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الرابطة المحمدية للعلماء

The Scientific Revolution and the Arab-Muslim Background

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A more expansive examination of the European scientific revolution of the seventeenth century reveals that it was larger in its contours and richer in its details than the standard accounts generally tell us. There were profound advances in optics, telescopy, microscopy, the study of human anatomy, pneumatics, the science of mechanics, and electrical studies, all of which bypassed the Muslim world. From 1600, the very first year of the seventeenth century, exceedingly important experimental inquiries were carried out and reported on. There was an amazing amount of experimental inquiry going on all over Europe, long before the founding of the Royal Society of London in 1661[1]. The invention of the telescope in 1608

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(1) Among other accounts see John Henry, The Scientific Revolution, third edition (New York: Palgrave MacMillan, 2008); Steven Shapin, The Scientific Revolution. Chicago: University of Chicago Press, 1996); and Herbert Butterfield, The Origins of Modern Science, third edition (New York: Free Press, 1957), who did grasp its radical implications. A good collection of primary sources is Science in Europe, 1500-1800. A Primary Sources Reader, edited by Malcolm Oster (London: Palgrave Press, 2002).

and then Galileo's use of it the next year opened a whole new vista of scientific inquiry. With this new*discovery machine*, as I have called it[1], the science of astronomy was transformed from a slow plodding inquiry into a new and dynamic exploratory science.

In that connection the fact has been overlooked that the telescope was taken all around the world in the decade and a half after Galileo's discoveries were announced in his *Starry Messenger* (of 1610). Indeed, the Chinese in 1615 had a report written in their own language telling of Galileo's discoveries, including a diagram of the strange "handles of Saturn" that were announced separately[2].

Similarly, the telescope was in the hands of the Ottomans, the Persians, and others in the Middle East by the late 1620s. It had arrived at the Mughal court of Sultan Jahangir in 1615. Yet there was no significant scientific response from those quarters when the telescope arrived. The Muslims were neither stimulated by its arrival to conduct new astronomical experiments, nor fascinated enough by it to make new and improved instruments such as the Europeans did all during the seventeenth century[3].

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(1) I have discussed the themes of this paper in more detail in Why the West? Science, Education and Economic Development (New York: Cambridge University Press, 2010).

(2) See Joseph Needham, Science and Civilisation in China (New York: Cambridge University Press, 1959), vol 3: 444f.

(3) Additional analysis of this episode can be found in T. Huff, "The Telescope and Scientific Curiosity in Non-Western Societies," in Science, Technology and Entrepreneurship in the Muslim World, edited by Leif Stenberg (University of Utah, forthcoming, 2010).

Nevertheless, for the last forty to fifty years, historians of Arab-Islamic science have given us new detailed studies of the high levels of technical achievement attained by Muslim astronomers during and after the Maragha period of the thirteenth century. Many studies have drawn attention to advances in mathematics, especially trigonometry and algebra. Likewise, the advances in optics achieved by Ibn al-Haytham have received considerable attention, along with the explanation of the rainbow put forth by Kamal al-Din al-Farisi and al-Shirazi in the early fourteenth century(1). Thereafter optics in the Middle East fell into quiescence, while it was an Italian craftsman in Florence who invented eyeglasses in 1286. A little more than a century later thousands of pairs of spectacles were being manufactured in Italy and shipped all over the world, especially to Istanbul, but also to Mughal India(2). It is difficult to imagine that affluent Muslims of the late fifteenth and early sixteenth century would have been unaware of this new technology.

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(1) Easily accessible accounts of these developments can be found in T. Huff, The Rise of Early Modern Science: Islam China and the West, 2nd ed (New York: Cambridge University Press, 2003); and "Understanding the Place of Science in Islamic Civilization," pp. 103-120 in Les sciences dans les sociétés Islamiques. Approches historiques et perspectives d'avenir, edited by Mohammed Abattouy (Casablanca: Fondation du Roi Abdul-Aziz al Saoud, 2007).

