* عند جميع الفلاسفة و هذا محال (p. 19, my emphasis).

And further ahead he says about this same assumption according to which a body can have two contrary substances: "this is an impossibility which we must refrain from considering; and it is still more the case for heavenly bodies because that [assumption] is worse than a [mere] contradiction أشدُّ امتناعا، لأن تلك أبعد من التضاد و هو من المحال الممتنع. و هو في الأجسام السّماوية" (p. 36). This is not the only place where Ibn al-Haytham explicitly mentions the philosophers. He also appeals to them when he discusses a similar point.

> And the *inquirers among philosophers believe* و المحقّقون من الفلاسفة يعتقدون that no two opposite motions can exist in the heavens. It is one of the most absurd impossibilities فمن أفحش المحال that they can be possessed by one and the same body of the heavenly bodies (p. 37, my emphasis).

By bringing the philosophers into the controversy, Ibn al-Haytham wants to make two important points: (i) the controversy has reached a point they can no longer ignore. The point is no longer a technical matter, as was first thought, but is now of philosophical interest since the question concerns the foundation of astronomy; and as a result (ii) he urges them to take a firm stance on the issue. This is rather a clever and powerful move which could have serious consequences. By involving the philosophers into the discussion, Ibn al-Haytham no doubt hopes they will take up the matter more deeply—an interesting attempt aimed at further radicalising the controversy: if it succeeds, it can only speed up the collapse of Ptolemy's system by bringing to the surface all its hidden assumptions and weaknesses. The aim of Ibn al-Haytham's argument is to establish that "each body having to have only one kind of motion" is a second fundamental principle of motion; the first being uniform circular motion. It is now easy for him to show by reductio ad absurdum that the assumed body required by the prosneusis hypothesis cannot exist.

(i) Assume that there is such a body B;
(ii) B must have two opposite motions;
(iii) But according to the second principle of motion, a body can have only one kind of motion;
(iv) Therefore B cannot exist.

And from the non-existence of *B* it follows that the prosneusis hypothesis cannot be justified. Ibn al-Haytham uses a similar line of reasoning to reject the equant hypothesis introduced by Ptolemy in his account of the motion of the superior planets.

4.1.2 The Refutation of the Equant Hypothesis

Ibn al-Haytham begins by presenting Ptolemy's argument.

> He says in Book IX, chapter 2, which is on the principles that need to be laid down for the wandering planets: 'Since it is our aim to show in the case of the five wandering planets, as we showed in the case of the sun and the moon, what all their apparent irregularities are, and that they are brought about by means of regular and circular motions, inasmuch as such motions are conformable to the nature of divine bodies and do not admit of disorder and irregularity.'
>
> And he says in Book IX, Chapter 5, which is on what needs to be put forward with respect to the principles employed for the five wandering planets, that he assumes for each of the five planets an eccentric sphere and an epicyclical sphere, and that he made the eccentric move the epicycle. Then he says at the end of this Chapter:
>
> 'And we also found that the centres of the epicyclical spheres move on circles equal to the eccentric spheres, I mean those that produce the irregularity. But these circles are not about the same centres. Rather, in the case of all the five planets except Mercury, they are about centres that bisect the straight lines between the centres of eccentrics and the ecliptic's centre. And, in the case of Mercury, [the circle is] about a centre distant from the centre that turns it around by as much as this [latter] centre is removed towards the apogee from the centre about which the motion of the anomaly takes place, of as much as this [last] centre is removed from the centre where the eye is placed. (p. 23–24)

After giving a faithful description of Ptolemy's general account for the motion of the five planets (Chapter 6), Ibn al-Haytham adds: "That which we have mentioned is the truth of what Ptolemy asserted regarding the motions of the five planets. But this is a notion that leads to the contradiction." In other words, Ibn al-Haytham considers that what Ptolemy states in Chapter 5 (implemented in Chapter 6), in which he introduces the equant notion as simply the point around which the centre of the epicycle moves uniformly, is in flagrant contradiction with the principle of uniform motion of the same book, reaffirmed just 3 chapters before.

The proof of the contradiction is constructed as follows:

(i) according to the principle of uniform circular motion: a spherical body moves uniformly and around its centre;
(ii) a spherical body cannot move uniformly and at the same time around two points; Ibn al-Haytham stresses here that it is Ptolemy himself who establishes the validity of this statement in Book III Chapter 3, devoted to the motion of the sun;
(iii) Ptolemy assumes that the centre of the epicycle moves uniformly around the equant;
(iv) from (ii) and (iii): the centre of the epicycle does not move uniformly around the centre of its own deferent;
(iv) contradicts (i)

As in the case of the prosneusis hypothesis, Ibn al-Haytham envisages cases in which the motion of the centre of the epicycle towards the equant point and not the centre of the deferent could be brought about by an assumed body. And he ends up with the following conclusion: the assumed body should not only have two opposite motions but would also be the cause of an irregular motion.

> If he assumes for the epicycle a body which moves it in such a way as to direct its diameter towards the farther point [i.e. the equant], as we assumed in the case of the moon epicycle with respect to the opposite point [i.e. the prosneusis], it will follow that this body has two opposite motions, just as this followed in the other case. It will also follow that [the assumed body] will move the diameter about the farther centre with an irregular motion, given that the epicycle's motion about the centre of the deferent is regular, as was shown earlier. But to assume the existence of a body of this description is impossible. (p. 28–29)

The clash between the mathematician-physician and the physician-mathematician over the structure of a planetary theory reflects in fact two underlying opposite philosophical approaches to the aim of a physical theory.

4.2 The Controversy over the Aim of a Physical Theory: Saving the Appearances or Explaining Their Underlying Regularities

Ptolemy is well aware of the objections that could be raised against his approach. By adopting the prosneusis and equant hypotheses, he knows very well that he is departing from the traditional way of studying astronomy. To defend his new approach against possible attacks, Ptolemy uses the following argument:

> Let no one, considering the complicated nature of our devices, judge such hypotheses to be over-elaborated. For it is not appropriate to compare human [constructions] with divine, nor to form one's beliefs about such great things on the basis of very dissimilar analogies. For what [could one compare] more dissimilar than the eternal and unchanging with the ever-changing, or that which can be hindered by anything with that which cannot be hindered even by itself? (Ptolemy 1984, p. 600)

It is interesting to note that to justify his new hypotheses Ptolemy uses, ironically, the well known dogma of ancient Greece. By insisting on the radical distinction between the supra and sublunar phenomena, he tries to abort any possible rapprochement between his hypotheses required by the motion of heavenly bodies and those required by terrestrial bodies. It is the attempt to establish this kind of rapprochement through the interpretation of his imaginary entities by physical objects that leads to the kind of absurdities pointed out by Ibn al-Haytham.

> Why should anyone think it strange that such complications can characterise the motions of the heavens when their nature is such as to afford no hindrance, but of a kind to yield and give way to the natural motions of each part, even if [the motions] are opposed to one another? Thus, quite simply, all the elements can easily pass through and be seen through all other elements, and this ease of transit applies not only to the individual circles, but to the spheres themselves and the axes of revolution. We see that in the models constructed on earth the fitting together of these [elements] to represent the different motions is laborious, and difficult to achieve in such a way that the motions do not hinder each other,

> while in the heavens no obstruction whatever is caused by such combinations. (ibid., pp. 600–601)

In his commentary of this passage, Duhem expresses more clearly the thinking behind Ptolemy's approach.

> C'est donc folie de vouloir imposer aux mouvements des corps célestes l'obligation de se laisser figurer par des mécanismes de bois ou de métal. […] Les mouvements multiples qu'il compose, dans la *Syntaxe,* pour déterminer la trajectoire d'un astre, n'ont aucune réalité ; le mouvement résultant est le seul qui se produise dans le ciel. (Duhem 1913, volume II p. 85)

Ptolemy and his commentator warn us against the temptation of interpreting *Almagest*'s complex machinery since it is the combination of purely fictional entities that have nothing to do whatsoever with the real physical world. Ibn al-Haytham, for his part, seems to accept Ptolemy's argument that the *Almagest* is an imagined theory, but he infers from this that his system cannot be regarded as an account of the actual motion of the heavenly bodies. And since Ptolemy admits that his theory is the product of his mind, Ibn al-Haytham concludes that the resulting motion of the various planets occurs solely in his own imagination, "that configuration produces in his own imagination the motions that belong to the planets تلك الهيئة تؤدّي حركات الكواكب في تخيُّله على ما هي عليه" (p. 38). But for Ptolemy, that is not the point. His hypotheses should not be judged other than by the result they produce i.e. the conformity of their consequences with empirical phenomena, and the simplicity criterion.