(2) Vincent Ilardi, "Eyeglasses and Concave Lenses in Fifteenth-Century Florence and Milan: New Documents," Renaissance Quarterly 29 (1976.): 341-360; idem, Renaissance Florence: The Optical Capital of the World." Journal of European Economic History 22 #3 (1993): 507- 542; and idem, Renaissance Vision from Spectacles to Telescopes (Philadelphia: American Philosophical Society, 2007).

Despite all this, the great hope of finding major scientific contributions from the Middle East in the thirteenth and fourteenth centuries has been pinned on the prospects of finding a major influence on Copernicus, either through the work of al-Tusi or Ibn al-Shatir. There appear to be similarities between some planetary parameters in Ibn al-Shatir's models and those of Copernicus, yet it remains true that there are no heliocentric models in any of the works of the Middle Eastern astronomers whose works have been found and examined. Consequently the connection with Copernicus remains tenuous at best.

Let us try to get beyond those episodes in order to focus on some of the unresolved problems that had to be surmounted in order to arrive at the new science of astronomy that would produce a *unified system of celestial and terrestrial* mechanics governed by the law of universal gravitation. That was the great task and successful accomplishment set forth in Isaac Newton's *Mathematical Principles of Natural Philosophy* of 1687.

Toward a Unified Celestial and Terrestrial Mechanics

If we think about the great challenge of getting to Newton's grand synthesis in broad terms, it is obvious that there were a half dozen or more fundamental principles that had to be worked out. A short list of these would include the following.

First of all the Ptolemaic system had to be replaced by a heliocentric system: Kepler's work and of course Newton's were predicated on this assumption of a sun-centered universe.

Second, Kepler saw that what was needed in Copernicus's new system was the idea of a *celestial physics based on physical causes*(1). He was the first to announce this agenda and recognized that Copernicus said nothing about what physical *causes* might be operative in the universe. Likewise, it would be very difficult to find an Arab astronomer who believed that some set of naturalistic physical causes governed the universe. Studies of Ali al-Qushji's writings of the fifteenth century, the astronomer who worked in Samarqand and later in Istanbul, for example, show that he was much more inclined to believe in the will of god than the forces of nature which Aristotelian natural philosophy was always predicated upon(2).

Third, it is evident that the Newtonian synthesis needed the *law of free fall* and the *law of inertia*, both formulated or articulated by Galileo, though sometimes not so clearly.

Fourth, in the actual working through of his synthesis, Newton needed Kepler's amazing third law, the one stating that there is some kind of physical constant in the orbits of all the planets such that the square of the period divided by the cube of the distance from the

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(1) Johannes Kepler, A New Astronomy Based upon Causes, or Celestial Physics...(Prague, 1609); English translation by William Donahue, New Astronomy (New York: Cambridge University Press, 1992).

(2) See Jamil Ragep, "'Ali Qushji and Regiomontanus: Eccentric Transformations and Copernican Revolutions," Journal for the History of Astronomy 36, pt 4 (2005): 359- 71 and Gerhard Endress, "Mathematics and Philosophy Through the Eyes of Abu Sahl al-Kuhi," pp. 119-176 in The Enterprise of Science in Islam. New Perspectives, edited by Jan P. Hogendijk and Abdelhamid A. Sabra (Cambridge: MIT Press, 2003), esp. pp.159-60.

center of the sun is the same for all planets. To the degree that this mathematical formula (based on mean periods of revolution) was mathematically correct, it was an advance on Copernicus's original idea that there is a relationship between the *distance* of the planets from the Sun and the *time* it takes for each of them to revolve around the Sun. Kepler's formula is a magical and inexplicable conception that is at once near and far from Newton's idea of universal gravitation. Kepler had a very poor explanation for the constant. He believed in an amalgam of magnetism and the mystical powers of the sun to push the planets around their orbits(1). Nevertheless, it was a fundamental principle on the way to Newton's synthesis.

Most important of all, let us notice that at the heart of astronomy as part of the new physics is the *science of motion*. In other words, planets are like projectiles and figuring out how the planetary system works required a *new science of motion*. Only those natural philosophers who had studied and advanced this discipline could contribute to the new science of mechanics at the center of Newton's revolution that was to emerge in the 1680s.

There are other elements missing in this sketch but it will serve for present purposes. I return to our underlying question: how does the Arab-Islamic background fit into this picture?

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(1) See Johannes Kepler, Epitome of Copernican Astronomy & Harmonies of the World. Translated by Charles Glenn Wallis (Amherst, New York: Prometheus Books, 1618-21/1995), especially pp. 55-60.

Stalemate in the Muslim World

The first thing to observe is that with regard to the sun-centered universe and the discovery of the relationship between planetary orbits and their distance from the sun, there is *no hint* of this in the Arab sources. Ever since Noel Swerdlow made his claim for a connection between Copernicus and Ibn al-Shatir[1], it has been assumed that sharing any set of orbital parameters, though all were derived from Ptolemy, must mean a real connection exists. But the problem is the fact that since the time of Ptolemy astronomers had worked with the same mathematical tools and the same Ptolemaic parameters for planetary orbits. The historian of mathematics, Otto Neugebauer stressed this point. He observed that comparing the tables of parameters for the *five* planets (Saturn, Jupiter, Mars, Venus, Mercury) in Ptolemy and in Copernicus, "the Copernican tables will produce practically the same results as the Ptolemaic ones"[2]. Essentially no new observations were added, even in the time of the thirteenth century reconstruction of the Alfonsine Tables (ca. 1252-70). Although Copernicus did make some observations of his own, in addition to eclipses, this was done mainly to confirm the accepted values taken from sources such as the Alfonsine Tables. Otherwise the *identity* of the Alfonsine and Ptolemaic parameters has been shown by

(1) Noel Swerdlow, "The Derivation and First Draft of Copernicus's Planetary Theory." Proceedings of the American Philosophical Society 117 (1973): 423- 512.

(2) Otto Neugebauer, "On the Planetary Theory of Copernicus," Vistas in Astronomy 10 (1968): 89-103 at p. 92 and 97.

computer calculations carried out by Owen Gingerich[1]. Consequently, the parameters for all the planets, not just Mercury and the Moon, were based on Ptolemaic values. From this it should not be surprising that models of planetary orbits in Copernicus and Ibn al-Shatir converged and were sometimes identical.

If we assume that Copernicus was tackling the same problems in astronomy as the Arab and Persian astronomers in thirteenth century Maragha, was pursuing the same astronomical objectives, using the same methods, and the same data (from the Ptolemaic-Alfonsine Tables), "it is by no means remarkable," the historian of astronomy, Mario Di Bono, has suggested, that Copernicus "obtains results very similar to those of his predecessors"[2]. Furthermore, the

(1) The identity of the tabular data in Ptolemy and the Alfonsine Tables has been tested and reported by Owen Gingerich: "'Crisis' versus Aesthetic in the Copernican Revolution," in pp 85-95 in Copernicus. Yesterday and Today. Vistas in Astronomy 17, edited by Arthur Beer and K. Aa. Strand (Oxford: Pergamon Press, 1975), p. 88; and in The Book that Nobody Read (New York: Walker and Company, 2004), p. 57. For discussions of the exact origins of the tables, see Emmanuel Poulle, "The Alfonsine Tables and Alfonso X of Castile," Journal for the History of Astronomy 29 (1988): 97-113; and José Chabâs and Bernard Goldstein, The Alfonsine Tables of Toledo (Boston: Kluwer Academic Publishers, 2003). Also see Owen Gingerich, "Commentary: Remarks on Copernicus's Observations," pp. 99-107 in The Copernican Achievement, edited by Robert S. Westman (Berkeley: University of California Press, 1975).

(2) Mario Di Bono, "Copernicus, Amico, Fracastoro and Tusi's Device," p. 147. Indeed, George Saliba produced a diagram for the upper planets showing the same point for planet P in Ptolemy, al-'Urdi, Ibn al-Shatir, Copernicus, and al-Khafri; see Islamic Science and the Making of the European Renaissance, p.206, figure 6.6.