> One should try, as far as possible, to fit the simpler hypotheses to the heavenly motions, but if this does not succeed, [one should apply hypotheses] which do fit. For provided that each of the phenomena is duly saved by the hypotheses, […] (Ptolemy 1984, p. 600)

This passage contains some keywords which have given rise to the title of Duhem's popular booklet *Sauver les Apparences,* an extremely condensed version of his monumental work *Le Système du Monde.* Duhem further develops the saving appearances doctrine to defend Ptolemy's approach.

> Les diverses rotations sur des cercles concentriques ou excentriques, sur des épicycles, rotations qu'il faut composer entre elles pour obtenir la trajectoire d'un astre errant, sont seulement des artifices ; ces artifices sont combinés en vue de sauver les phénomènes à l'aide des hypothèses les plus simples qui se puissent trouver. Mais il faut bien se garder de croire que ces constructions mécaniques aient, dans le ciel, la moindre réalité. (Duhem 1913, volume II p. 85)

Consequently, the evolution of astronomy has, according to Duhem, led Ptolemy to propose—for the first time since Plato—a major shift in the task of the astronomer.

> L'astronome de Péluse [i.e. Ptolemy] dut reconnaître que des règles aussi rigides laisseraient malaisément construire une théorie capable de sauver les apparences ; ces règles, il les assouplit peu à peu jusqu'à les fausser ; il en vint enfin à professer cette doctrine : l'astronome qui cherche des hypothèses propres à sauver les mouvements apparents des astres ne doit connaître d'autre guide que la règle de la plus grande simplicité. (ibid., p. 84)

The saving appearances doctrine looks so powerful that it is hard to imagine stronger counterarguments capable of challenging it, let alone defeating it. This explains why it dominates the astronomical scene for so many centuries. It remains to be seen whether Ibn al-Haytham can change the situation in his favour by successfully refuting or at least undermining the saving appearances position, and if so by what means this change could be brought about. Ibn al-Haytham adopts a clever strategy to attack Ptolemy's approach by considering the price to be paid for saving the appearances. He begins as usual by quoting a passage from the crucial Book IX, Chapter 2 of the *Almagest* in which Ptolemy admits that his conception is a departure from the intuitive way of reasoning.

> And this, I suspect, appeared difficult even to him — he means to Hipparchus. The point of the above remarks was not to boast of our own achievement. Rather, for we are at some point compelled by the nature of our subject to use a procedure not in strict accordance with the intuitive way of reasoning. For instance, when we carry out proofs using without further qualification the imaginary circles described in the planetary spheres by the movement of the body. (p. 33)

And he then shows that this departure from the intuitive way of reasoning is a consequence of the contradiction of his hypotheses with the extant principles.

> Ptolemy has thus admitted that his assumption of motions along imaginary circles is the intuitive way of reasoning, then it would be more so for imaginary lines to move around assumed points. And if the motion of the epicyclic diameter around the distant centre [i.e. the equant] is also a departure from the [intuitive] way of reasoning, and if the assumption of a body that moves this diameter around this centre is also a departure from the [intuitive] way of reasoning for it contradicts the principles, then the arrangement, which Ptolemy had organised for the motions of the five planets, is a departure from the [intuitive] way of reasoning. (p. 33)

What is the point of quoting this passage, however important it may be, for Ibn al-Haytham? Even if Ptolemy has admitted that he has contradicted the established principles, this admission seems to have no effect on his overall position. On the contrary, Ptolemy seems to justify his departure from the intuitive way of reasoning by appealing to pragmatic reasons: the need to offer a workable account for the apparent irregularities of the motions of the planets. So far, Ibn al-Haytham's argument can be seen as a weak argument. But the situation changes dramatically when he adds

> Ptolemy has admitted he had used in [the construction of] the configurations of the motions of the planets, some considerations which depart from the intuitive way of reasoning, and it is these considerations that necessarily lead him to the contradiction. For the contradiction which is necessarily involved in his configurations of the motions of the planets is due to his assumptions of attributing motion to imaginary circles and lines and not to existing bodies. But once the existence of real bodies is assumed, the contradiction then became clear (pp. 38–39).

Ibn al-Haytham seems to be saying in this crucial passage that the contradiction is already there before the interpretation of the imaginary entities in terms of concrete objects. And that this contradiction follows immediately from his adopting a mode of reasoning which is contrary to the intuitive way of reasoning; in other words the contradiction is internal since it is of a conceptual nature. But where does he see the contradiction? What is the sign that indicates that Ptolemy's system contains contradictory elements? We can find some clue to the answer in Ibn al-Haytham's use of the plural "configurations" rather than the frequently singular "one configuration." And further, because here the plural noun is used twice and in conjunction with assumptions (or considerations)—since different assumptions give rise to different configurations. The consequence of departing from the intuitive way of reasoning is the fragmentation of theoretical astronomy. Ptolemy believes that he can escape the difficulty by stressing that his imaginary entities are not subject to interpretation. For Ibn al-Haytham, this approach can only make science a more confused and complicated enterprise. By radicalising the distinction between the supra and the sublunar world, Ptolemy makes it impossible to find common principles, let alone unifying ones, by which the motion of heavenly bodies could be explained. The task of the astronomer is rather hopeless: not only are there no common principles which could explain the behaviour of the planets, but different planets have different assumptions since each planet has its own peculiar course of motion.

> We know, finally, that some variety in the type of hypotheses associated with the circles [of the planets] cannot plausibly be considered strange or contrary to reason especially since the phenomena exhibited by the actual planets are not alike [for all] (Ptolemy 1984, p. 423).

Furthermore, the motion of heavenly bodies cannot be understood in the same way as the motion of terrestrial bodies, since the principles of supralunar phenomena have nothing to do with those of sublunar phenomena. Ptolemy expresses this idea unambiguously when he discusses the notion of simplicity.

> We should not judge 'simplicity' in heavenly things from what appears to be simple on earth, especially when the same thing is not equally simple for all even here. For if we were to judge by those criteria, nothing that occurs in the heavens would appear simple, not even the unchanging nature of the first motion, since this very quality of eternal unchangingness is for us not [merely] difficult, but completely impossible (ibid., p. 601).

The resulting account of the *Almagest* is not an account of the structure of the planetary system but rather a mere collection of geometric constructions of the imaginary motion of individual planets that bear no relation whatsoever to each other. Let us give a brief summary of the account for the motion of the heavenly bodies and their corresponding assumptions:

The motion of the sun is accounted for by the principle of uniform circular motion.
The motion of the moon is accounted for by the prosneusis hypothesis.
The motion of the four planets is accounted for by the equant hypothesis.
The motion of Mercury is accounted for by mixed prosneusis-equant hypotheses.

There is no contradiction if the *Almagest* is considered as a piecemeal theory. But as a unified theory, the prosneusis and equant hypotheses contradict the principle of uniform circular motion as we have already explained.

Ibn al-Haytham opposes Ptolemy’s cosmological conception with the following:

> The truth that leaves no room for doubt is that there are correct configurations for the movements of the planets, which exist, are *systematic*, and entail none of these impossibilities and contradictions هيئات صحيحة موجودة *مطّردة* لا فيها شيء من المحالات و لا من المناقضات
> و الصّحيح الذي لا شبهة فيه أن هيئات حركات الكواكب, but they are different from the ones established قرّرها by Ptolemy (p. 64, my emphasis).

And he concludes more forcefully:

> It becomes clear, from all that we have shown so far, that the configuration, which Ptolemy had established for the motion of the five planets, is a false configuration, and that the motions of these planets must have a correct configuration, which includes bodies moving in a uniform, perpetual, and continuous motion, without having to suffer contradiction, or be blemished by any doubt. That configuration must be other than the one established by Ptolemy. (p. 34)

What is required is not a piecemeal configuration that accounts individually for the motion of the heavenly bodies but a single systematic configuration whose validity is determined by its ability to be interpreted by means of physical objects. Here Ibn al-Haytham shifts the course of argumentation. It is not merely the question of subordinating the principles of physics to those of mathematics (or vice versa) but as Sabra[4] points out the problem is much deeper than that: it is the question of the possibility of the existence of astronomy as a theoretical physical science. Astronomy cannot exist as a truly physical science without a coherent theoretical structure based on some fundamental principles that could explain a wide range of apparently unrelated phenomena. Ptolemy’s conception yields an astronomy of irregularity/account: his starting point is that the heavenly bodies present certain irregularities, and the problem of the astronomer is how to account for what is taken as merely apparent anomalies so that he can determine as accurately as possible the future positions of the various planets. But for this we do not need the whole machinery of the *Almagest* since the Babylonians have succeeded in predicting some cosmological phenomena such as lunar eclipses with remarkable accuracy by simply accumulating a large amount of data over many centuries. As one scholar of the history of ancient astronomy remarks: “the first successes in predicting the behaviour of the planets came from the recognition that, over long enough time intervals, the patterns repeat.” (Evans 1998, p. 312). This could be seen as a failure on the part of Ptolemy since the motivation of the whole *Almagest* enterprise represents a step backwards.