"reciprocation device," often referred to as the Tusi Couple, "could equally well have been derived from an independent reflection on these same problems"(1). And there are other pre-Arab sources of the mechanism pointed out by historians of science(2).

Most important of all, the *orientations* of the two systems - one heliocentric and one geocentric- are radically different. In the meantime, no one has shown that Copernicus actually had access to Arabic documents (or others) that contained the Tusi mechanism or Ibn al-Shatir's models. Likewise, no one has shown that having access (hypothetically) to this material had anything to do with Copernicus's thinking that led him to his heliocentric models.

Mathematics

Let me turn now to perhaps the most plausible case for an Arab/Muslim *facilitating* influence on the path to modern astronomy: the role of Middle Eastern and Hindu mathematics.

(a) Algebra. The Hindu-Arabic numeral system was invented in India sometime before or during the seventh century and transmitted to Syria in 662 by Severus Sebokt. Soon thereafter the system of ten numerals including a zero, was adopted by the Persian scholar, al-Khwarizmi around 825.(3) It came to Europe in the late tenth century.

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(1) Ibid.

(2) I. N. Veselovsky, "Copernicus and Nasir al-Din al-Tusi," Journal for the History of Astronomy 4 (1973): 128-130.

(3) Paul Kunitzsch, "The Transmission of Hindu-Arabic Numerals Reconsidered," pp. 3-21 in The Enterprise of Science in Islam, edited by Jan P. Hogendijk and ➦

Slowly over several hundred years it was adopted for use by Europeans, although a mix of Roman and Arabic numerals continued to be used through the time of Copernicus. Indeed, Copernicus himself used such a mixture of these in *The Revolutions of the Heavenly Spheres*. He used Latin (that is Roman) numerals for angles and for dates, as well as for years and days, but used Arabic numbers that he called *Hindu* numerals for lengths of measurement(1). However, the prime operators (+ , -) [plus and minus] were not added to the system until the fifteenth century by Europeans, and the equal sign (=) was introduced by Robert Recorde around 1557(2). Consequently,

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A. I. Sabra (Cambridge: MIT Press, 2003). He writes, "All the oriental testimonies speak in favor of this line of transmission, beginning from Severus Sebokt in 662 through the Arabic-Islamic arithmeticians themselves and to Muslim historians and other writers," p. 4. For earlier discussions of these origins, see Louis C. Karpinski, "The Hindu-Arabic Numerals," Science 35 #900 (1912): 969-70; Florian Cajori, "The Controversy on the Origins of Our Numerals," The Scientific Monthly 9 #5 (1919): 458-64; and A. I. Sabra, "Ilm al-Hisab," Encyclopaedia of Islam, 2nd edition 3 (1979): 1138-1141.

(1) I was alerted to this practice by Owen Gingerich. See A. M. Duncan, translator, Copernicus on the Revolutions of the Heavenly Spheres, p. 320n 33. Similarly, Florian Cajori remarked on the continuing mix of Arabic and Roman numerals in written works in the sixteenth and seventeenth centuries, and even more examples in Spanish writings up to the nineteenth century. See Florian Cajori, in a review of The Hindu-Arabic Numerals by David Eugene Smith and Louis Charles Karpinski (Boston & London: Ginn and Company, 1911) in Science, n.s. v. 35 #900 (1912), p. 503. Also see Richard Lemay, "The Hispanic Origin of Our Present Numeral Forms," Viator 8 (1977): 435-59.

(2) For some of this background see Florian Cajori, A History of Mathematical Notation (La Salle, Illinois: Open Court, 1928), vol. 1: 128, 230-1, 235. For a

Copernicus did not know the modern algebraic notation so that, as his translator A. M. Duncan put it, Copernicus's "notation and expressions are entirely geometrical, following the Greek sources"[(1)].

Likewise, though Newton had invented some elements of the calculus in the 1660s, his full system did not emerge until after his *Principia* had been published in 1687. Hence his masterwork is a work of almost pure *geometry*, not algebraic calculation. His *Principia* contains no *equal signs*[(2)].

table listing the dates of the first European use of the four basic operators (+, -, x, : [addition, subtraction, multiplication, and division]) see Frank J, Swetz, Capitalism and Arithmetic. The New Math of the 15th Century (La Salle, Illinois: Open Court Press, 1987). For a useful review of the European receptive of this, see Alfred W. Crosby, The Measure of Reality. Quantification and Western Society, 1150-1600 (New York: Cambridge University Press, 1994), chapter 6.

(1) A. M. Duncan, trans., Copernicus: On the Revolutions of the Heavenly Sphere, p. 321n 34.

(2) Many recent scholars have deflated the calculus myths as regards the Principia; see A. R. Hall, Isaac Newton. Adventurer in Thought (New York: Cambridge University Press, 1992), pp. 212-213; I. B. Cohen, "A Guide to Newton's Principia," in The Mathematical Principles of Natural Philosophy. A New Translation by I. B. Cohen and Anne Whitman, assisted by Julia Budenz (Berkeley: University of California Press, 1999), pp. 49, 50, and Sect 5.4, pp. 114 if where the question of whether the Principia was written in "the manner of Greek Geometry" is discussed. For an analysis of Newton's revolutionary insights in the use of geometry to measure force, see Francois de Gandt, Force and Geometry in Newton's Principia, translated by Curtis Wilson (Princeton: Princeton University Press, 1995); J. Bruce Brackenridge and Michael Nauenberg, "Curvature in Newton's Dynamics" pp. 85-137 in The Cambridge

(b) Trigonometry. It is generally recognized that Middle Eastern mathematicians did a great deal to consolidate and develop trigonometry. The consensus among historians of Arabic-Islamic science is that the Arabs "were indisputably the founders of plane and spherical trigonometry, which properly speaking, did not exist among the Greeks"(1). Likewise, E. S. Kennedy agreed that trigonometry, the study of the plane and spherical triangle, "was essentially a creation of Arabic-writing scientists"(2). What this meant was that calculations of the sizes and dimensions of planes and spheres, triangles and related figures were greatly simplified. By the tenth century the mathematical functions known as the *sine*, *cosine*, and *tangent*, along with their tables of application, had been invented in the Middle East. With the great translation movement of the eleventh and twelfth centuries, these mathematical advances were brought to Europe, along with translations of Ptolemy's astronomy, known as "the greatest book," the *Almagest*, by the Arabs. Even so, just when and from whom

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→ Companion to Newton ed. I. B. Cohen and George E. Smith (New York: Cambridge University Press, 2002). For ways in which Newton's mathematics went beyond the classic geometric principles, see D. T. Whiteside, "The Mathematical Principles Underlying Newton's Principia Mathematica," Journal of the History of Astronomy 1 (1970): 116-138.

(1) Carra de Vaux, "Astronomy and Mathematics" in The Legacy of Islam (Oxford University Press, 1955, 1st ed.), p. 276.

(2) E. S. Kennedy, "The Arabic Heritage in the Exact Sciences" Al-Abhath 23 (1970): 337. Also see Kennedy, "The History of Trigonometry: An Overview" in Studies in the Islamic Exact Sciences, ed. E. S. Kennedy et al. (Beirut: American University Beirut Press, 1983), pp. 3-29.

Europeans learned of the rich details of trigonometry remains somewhat obscure [1].