Ibn al-Haytham’s approach, on the other hand, yields an astronomy of explanation and understanding, as Neugebauer has already noticed:

> [Ibn al-Haytham’s] objections are right on the mark if Ptolemy’s models are to be taken seriously as physical bodies in the heavens. And there is no doubt that Ibn al-Haytham and other astronomers wished to do so, that is, they were not content with a mathematical representation of the apparent motions of the planets using models that were to be taken only as geometry, but wished to *understand the structure of the physical mechanisms*, composed of rotating spherical bodies, that carried the visible bodies of the planets through their apparent motions. (Neugebauer and Swerdlow 1984, p. 44; my emphasis)

Ibn al-Haytham's remarkable insight is not only that our actual world could be understood but that it should be understood, and mathematics is just a tool helping us reach that goal by putting to the test the various mathematical theories. That is what his optical works taught him.[5] According to this view, to account for irregularities is to explain them: why does the motion of the heavenly bodies appear irregular? Why is the behaviour of the inferior planets more irregular than that of the superior planets? It is the answers to questions like these which can lead to a theoretical system in order to explain the order underlying the apparent anomalies. When such an explanation is given, the so-called anomalies will no longer be regarded as such due to the increase in our understanding of the relationship between the heavenly bodies. In sharp contrast with the saving appearances doctrine, Ibn al-Haytham states time and again that there is a correct single configuration for the motion of the heavenly bodies. But how can he be sure of the existence of such a configuration? And by what means can it be found? As for the first question, Ibn al-Haytham claims that "it is not true there should be uniform, perceptible and perpetual motion which does not have a correct configuration in existing bodies" (*al-Shukūk*, p. 42). Ibn al-Haytham's strong conviction of the existence of a correct configuration is based on a more general principle: the regularity of motion of the planetary system. Furthermore his firm conviction of the existence of a "correct configuration in existing bodies" reflects the close connection between Ibn al-Haytham's structural conception of the universe and his model-theoretical approach in the investigation of natural phenomena. Such a systematic configuration can only be discovered by adopting certain basic assumptions as principles of its construction. And the same passage also indicates the means by which the correct configuration could be brought about: it is the principle of uniform circular motion. But why should uniform circular motion be regarded as the best candidate?

> (i) It is impossible for the motion of the planets, which is perpetual, uniform, and unchanging to be contrary to the intuitive way of reasoning. (ii) Nor should it be permissible to attribute a uniform, perpetual, and unchanging motion to anything other than correct principles, (iii) واجبة بالقياس المطّرد الذي لا شبهة فيه (p. 34, with the numbers added).

The crucial sentence of this passage is translated by Saliba as "(other than correct principles) which are necessarily due to accepted assumptions that allow no doubt" (Saliba 2000, p. 78) and by Sabra as: "(except in accordance with true hypotheses) entailed by consistent reasoning that is subject to uncertainty" (Sabra 1998, p. 302). The difference between the two translations is an indication of the difficulty of what seems to be an extremely condensed Arabic expression. To put it in broad terms, it seems that Saliba attempts to capture the intended meaning while Sabra's translation tries to be literally closer to the original sentence.

Let us look more closely at the whole passage in which Ibn al-Haytham makes the three following points.

(i) If there are correct principles other than uniform circular motion then the latter cannot be contrary to the former.
(ii) Hence uniform circular motion can be added to the correct principles and by doing so it becomes itself a correct principle.

Now a theory of motion whose assumptions are contrary to uniform circular motion is a theory which disputes in fact the correct principles. The dispute then moves to the higher level i.e. to the meta-theoretical level since we have two sets of principles which are contrary to each other. Which of the two theories has thus the burden of proof: the established or the challenging theory?

(iii) It is in this context that we have to understand Ibn al-Haytham's third point and the whole enterprise of *al-Shukūk.* He tries to show that the principles of the extant theory are not accepted or taken as correct dogmatically but that these established principles are correct because they can be justified. It remains to be seen how. A linguistic analysis of the Arabic expression is the first step in this direction.

(1) *Wājiba* (واجبة): Sabra translates this word by "entailed", but this term alone does not render the idea of necessity contained in the original term. Wājiba is from wājib which commonly means duty. The word is used here in the passive present participle, and the combination of both the meaning and the grammatical form suggests the following translation: (something) required or necessarily due (by virtue of something, usually a condition or a rule). This is the translation proposed by Saliba ("necessarily due").

(2) *Al-qiyās al-muṭṭarid* (القياس المطّرد): Saliba's translation is "accepted assumptions", and "… *wājiba bil-qiyās al- muṭṭarid*" is rendered by "correct principles which are necessarily due to accepted assumptions". In some sense he is right by virtue of the use of the word wājiba. Saliba prefers however to use "assumptions" instead of stronger terms such as rules or conditions as implied by the Arabic word *wājib*, as explained above. Furthermore, Saliba's translation establishes a logical consequence relation between (accepted) assumptions and (correct) principles; this leaves the question of the justification of accepted assumptions unanswered. That is why here we follow Sabra, who tries to be closer to the proper meaning of *al-qiyās al-muṭṭarid* by translating it as "consistent reasoning". Sabra does not specify, however, in what way "consistent" should be understood, since it is much more than the mere non-contradiction meaning which is intended here. *Muṭṭarid* usually means systematic, regular, but it can also mean general, such in, for example, قاعدة مطردة a general rule. The latter seems to be more convenient since the subject of reasoning is the principles of a given theory. From this point of view, *muṭṭarid* can be understood as simply referring to the level of reasoning, i.e. meta-theoretical reasoning. We shall come back to *al-qiyās al-muṭṭarid* later.

(3) *Lā shubhata fīh* (لا شبهة فيه): by translating it as "uncertain", Sabra is clearly far away from the intended meaning since this expression conveys in no way the idea of certainty. Sabra probably chooses this word because of the necessarily logical consequence that he establishes in his translation between "true hypotheses" and "consistent reasoning". According to this reading, hypotheses are true because they are (necessarily) entailed by uncertain reasoning. We suggest proceeding the other way round: it is rather *lā shubhata fīh* which specifies the quality of reasoning involved. Here we follow Saliba's translation of this expression: "(allow) no doubt". But the proper meaning of *lā shubhata fīh* is "unambiguous",

and this meaning is complementary to that proposed by Saliba since it specifies the way by which doubt is raised. So *lā shubhata fīh* indicates the nature of meta-theoretical reasoning involved in establishing the principles of a scientific theory, i.e. the meta-theoretical reasoning should be so unambiguous that no doubt can be raised. To put it positively, the meta-theoretical reasoning should carry conviction or more simply "a convincing meta-theoretical reasoning". This translation agrees with the translation of *khārija ʿani al-qiyās* by "intuitive way of reasoning."

Furthermore our interpretation is confirmed by some passages of Ibn al-Haytham where he uses explicitly "conviction" and similar words in discussing Ptolemy's arguments. In page 45, he says for example: "then he [Ptolemy] mentions the proportions of the distances of the planets from the earth and their values in a convincing way بطريق إقناعي"; while in another passage he says that the value of eccentricity used by Ptolemy is unreliable غير موثوق به (p. 32). According to our interpretation, the translation of the full Arabic expression is: correct principles which are necessarily due to a convincing meta-theoretical reasoning. But there is a difficulty here: how is something (principles) necessarily due to something (convincing reasoning) which is merely probable? This explains why Saliba substitutes accepted assumptions for *al-qiyās al-muṭṭarid* to avoid the necessarily logical consequence relation between principles and convincing reasoning. We have already mentioned the problem posed by the substitution of accepted assumptions for *al-qiyās al-muṭṭarid*. On the other hand Saliba is right in using some more general propositions (to which the correct principles are due) by virtue of the use of the grammatical form *wājib*. The underlying and interesting idea of Saliba's is that *wājib* implicitly introduces an intermediary notion between the principles of a theory and the meta-theoretical reasoning. As explained above, however, Saliba prefers to use "assumptions" instead of stronger terms such as conditions or rules as implied by the Arabic word. By sticking to the grammatical use of *wājib*, the resulting translation will shed new lights on Ibn al-Haytham's thought: "correct principles that should satisfy conditions which are established by a convincing meta-theoretical reasoning". Is this not precisely what Ibn al-Haytham is doing in his *al-Shukūk*? Is he not trying to establish, by means of a convincing meta-theoretical reasoning, the conditions which should be justified by the principles of a scientific theory? From our analysis of the controversy, Ibn al-Haytham seems to identify at least two conditions which should be justified by assumptions designed to play the role of principles of an astronomical theory: (1) They should have some universality or generality feature so that they can work as unifying principles. (2) They should be consistent with the principles of physics. Ibn al-Haytham mentions two kinds of such principles: (i) a body cannot have two contrary properties at the same time; (ii) imaginary entities can be used provided they are not given physical properties. These are formal conditions which are imposed on the construction of an astronomical theory, and it is up to the physician-mathematician to specify their content. To Ibn al-Haytham, it seems that uniform circular motion could be such a principle since it satisfies both conditions and there is no evidence up to now that heavenly bodies move otherwise. This explains why any configuration of the planetary system should be set up on the principle of uniform circular motion. It also explains why the challenging theory has the burden of proof:

(1) it must first make its principles explicit;
(2) it must show that its principles are correct, i.e. that they satisfy the conditions established in the meta-theory;
(3) it must show that the principles of the established theory are not correct either by challenging one or several conditions underlying its principles or by showing that the established theory does not fully satisfy the underlying conditions.