The most important European consolidator and transmitter of the new trigonometry was the German mathematician and printer Regiomontanus (also known as Johann Müller, 1436-1476) who later taught mathematics at the University of Vienna, though he also traveled around Europe a great deal. But it was his teacher, Georg Peurbach (1423-1461) who launched the detailed study and assimilation of Ptolemy's *Almagest*. Though Peurbach died prematurely, he and Regiomontanus produced the most important European work in astronomy of the Renaissance, the *Epitome of the Almagest*[2]. The *Epitome,* however, was not a simple translation of Ptolemy's masterwork, but a very high-level commentary and exposition of the fundamentals of the Ptolemaic system that Peurbach and Regiomontanus deeply explored. It remained the most widely

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(1) Among the familiar Arabic or Persian names whose trigonometric works were studied by Europeans we find al-Battani, al-Farghani, al-Biruni, Abu l'Wafa, Az-Zaqali, and Nasir al-din al-Tusi. See John David Bond, "The Development of Trigonometric Methods down to the Close of the XVth Century," Isis 4 #2 (1921): 295-323; Barnabus Hughes, "Introduction" to Regiomontanus on Triangles. Translated with an Introduction and notes by Barnabus Hughes (Madison: University of Wisconsin Press, 1967), pp. 3-13; and J. L. Berggren, "Trigonometry in the Islamic World," in Episodes in the Mathematics of Medieval Islam (New York: Springer Books, 2003), pp. 127- 153.

(2) C. Doris Hellman and Noel Swerdlow, "Peurbach" DSB 15 (2008): 473-479; Michael Shank, "Regiomontanus" DSB 11 (2008): 216-219; and "Regiomontanus," www-history.mcs.st-andrews. ac. uk/Biographies/ Regiomontanus.html.

used work on Ptolemaic astronomy throughout this era. Accordingly, Regiomontanus's *Epitome* (finished in 1461 or 1463 but not printed until 1496)[1], was a work that Copernicus studied carefully.

What is also significant in the present context is the fact that Regiomontanus wrote a work on triangles (completed in 1464 but not published until 1533 in Nuremberg) that consolidated a large portion of what was known of the trigonometry that had been brought to Europe through various routes since the twelfth century renaissance[2]. That work also influenced Copernicus who introduced trigonometric material from *De Triangulis* into his *De Revolutionibus*[3]. Although this facilitating role is to be seen in the work of Copernicus, it does not give us the key to the latter's great leap to the heliocentric worldview discussed earlier. Although the exact path of Copernicus's heliocentric innovation is still not fully understood, it involved a transformation of epicyclic models into eccentric models using a geometrical transformation device articulated by Regiomontanus that has also been found earlier in the writings of Ali Qushji who worked both in Samarqand and Istanbul[4].

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(1) Michael H. Shank, "Regiomontanus, Johannes" Dictionary of Scientific Biography 11 (2008), p. 216.

(2) Regiomontanus on Triangles.

(3) Book One chapter 12 of De Revolutionibus contains an explanation of the method of calculating the sines of angles.

(4) Swerdlow, ibid.; J Ragep, "'Ali Qushji and Regiomontanus: Eccentric Transformations and Copernican Revolutions," Journal for the History of Astronomy 36, pt 4 (2005): 359- 71; Gingerich and MacLachlan, Nicolaus Copernicus. Making the Earth a Planet (New York: Oxford University Press, 2005), pp 57ff.

When Copernicus employed the transformation device, something spectacular occurred-something not achieved by any of the other astronomers who knew about the parallelogram transformation. That is, Copernicus, unlike others who had encountered the device, ended up in a *solar* system-one centered on the sun. Geometrically, as we see in Figure 1, the two models are identical, and astronomers all the way back to Ptolemy had run across this geometric fact. But getting from there to a new astronomical system required additional steps. Since observationally the two models gave the same results, there was no