This is the underlying method followed by Ibn al-Haytham in his optical studies. In sharp contrast, Ptolemy fails to satisfy any of the three criteria mentioned above. As a result, Ibn al-Haytham excludes Ptolemy's *Almagest* from being a possible model of our actual world. Nor is he interested in a scientific theory which is about an imaginary world and not about our world, as Saliba rightly put it:

> To Arabic astronomers the world was constituted in only one of two ways: either it was made of real physical bodies that retained their physical properties throughout the process of accounting for their observable behavior, or of imaginary mathematical concepts that do not apply to this particular world that we see. One could not have it both ways, as Ptolemy seemed to be doing (Saliba 2000, p. 331).

As for the saving appearances doctrine invoked by Ptolemy as a justification for his hypotheses, Ibn al-Haytham responds:

> Ptolemy assumed an arrangement that cannot exist, and the fact that this arrangement produces in his imagination the motions that belong to the planets does not free him from the error he committed in his assumed arrangement, for the existing motions of the planets cannot be the result of an arrangement that is impossible to exist [sic.] (p. 38).

And a little further after quoting Ptolemy's following statement from Book IX, Chapter 2: "if something assumed without proof is later found to agree with the phenomena, then it could not have been discovered without following one of the ways of scientific knowledge, even though it would be difficult to describe how it was apprehended", he comments

> The way Ptolemy followed was indeed a legitimate beginning, but since it led him to what he himself admitted to be a departure from the intuitive way of reasoning, he should have declared his assumed arrangement to be false (p. 39).

(1) Ibn al-Haytham interprets the saving appearances argument as an admission of failure by Ptolemy since he does not show that the motion of the heavenly bodies could not be accounted for by the principle of uniform circular motion, i.e. Ptolemy fails to show that the planets can perform a motion other than uniform circular motion. (2) The second reason, akin to the first, is that Ptolemy fails to recognise the possibility of finding a more consistent configuration with the principles of physics, thus giving the impression that there is no other theory than his own. It is because of the second reason that Ibn al-Haytham uses the following harsh words against Ptolemy.

> Ptolemy either knew of the impossibilities that would result from the conditions that he had assumed and established, or did not know. If he had accepted them without knowing of the resulting impossibilities, then he would be incompetent in his craft, misled in his attempt to imagine it and to devise configurations for it. And he would never be accused

> of that. But if he had established what he established while he knew the necessary results — which may be the case befitting him — with the reason being that he was obliged to do so for he could not devise a better solution, and [on top of that] he went ahead and knowingly fell into these contradictions, then he would have erred twice: once by establishing these notions that produce these impossibilities, and the second time by committing an error when he knew that it was an error. When all is considered, and to be fair, Ptolemy would have established a configuration for the planets that would have been free from all these impossibilities, and he would not have resorted to what he had established — with all the resulting grave impossibilities — nor would he have accepted that if he could produce something better. The truth that leaves no room for doubt is that there are correct configurations for the movements of the planets, which exist, are systematic, and entail none of these impossibilities and contradictions, but they are different from the ones established by Ptolemy. And Ptolemy could not comprehend them, nor could his imagination come to grips with them (pp. 63–64).

The controversy stretches over to the epistemological and philosophical field, considerations which motivate first and foremost the composition of *al-Shukūk*. By reflecting on his job and on his discipline, the scientist turns surprisingly into a profound philosopher of science.

5 The Epistemological Dimension of *al-Shukūk*: Science as an Open System and the Progress of Science as a Process

According to Ibn al-Haytham, Ptolemy's crime is not so much that he knowingly proposes a false configuration—after all no human being is immune from error, as he points out in his introduction: "God has not preserved the scientist from error and has not safeguarded science from shortcomings and faults." Ptolemy's crime is that he presents his work as an achieved science by overlooking the difficulties he encounters and denying thus, at least implicitly, the possibility of the existence of more acceptable theories. For ignoring the existence of a correct model has the effect of preventing Ptolemy from making any suggestion which could lead to the discovery of much more improved theories than his own. In short, Ptolemy's approach is not the right path to be followed if science is to make any progress at all. The synthetic approach, which characterises the Greek way of exposing science, has no doubt the advantage of systematically presenting a scientific theory. But its drawback is that it hampers more than it contributes to the progress of science by closing the door to further theoretical research. It is this synthetic feature of the *Almagest* which prompts Ibn al-Haytham to warn his fellow colleagues not to be lured by the mathematical systematic exposition of any scientific theory by taking the truth of its results for granted or by naïvely following the methods of their predecessors.

> Truth is sought for its own sake. And those who are engaged upon the quest for anything that is sought for its own sake are not interested in other things. Finding the truth is difficult, and the road to it is rough. For the truths are plunged into obscurity. It is natural to everyone to regard scientists favourably. Consequently a person who studies their books, giving a free rein to his natural disposition and making his object to understand what they

> say and to possess himself of what they put forward comes to consider as truth the notions they had in mind and the ends which they indicate (p. 3).

To prevent such a situation from happening, Ibn al-Haytham makes it the duty of every scientist to strongly and thoroughly challenge the claims of his predecessors. In fact the progress of science requires of a scientist not only that he adopt the systematic exposition of science but also that he complement this synthetic method by the systematic critical analysis of his theory and of the theories of his opponents through the exchange of arguments and counterarguments.

> It is not the person who studies the book of his predecessors and gives a free rein to his natural disposition to regard them favourably who is the [real] seeker after truth. But rather the person who in thinking about them is filled with doubts, who holds back with his judgement with respect to what he has understood of what they say, who follows proofs by argumentation (الحجّة) and demonstration (البرهان) rather than the assertions of a man whose natural disposition is characterised by all kinds of defects and shortcomings. A person who studies scientific books with a view of knowing the real facts (الحقائق), ought to turn himself into an opponent of everything that he studies, he should thoroughly assess its main as well as its margin parts, and oppose it from every point of view and in all its aspects. And while thus engaged in his opposition, he should also be suspicious of himself and not allow himself to become abusive or be indulgent [in his assessment]. If he takes this course, the real facts (الحقائق) will be revealed to him, and the possible shortcomings and flaws of his predecessors' discourse will stand out clearly (pp. 3–4).

Ibn al-Haytham is not a naïve or narrow-minded realist as he is often portrayed by some historians such as Duhem. He not only envisages the possibility that the same phenomena could be accounted for by more than one theory, but he seems to be well aware of the fact that producing a new conflictual theory is not sufficient to destroy its predecessor. The destruction of the established theory can only be brought about by defeating its central arguments. This view is confirmed to us by what al-Bayhaqi reports him to have said

> We have imagined certain modes appropriate to the celestial movements, if we now imagine other suitable to the same movements, there would be no objection to them, as long as it has not been proved that the first modes imagined are the only ones tenable (al-Bayhaqi 1946, p. 87).

Many historians of science who review *al-Shukūk* seem to be disappointed in stressing that Ibn al-Haytham adopts a merely negative stance in astronomy in contrast with his outstanding positive contributions in optics. This shows considerable misunderstanding of Ibn al-Haytham's real intention. And I think we cannot fully understand the epistemological motivations of Ibn al-Haytham if we isolate *al-Shukūk* from his other writings, and mainly from his optical works, as many historians have done. Since Ibn al-Haytham has already produced a major treatise in which he proposes an optical theory alternative to that of Ptolemy, what is the point of devoting the last chapter of *al-Shukūk* to a critical examination of Ptolemy's optical theory? This seems just another detail since it is ignored by nearly all historians. By including a critical review of Ptolemy's optics similar to that of astronomy, Ibn al-Haytham wants to inject some form of dynamism into astronomy through the power of argumentative analysis. In particular, he wants to remind his readers that his new and successful optical theory does not come out of the blue, but is the result of challenging Ptolemy's theory by putting to the test his fundamental claims. His critical analysis of many of Ptolemy's arguments proves beyond any doubt that the latter's theory is false and that a new theory is needed for optics. And Ibn al-Haytham is strongly convinced that the same can be done for astronomy. In *al-Shukūk,* he has done the hard part of the job by showing that the *Almagest* cannot be a correct configuration of the planetary system. It is up to later generations of astronomers and philosophers to finish the job.

> When we examine the writings of a man who, is famous for his excellence, shows great ingenuity in his mathematical ideas, and who is [always] being cited in the true sciences, I mean Claudius Ptolemy, we find in them many scientific doctrines and precious, most instructive and useful ideas. But when we oppose and we assess them, and we enquire into doing justice to him and taking a fair decision between him and the truth, we find in them obscure passages, improper terms, and contradictory notions; there are however fewer of them, if they sit beside the correct notions which he hit upon. In our view, to disregard all this is not to serve the truth, illegal, and to act unjustly towards *those who will examine his writings after us* by not disclosing all that. We find that first and foremost we have to mention their places, and to make them explicit for those who afterwards want to make an effort in filling the gaps and correcting these notions by any means susceptible to lead to the truth (p. 4, my emphasis).

As Morelon rightly points out (Morelon 2000, p. 110), this sounds like a research programme proposed by Ibn al-Haytham to his successors: to find a correct and systematic configuration, based on the correct principles of physics, which can explain the regularities underlying the apparent motions of the planets through its interpretation into real spherical bodies. *Al-Shukūk* is not simply a book about astronomy as is generally believed; it is much more profound than that. It is an unprecedented philosophical and epistemological doctrine on how progress in science can be achieved. The book is clearly divided into two parts; the first of which is an introduction, extremely condensed and poetical (to ensure that his discourse will have as much effect as possible), in which Ibn al-Haytham exposes his dynamic approach to the development of science. The rest of the book is an implementation of this approach to astronomy, the most advanced scientific discipline.

6 The Impact of *Al-Shukūk*: The Deepening of Controversies over the Foundations of Astronomy

Al-Shukūk was widely known and quoted both in eastern and western Arabic countries. His strong counterarguments to the *Almagest*'s hypotheses have had the desired effect, since his forceful appeal has been answered by both astronomers and philosophers. Sabra describes in these terms the extent of the influence of Ibn al-Haytham's book in the East:

> We now know that Abū ʿUbayd al-Jūzjānī, the pupil of Avicenna, not only discussed the equant problem with a view to solving it, as was first made known by Saliba in 1980, but did so almost certainly under the influence of Ibn al-Haytham's writings. […] That Tusi was acquainted with at least some of Ibn al-Haytham's writings about Ptolemy's configurations is known from his direct references to the latter's *Treatise on the Winding Movement* both in

> the *Memoir on Astronomy (al-Tadhkira)* and in the early Persian treatise. In his "Book on al-Hay'a", 'Urdi mentions Ibn al-Haytham by name as one of two astronomers who had raised doubts against the Ptolemaic configurations for planetary motions but stopped short of any solution (the other astronomer being "Ibn al-'Aflah al-Maghribī", who flourished in the middle of the twelfth century). His discussion before and after this explicit mention contains statements and expressions that leave no doubt that he not only read Ibn al-Haytham's *Aporias Against Ptolemy* [*al-Shukūk*], but more importantly, that he shared the book's premises and its general diagnosis (Sabra 1998, pp. 304–306).

It is remarkable that after intense theoretical research carried out by eastern astronomers of the Marāgha School, a positive answer has been given to the technical part of Ibn al-Haytham's demand. The climax of this intense activity was reached in the fourteenth century by Ibn al-Shāṭir who constructs mathematical models, alternative to those of Ptolemy, that contain no eccentrics whatsoever (see Saliba 1994, pp. 233–241 and pp. 299–302; also Saliba 1996, pp. 100–103, pp. 108–113 and pp. 120–121).

Interestingly, the fever of Ibn al-Haytham's *Doubts* spread to the West in Arabic Spain. *Al-Shukūk* is explicitly mentioned by the great Andalusian philosopher Ibn Bājja in a letter to Abū Ja'far Yusūf ibn Hasday (Pines [1962] 1964). In his *Summary of the Almagest,* the other great Andalusian philosopher Ibn Rushd explicitly invokes doubts expressed by Ibn al-Haytham concerning the movement of the moon (quoted in Duhem, volume II of *Le Système du Monde*, p. 127). The western Arabic philosophers deepen the controversy on the foundations of astronomy by explicitly rejecting out of hand the *Almagest* machinery. To illustrate such an outright rejection by the western tradition, we present the final verdict of Ibn Rushd taken from his *Commentary on Aristotle's Metaphysics* in which he condemns once and for all the Ptolemaic system.

> The astronomer should build an astronomical system from which the heavenly motions follow and such that there is no impossibility from the physical standpoint … Ptolemy has not succeeded in putting astronomy on its true foundations. The epicycle and the eccentric are impossible. It is then necessary to conduct new research for this true astronomy whose foundations are the principles of physics. In my opinion, this astronomy is based on the motion of a single orb simultaneously around two or several different poles; the number of these poles is suitable for the explanation of phenomena; such motions can account for the acceleration and the retardation of the stars, for their accession and recession motion, in one word for all appearances that Ptolemy failed to explain by means of a correct astronomy. In my youth I had hoped to accomplish this investigation, but now in my old age I have despaired of that, having been impeded by obstacles.

And he ends up with the same conclusion as that of Ibn al-Haytham

> But let this discourse spur someone else to inquire [further] into these matters. For nothing of the true science of astronomy exists in our time, the astronomy of our time being only in agreement with calculations and not with what exists (in Duhem 1913, volume II, p. 138).

The new astronomy should thus be founded on the strict principles of physics: this task is left to a younger generation of astronomers. It is in this context that al-Bitrūjī composes his *on the Principles of Astronomy* in which he proposes a new conception of the universe based on the principles of dynamics

> The supreme body [the ninth orb] is distinct from the power which it bestows on those spheres below it, just as one throws a stone or shoots an arrow is distinct from the object thrown, and he is not bound to the power which he imparts to them. The stone propelled by a staff and the arrow shot by an archer continue to move as long as their power remains. But that power becomes weak as they move away from their mover until finally it is exhausted and they fall (to the ground). Similarly, the power which the supreme sphere imparts to those spheres below it continues to diminish until it reaches the earth, which is at rest by its nature. (in Duhem 1913 volume 8, p. 173; also Al-Bitrūjī 1971, p. 61)

Here Al-Bitrūjī seems to apply the two interesting dynamic ideas suggested by Ibn Bājja in his famous challenge to the Aristotelian argument on the non-existence of the void: (i) a body (e.g. planets and fixed stars) moves, even in the void, with a finite velocity; (ii) when motion takes place in a medium, it suffers retardation which is proportional to the density of the medium. An idea which could be used to explain the immobility of the earth due to the slowness or deceleration observed in projectile motion: the underlying idea is that of a power imparted to the celestial bodies which makes the latter continue in motion until that power is exhausted. We will give Ibn Bājja's explanation of the immobility of the earth to indicate that al-Bitrūjī was writing under the influence of the dynamics of his time which is Ibn Bājja's dynamics.

Ibn Bājja states, as a matter of digression, first the immobility of the earth in his *Commentary to the Aristotelian Meteorology*: "There is a reason for the fact that the earth is at rest and does not rotate (around its axis through its centre) in a circle; the place suitable for its discussion is *De Caelo*" (Lettinck 1999, p. 457). And he stresses that this reason is quite different from that given by Aristotle and the ancient philosophers which is based more on speculations (what is said) than on observations.

> Let us establish the matter according to what is observed and to what is given in the account and leave the investigation of the cause of this condition of rest to another place. For (one should note) that this (kind of) rest is different from the one studied in *De Caelo*. In *De Caelo* it is investigated whether the earth as a whole has a rectilinear motion. Thus, (the earth) as a whole it has no motion at all, neither rectilinear, nor circular… The ancient natural philosophers have especially studied the earth (and investigated) what kept it at rest and why it was at rest here, for they thought that every part of it was moving in the air. Also, he who thought that it was not circular and thought that it is extended without limit, conceived a bearer for it, such as the Greeks talked about Atlas (Lettinck 1999, p. 457).

After attributing to only the fifth body, i.e. the celestial sphere, an internal motive power, Ibn Bājja goes on to explain how the other three elements are generated from fire by the weakening of the received fire's motion due to the distance traversed

> The fifth body has a nature or a soul by which it moves, and mover and moved are in the (same) moving body such the doctor who heals himself. The mover [of fire], however, is external, such as the hand which moves the pen. This is the cause of the perishing of fire, for it only perishes by getting wet or cold, and this only occurs when it is at rest. Therefore it moves with these motions until it gets further away from the daily motion; the motion in it becomes weaker, it arrives in another place and becomes air. If it occurs that it gets even farther away, so that it comes to rest completely, it becomes water or earth. This account is

> more fitting for *De Generatione et Corruptione*, for it gives the cause of the continuous generation of elements of each other (ibid., p. 461).

And in the following passage he gives his own reason why, unlike fire, the earth cannot be moved

> What is light can easily be divided and shaped and is in general easily receptive of motion, whereas earth by itself does not move at all, unless something strong forces it (to move) وٱلأرض غير متحركة جملة بذاتها إلا أن يقهرها قاهر قوي. If a part of a fire is always larger than a part of the earth, it has this kind of quantity not because its depth, length and width have a known proportion to each other – that is also the case for the earth, but there they exist permanently and have certain proportions which do not change unless by something which causes them to change; then it changes. Fire can easily be divided, and if it *meets the least of resistance* these proportions do not remain the same, but the proportions of the sizes change و النار سريعة التقسيم فإذا *صادفت أقل من مقاوم* لم تبق على تلك النسبة بل يتغير نسب أقطارها … The earth is not easily divisible; it can be divided only by something which *overpowers it in an appreciable time* و الأرض ليس لها هذا التقسيم سريعا إلا *بقاسم قاهر في زمان محسوس*. This is the essence of thickness and thinness (pp. 463–465, my emphasis).

According to Ibn Bājja, two reasons explain the immobility of the earth: (i) the weakening of motion coming from the fifth body; (ii) the inertial nature of matter: the strong resistance of the earth due to the high degree of density of the matter of which it is composed. The connection between Ibn Bājja's dynamic principle mentioned above and the explanation of the supralunar phenomena is very clear; all the main ideas are present: the weakening or retardation of motion in terms of the distance, the finite magnitude of velocity, the resistance function of the milieu and of the body to be moved (this is explicitly stated and discussed by Ibn Bājja). A full exposition of Ibn Bājja's interesting dynamics, which is different from that traditionally attributed to Philoponus, is beyond the scope of this paper. Duhem is perfectly right when he points out that "la *Théorie des planètes* [al-Bitrūjī's book] ne suggérait cette pensée [the passage quoted above] que d'une manière fugitive, dans le seul but de développer une comparaison" (*Le Système du Monde*, volume VIII, p. 175).

This brings the physical status of the earth more closely into the scientific discourse since the immobility of the earth is no longer assumed dogmatically but is integrated into the global explanation of the universe; and it appears to be a consequence of Ibn Bājja's dynamic principles. It thus appears that the importance given by al-Bitrūjī to the qualitative nature of his system is an attempt to fulfil the other part of Ibn al-Haytham's appeal: the explanation of the regularities of the movements of the heavenly bodies by adopting a more systematic physical approach to the study of empirical phenomena. With al-Bitrūjī, astronomy and dynamics become more closely linked than ever and the frontier between celestial and terrestrial phenomena is forever abolished. This is implicitly recognised by Duhem in his comment on al-Bitrūjī's conception of the universe:

> Au mouvement de la huitième sphère, al-Bitrūjī rattache ainsi les grandes variations de la surface terrestre, les déplacements des continents et des mers, dont les anciens philosophes grecs avaient affirmé la réalité et qu'Aristote, au second livre des *Météores,* réduisait aux proportions plus modestes d'inondations causées par l'abondance des pluies (Duhem 1913, volume II p. 156).

The underlying fruitful idea of al-Bitrūjī is that both sublunar and supralunar worlds, which were sharply distinguished by Ptolemy, have to be explained by a universal dynamics. This explains why al-Bitrūjī's system enjoyed an enthusiastic reception among medieval European philosophers. Albertus Magnus, for example, expresses his "fascination by a very simplified model of the theory of al-Bitrūjī i.e. the attempt to explain all celestial appearances by means of a single driving force that would carry all the celestial bodies in a more or a less rapid motion towards the west, which would account for their apparent motions towards the east" (in Rashed and Morelon 1996, p. 294). And Duhem confirms, at the end of his account of la *Théorie des planètes* or *On the Principles of Astronomy,* that al-Bitrūjī's conception has succeeded in being favoured by some European astronomers and mainly the Italian Averroists up to Copernicus.

> Tel est dans ses grandes lignes, cet ouvrage d'al-Bitrūjī qui devait, jusqu'au temps de Copernic, inspirer tous les adversaires, frayant ainsi la voie à l'astronome de Thorn (ibid., p. 156).

It is because of this deep foundational crisis in which astronomy finds itself that Copernicus proposes his heliocentric system.

> Après que j'eus longtemps roulé dans ma pensée cette incertitude où se trouvent les traditions mathématiques, touchant la théorie des mouvements célestes, il me prit un vif regret que les philosophes dont l'esprit a si minutieusement scruté les moindres objets de ce Monde, n'eussent trouvé aucune raison plus certaine des mouvements de la machine du Monde (quoted by Duhem 1994, pp. 73–74).

And if Copernicus succeeds in finding the heliocentric system, it is not because he takes the idea of placing the sun at the centre and making the earth move around it as a purely fictional hypothesis, but because he is strongly convinced that the new system is the true one; in other words it is because Copernicus, and the entire School of Padua which was the challenging capital to the domination of the Ptolemaic system in the rest of Europe, philosophically adheres to what Duhem calls the Arabic realist tradition.

> Copernic conçoit le problème astronomique comme le conçoivent les physiciens italiens dont il a été l'auditeur ou le condisciple; ce problème consiste à *sauver les apparences au moyen d'hypothèses conformes aux principes de la Physique.* (ibid., p. 73)

7 The Controversial-Based Nature of the Progress of Science: *Al-Shukūk* Vindicated by *Le Système du Monde*

We can now understand the sharp contrast between the Greek and the Arabic approach to the foundations of astronomy so much emphasised by Duhem in his introduction to the second chapter of *Le Système du Monde*, devoted to the Arabic physicians and astronomers.

> Le génie géométrique des Grecs s'était efforcé, avec autant de persévérance que de succès, à décomposer le mouvement compliqué et irrégulier de chaque astre errant en un petit

> nombre de mouvements circulaires simples. Leur génie logique et métaphysique s'était appliqué, de son côté, à l'examen des combinaisons de mouvements imaginées par les astronomes ; après quelques hésitations, il s'était refusé à regarder les excentriques et les épicycles comme des corps doués, au sein des cieux, d'une existence réelle ; il n'y avait voulu voir que des fictions de géomètre, propres à soumettre au calcul les phénomènes célestes ; pourvu que ces calculs s'accordassent avec les observations, pourvu que les hypothèses permissent de sauver les apparences, le but visé par l'astronome était atteint ; les hypothèses étaient utiles ; seul, le physicien eut été en droit de dire si elles étaient ou non-conformes à la réalité ; mais, dans la plupart des cas, les principes qu'il pouvait affirmer étaient trop généraux, trop peu détaillés pour l'autoriser à prononcer un tel jugement. Les Arabes n'ont pas reçu en partage la prodigieuse ingéniosité géométrique des Grecs ; ils n'ont pas connu davantage la précision et la sûreté de leur sens logique. Ils n'ont apporté que de bien minces perfectionnements aux hypothèses par lesquelles l'Astronomie hellène était parvenue à résoudre en mouvements simples la marche compliquée des planètes. Et d'autre part, lorsqu'ils ont examiné ces hypothèses, lorsqu'ils ont tenté d'en découvrir la véritable nature, leur vue n'a pu égaler en pénétration celle d'un Posidonius, d'un Ptolémée, d'un Proclus ou d'un Simplicius ; esclaves de l'imagination, ils ont cherché à voir et à toucher ce que les penseurs grecs avaient déclaré purement fictif et abstrait ; ils ont voulu réaliser, en des sphères solides roulant au sein des cieux, les excentriques et les épicycles que Ptolémée et ses successeurs donnaient comme artifices de calcul ; mais, dans cette œuvre même, ils n'ont fait que copier Ptolémée (Duhem 1913, volume II pp. 117–118; also Duhem 1994, pp. 27–28).

Unfortunately for Duhem, history has proved him wrong especially regarding the last claim. When he was writing these lines, he obviously did not know of Ibn al-Haytham'*al-Shukūk* nor of the works of the Marāgha School. What he calls Arabic realism does not appear by chance, nor by lack of imagination (interestingly Ibn al-Haytham has responded to the imagination argument), but is triggered by the desire for understanding on the part of Arabic physicians and astronomers. *Al-Shukūk* is a landmark in the history of science since it has the unprecedented effect of a priori destroying what seems to be an undisputed scientific theory (on empirical grounds) by successfully challenging its dogmatic and philosophical assumptions. For Arabic philosophers and astronomers both in the East and in the West, Ptolemy's approach, aiming at merely saving appearances, is dead. The influence of *al-Shukūk* has far exceeded the author's original expectations. Not only his successors, philosophers and astronomers alike, unanimously rejected the Ptolemaic model, but the criticism of the *Almagest* becomes widespread and extends to other areas not discussed by Ibn al-Haytham such as the problem of the order of the planets or the discrepancy between the moon's observation and Ptolemy's calculations. *Al-Shukūk* has changed the epistemological status of the *Almagest* forever: before Ibn al-Haytam's book, the Ptolemaic model was considered a well established and confirmed scientific theory; after *al-Shukūk,* it was no longer the case since it became instead the subject of intense theoretical and observational investigations aimed not only at finding new alternative models but more importantly at making astronomy a genuine scientific discipline by firmly basing it on sound and universal dynamic principles. It is then wrong to believe that it is Ibn al-Shāṭir or even Copernicus who satisfactorily answers Ibn al-Haytham-Ibn Rushd's unprecedented historical appeal since they both fail to provide the correct physical principles on which their model is founded. Nontheless their achievements are undoubtedly a great step in the right direction, and more research which means more controversies is needed before this task can be accomplished by Kepler and Newton.[6] Furthermore the appearance of *al-Shukūk* on the scientific scene creates a new environment which is described to us by Saliba in the following terms:

> In a very interesting additional comment, Ibn al-Akfānī goes on to say: 'The ancients continued to restrict themselves to pure circles in regard to the representations of the configurations of the celestial spheres until Abu Ali Ibn al-Haytham explicitly stated the corporeality of the latter and mentioned the conditions and the implications resulting therefrom. The later [astronomers] followed him in that.' In that regard, the content and composition of the *Tadhkira* [al-Ṭūsi's *Memoir*] made it an excellent introduction to that type of theoretical astronomy [...] and thus may have become suitable for School instruction. The number of commentaries written on it from within those Schools, and the direct evidence from later astronomers who studied commentaries on the *Tadhkira* as part of their School curriculum, attest very well to its popularity. This type of astronomical literature allowed people to discuss highly sophisticated astronomical matters, but this time in terms of real physical bodies, as was required by Ibn al-Haytham. It is this intersection of the mathematical and physical disciplines that formed the core of this type of texts. From that perspective, the inclusion of the *Tadhkira,* along with other *hay'a* [astronomical] texts, in the School curriculum must have meant that the subject matter of *hay'a* was no longer restricted to the few astronomers who were interested in reforming Ptolemaic astronomy. It must have then become the subject of various discussions by jurists and theologians who would have been among the regular students and teachers of such Schools. In that regard, the faults of Ptolemaic astronomy and the need to reform it must also have been well understood by the larger community (Saliba 1994, pp. 34–35).

This controversial attitude towards the Greek scientific writings, which characterises the Arabic literary tradition long before the advent of Islam, is not limited to astronomy but is common to nearly all the various scientific disciplines: in medicine and biology (Rāzī's *al-Shukūk 'ala Jālinus (Galen)*), in philosophy and metaphysics (al-Ghazālī's *al-Tahāfut*), in optics (Ibn al-Haytham's *Optics*), in physics (Ibn Bājja's famous refutation of the Aristotelian argument on the non-existence of the void), in logic (Ibn Taymiya's *Against the Greek Logicians*), to name just the most famous writings. It is this thorough, systematic and sustained challenge of the Greek scientific and philosophical works which, through its transmission to medieval European scholars, opens the way for modern science. And for this to happen, it is of cultural necessity that some pieces of the Greek scientific and philosophical shipwreck should be recovered from the sea's dark depths and brought to a more favourable milieu, and of historical necessity that science and philosophy should flourish once again in the middle East before they move westwards due this time to the rapid spread of knowledge. It is wrong, though, to infer from this that modern science is the result of the fruitful cultural exchanges between solely the two great civilisations of the Greeks and the Arabs; many ancient civilisations such as the Sumerians, the Babylonians, the Chaldeans, the Egyptians, the Phoenicians, the Persians, the Chinese, the Indians, have also contributed in one way or another to our present understanding of the world we live in. Interaction between various scientific disciplines has been universally recognised as indispensable to the good progress of science, but the role of intercultural scientific exchanges between different civilisations throughout history in the development of science has yet to be fully appreciated by historians of science and philosophy. If, however, we pay a little attention to the history of science, we shall find out that each civilisation, since the invention of writing, has tried, according to its cultural, historical and geographical background, to benefit from and build upon the achievements and inventions of its predecessors. And the construction of this magnificent scientific edifice does not progress monotonically, i.e. by accumulation or by steady and constant increase; this static interpretation assumes naïvely that history moves along a straight line which is actually not the case. It is obvious that the evolution of science is much more complicated than that since there are huge gaps in the making of science which cannot be explained by the monotonic approach. This explains why the logic of the history of science and philosophy follows, on the contrary, a rather nonmonotonic pattern: a scientific theory, astronomy for example, reaches a point where controversies are necessary for its further development. More precisely, a thesis (or theory), no matter how firmly it is established, will, sooner or later, be attacked by the construction of one or more arguments. The strength of the thesis is then put to the test depending on the arguments it produces to defend itself. The thesis preserves its position as an established or dominant doctrine if it succeeds in producing one or more counterarguments capable of defeating the arguments which are hostile to it. If, on the contrary, its counterarguments are defeated, this has an impact on the status of the thesis which finds itself refuted. Is the refutation of the former established thesis definitive?

Not at all — the refuted theory can be reinstated, either totally or partially, by the future emergence of one or several counterarguments strong enough to defeat the previous argument which defeats it. The status of the thesis is then assessed with respect to the set of all arguments available at a certain stage of the process of the exchanges of arguments and counterarguments; a status which is subject to change as soon as more arguments are constructed with the passage of time. In short nonmonotonic logic allows us to draw a provisory conclusion which can be modified or completely withdrawn when new information becomes available. It is this main feature of nonmonotonic logic that makes it a suitable instrument for capturing the structure of scientific controversies which are the driving force behind the dynamic development of science.

Unlike many modern historians of science who retain a narrow interpretation of the evolution of science, this point has not been missed out by Duhem since he recognises the necessary role of scientific and philosophical controversies in the advancement of science. The instrumentalist philosopher reflects on the consequences of the bitter controversy produced by al-Bitrūjī's doctrine on the development of astronomy throughout the Middle Ages up to Copernicus, and though throughout his exposition he makes full use of his good writing talent at the service of the saving appearances camp with the aim of persuading the reader of the superiority of the non-realist approach (giving thus more credit to the Non-Innovationists), he cannot resist drawing the right lesson:

> Il est une proposition qu'on peut formuler sans réserve et que la suite de cet écrit justifiera: cette œuvre qui n'est qu'une tentative et qui ne s'achève pas, aura la plus grande influence sur l'évolution de l'Astronomie occidentale. Cette influence, nous la reconnaîtrons partout et pour toujours, côtoyant celle qu'exerce la doctrine de Ptolémée, la contrariant et l'empêchant de ravir l'acquiescement unanime des astronomes. Le perpétuel conflit de ces

> deux influences entretiendra le doute et l'hésitation à l'égard de chacune d'elles ; il ne permettra pas aux intelligences d'être asservies par l'empire incontesté de l'une ou de l'autre d'entre elles ; il assurera aux esprits curieux la liberté de recherche sans laquelle la découverte d'un nouveau système astronomique fût demeurée impossible (Duhem volume II, p. 171).

And this is what *al-Shukūk* and other similar challenging arguments are all about. It is amazing to see that *Le Système du Monde* is just a vindication of Ibn al-Haytham's philosophical approach to the formation of science: the correct structure of the universe that he has called for did not emerge overnight from the mind of an individual scientist or even from the work of a single School of thought but it is the product of a long process in which scientists and philosophers, belonging to various currents of ideas, have taken part in a series of controversies through the exchange of arguments and counterarguments.

In his attempt to explain why there is a lack of originality in the Islamic tradition, de Vaux does not deny that Islamic thinkers enjoy free thinking which manifests itself in the critical attitude towards religious and scientific writings: "la science arabe", he admits, "avait vis-à vis de la parole révélée aussi bien que vis-à-vis de l'enseignement antique, toute la liberté de pensée nécessaire à son développement et à sa transformation" (in Carra de Vaux 1893, p. 337). But it seems to de Vaux that free thinking and the critical spirit are not sufficient to produce a scientist of genius such as Copernicus because the Arabic tradition lacks "la force du génie". Commenting on a letter sent by Copernicus to the Pope, Duhem tells us, on the other hand, how not men of genius but ideas of genius such as that of Copernicus are born, and why that gift of la "force du génie" of Copernicus appears in Padua and not in Torun or elsewhere.

> Ce passage évoque à nos esprits les grands débats qui agitaient les Universités italiennes au temps où Copernic est venu s'asseoir sur leurs bancs : d'une part, les discussions touchant la réforme du calendrier et la théorie de la précession des équinoxes ; d'autre part, l'ardente querelle entre les Averroistes et les partisans du Ptolémée ; du choc entre ces deux écoles a jailli l'étincelle qui a allumé le génie de Copernic (Duhem 1994, p. 73).

In view of the newly discovered eastern influence, however, we now know why the Copernicus model could not make its appearance before the fourteenth century: the time was needed for the mathematical apparatus to be fully developed by the Marāgha School.

The questions raised in the introduction have now been fully answered. As a conclusion, let us briefly recapitulate our views. It seems to me that one of the main achievements of the Arabic-Islamic civilisation is the institution of a lasting and an unprecedented dynamic research tradition, stretching from Samarkand in the East to Toledo in the West, in which diversity is the driving force behind its open and controversy based-approach to scientific and philosophical learning. Its contribution lies simply in its huge impact on the rest of the world. And it seems that it is the neighbouring south-western European countries which have benefited the most from the unprecedented globalisation of knowledge and learning in which Arabic was the vehicle language par excellence. The scientific and philosophical orient express can now continue uninterrupted its journey that started when it was first indefinitely propelled and unmistakably set on the right track.

A forthcoming paper will use concepts of the logic of defeasible argumentation, developed in our unpublished thesis and successfully applied to the study of the controversies on the foundations of mathematics, as an instrument for capturing the different levels of argumentation by sharpening the analysis of the exchange of arguments and counterarguments between Ptolemy and Ibn al-Haytham.

Acknowledgements

This paper has been developed in the context of the research project “La Science dans ses Contextes” directed by Shahid Rahman at the University of Lille 3, supported by MSH-Nord-Pas de Calais and the UMR 8163 “Savoirs, Textes, Langage” (STL). I would like to thank Laurence Broze, the director of the already mentioned MSH, and Fabienne Blaise and Philip Miller, the respective director and subdirector of the STL. My special thanks go to Professor Ahmad Hasnawi who kindly sent me a copy of Ibn al-Haytham’s *al-Shukūk*; to Professor Shahid Rahman who suggested some corrections and improvements on an earlier draft of the paper, and to Professors François de Gandt and Roshdi Rashed for their important remarks. My warm gratitude goes to Cheryl Rahman for having revised the English language.

Notes

1. “A person, who studies scientific books aiming at the knowledge of the real facts (الحقائق), ought to turn himself into an opponent of everything that he studies, he should thoroughly assess its main as well as its marginal parts, and oppose it from every point of view and in all its aspects. And while thus engaged in his opposition, he should also be suspicious of himself and not allow himself to become abusive or be indulgent [in his assessment]. If he takes this course, the real facts (الحقائق) will be revealed to him, and the possible shortcomings and flaws of his predecessors’ discourse will stand out clearly.” (p. 4)
2. The number of pages refers to the 1953 Dover edition reprinted as *A History of Astronomy from Thales to Kepler*.
3. All Ibn al-Haytham quotations refer to *al-Shukūk* unless stated otherwise. We have greatly benefited from the translation by G. Saliba and A. Sabra of some passages of Ibn al-Haytham’s book.
4. Sabra 1998, p. 312. But Sabra attributes these views to al-‘Urdi. I think that we do not have to wait until the thirteenth century to find this kind of argument concerning the foundations of astronomy. They are already present in the *al-Shukūk*.
5. For more details on Ibn al-Haytham’s epistemologically original approach in optics, see Simon 2003, mainly pp. 88–113.
6. See Duhem’s volume VIII of *Le Système du Monde* on the impact of another famous controversy concerning the principles of dynamics between Ibn Rushd and Ibn Bājja which is sparked off by the latter’s outstanding refutation of the Aristotelian argument on the non-existence of the void that signalled the beginning of the end of the Aristotelian physical system.

References

Primary Sources

Ibn al-Haytham: 1971, *al-Shukūk ʻala Batlamyus*, Edition of the Arabic text by A.I. Sabra and N. Shehaby, Dar al-Kutub, Cairo.

Ptolemy, C.: 1984, *The Almagest*, Translated and annotated by G. J. Toomer, Duckworth, Classical, Medieval and Renaissance editions, London.

Secondary Sources

Al-Bayhaqi: 1946, *Tarikh ḥukama' al-Islam*, al-Taraqqi Press, Damascus.

Al-Bitruji: 1971, *On the Principles of Astronomy*, Translated and annotated by B. Goldstein, 2 volumes, New Haven, Yale University Press.

Carra, de V.: 1893, "Les sphères célestes selon Nasīr Eddīn-Attūsī" in P. Tannery, *Recherches sur l'histoire de l'astronomie ancienne*, appendice VI, pp. 337–361, Editions Jacques Gabay.

Dreyer, J. L. M.: 1953, *History of Astronomy from Thales to Kepler*, Dover. (a replication of the 1906 *History of the Planetary Systems from Thales to Kepler*, Cambridge University Press.)

Duhem, P.: 1913–1965, *Le Système du monde: Histoire des doctrines cosmologiques de Platon à Copernic*, 10 volumes, Hermann, Paris.

Duhem, P.: 1994, *ΣΩΖΕΙΝ ΤΑ ΦΑΙΝΟΜΕΝΑ*: *Essai sur la notion de théorie physique*, Mathesis, Vrin, Paris.

Evans, J.: 1998, *The History and Practice of Ancient Astronomy*, Oxford University Press.

Hebraeus, B.: 1899, *Le livre de l'ascension de l'esprit*, Edition et Traduction de F. Nau, Bouillon, Paris.

Koestler, A.: 1968, *The Sleepwalkers*, The Danube Edition, Hutchinson of London.

Kuhn, T. S.: 1957, *The Copernican Revolution: Planetary Astronomy in the Development of western Thought*, Harvard University Press.

Lettinck, P.: 1999, *Aristotle's Meteorology and Its Reception in the Arab World: With an Edition and Translation of Ibn Suwar's Treatise on Meteorological Phenomena and Ibn Bājja's Commentary on the Meteorology*, Brill Academic Publishers.

Morelon, R.: 2000, "Ibn al-Haytham et ses arguments cosmologiques" in *Cosmologie et Philosophie* [Texte imprimé] = *Cosmology and philosophy*: hommage à Jacques Merleau-Ponty: [actes] du colloque / réalisé avec le concours du Centre de philosophie et d'histoire des sciences de l'Université de Paris 10-Nanterre, l'Équipe REHSEIS (UMR, CNRS et l'Université Paris 7 Denis Diderot) et le Centre d'Histoire des sciences cosmologiques de l'Université de Reims, Champagne-Ardennes, Paris-Nanterre, 6–8 octobre 1997; sous la direction de J. Seidengart & J.-J. Szczeciniarz ; Epistémologiques, pp. 101–111.

Neugebauer, O. and Swerdlow, N. M.: 1984, *Mathematical Astronomy in Copernicus's De Revolutionibus*, 2 volumes, Springer-Verlag.

Pines, S.: 1964, "Ibn al-Haytham's critique of Ptolemy", *Actes du dixième congrès international des sciences* I **10**, pp. 547–550, Paris.

Rahman, S. and Symons, J.: "Logic, Epistemology and the Unity of Science: An Encyclopedic Project in the Spirit of Neurath and Diderot" in Rahman, S., Gabbay, D., Symons, J. and J.P. van Bendegem (eds.): 2004, *Logic, Epistemology and the Unity of Science*, Dordrecht, Springer/Kluwer, pp. 3–17.

Rashed R. and Morelon R.: 1996, *An Encyclopedia of the History of Arabic Science*, 3 volumes, Routledge.

Sabra, A. I.: 1994, *Optics*, *Astronomy and Logic*, *Studies in Arabic Sciences and Philosophy*, Aldershot-Variorum.

Sabra, A. I.: 1998, "Configurating the universe: aporetic, problem-solving and kinematic", *Perspectives on Science* **6**, pp. 288–330.

Saliba, G.: 1994, *A History of Arabic Astronomy*, *Planetary Theories during the Golden Age of Islam*, New York University Press.

Saliba, G.: 1996, "Arabic Planetary Theories" in R. Rashed and R. Morelon, 1996, *An Encyclopedia of the History of Arabic Science*, volume 1, Astronomy: Theoretical and Applied, pp. 58–127, Routledge.

Saliba, G.: 2000, "Arabic versus Greek Astronomy: A Debate over the Foundations of Science", *Perspectives on Science* **8.4**, pp. 328–341.

Simon, G.: 2003, *Archéologie de la vision: l'optique*, *le corps*, *la peinture*, Editions du Seuil, Paris.

Tahiri, H.: 2005, *La dynamique de la négation et la logique avec inconsistances : quelques conséquences scientifiques et épistémologiques*, *vers un rapprochement entre la philosophie et l'histoire des sciences*, Université de Lille 3 (unpublished thesis).