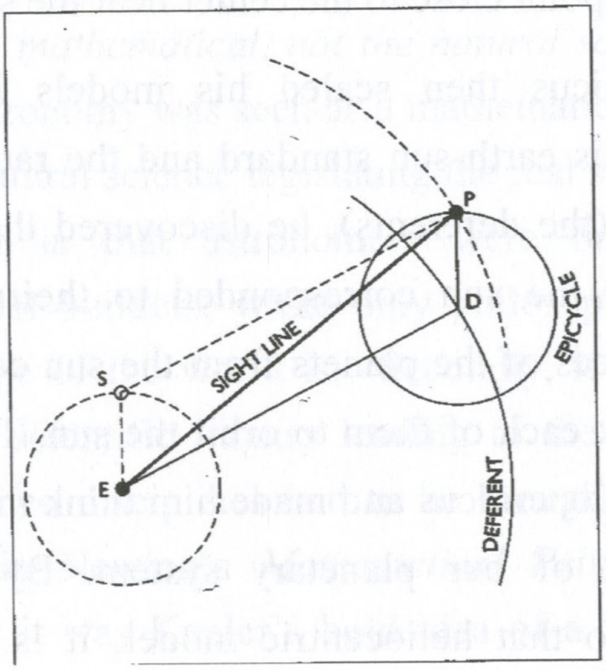

Figure 1. ***The Geometrical Transformation Device. In this diagram angles EDP and ESP are equal so that the same observational results are obtained regarding the orbit of planet P at point E or S, that is, a geo-centric or solar-centric point***[1].

easy way to decide which model was the true one. For some unknown reason, Copernicus decided to use the earth sun-distance as a standard

(1) From Gingerich and MacLachlan, ibid., p. 58; with permission. A more detailed account of this transformation appears on pp, 58-59 of that work.

for computing the relative sizes of the obits of the planets now centered on the sun. Previously, all the orbits were simply considered equivalent with varying epicycles. It was the dimensions of the epicycles that had actually been computed from observations in the past, not the size of the deferent circles.

Moreover, in this new model, epicycles and the deferents switched places so that the small epicycles were placed at the center around the sun while the deferents became very large circles, rotating on a moving epicyclic point close to the center near the sun[1].

When Copernicus then scaled his models in a sun-centered universe using this earth-sun standard and the ratios of epicycles to the large circles (the deferents), he discovered that the distances of the planets from the sun corresponded to their periods. In other words, the distances of the planets from the sun corresponded nicely to the time it took each of them to orbit the sun. This, naturally, was very pleasing to Copernicus and made him think that this must be the real arrangement of our planetary system. By whatever means Copernicus got to that heliocentric model, it is clear that Middle Eastern astronomers failed to get there.

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(1) I have followed the account of Gingerich and MacLachlan, Nicolaus Copernicus, pp. 58-60 and 66-67. Equally useful is Noel Swerdlow, "Copernicus, Nicolaus (1473-1543)," Encyclopedia of the Scientific Revolution (New York: Garland Press, 2000), especially pp. 163f.

Astronomy and the Science of Motion

Finally let us return to the other major breakthrough that was needed: a grand synthesis anchored in the science of physics. This brings us finally to the centrality of *mechanics as the science of motion* without which the great leap to Newton's synthesis would not have been possible. Physics and the science of motion had been central to Aristotelian physics since before Aristotle's time. On the other hand, *astronomy* in Aristotle's conception of the sciences was located among the *mathematical, not the natural sciences*. It was for that reason that astronomy was seen as a mathematical model-building enterprise, not a natural science legislating the real shape of the world. What that meant is that astronomers were only meant to be mathematical model builders, while only philosophers could decide what the real shape of the world is. Secondly, it meant that in the great long run of scientific inquiry leading to the modern scientific revolution, those two disciplines had to be brought together, as they ultimately were, in Newton's *Mathematical Principles of Natural Philosophy*(1). But it was Kepler's bold idea of a "celestial physics" that broke the mold by suggesting that the mathematical model-builders of the past—astronomers—might actually be able to say something true about the constitution of the world. Kepler thus acted as a natural *philosopher,* one who claimed to understand the workings of the cosmos.

(1) This broad line of development is very nicely traced out by Edward Grant in, A History of Natural Philosophy (New York: Cambridge University Press, 2007).

In the extended interval before Newton's synthesis, progress had to be made in the science of mechanics as well as astronomy. In the Muslim world very limited progress was made throughout the so-called golden age. It ended altogether in the early twelfth century. The last significant contributor to the science of motion was Ibn Bajja, the Andalusian Muslim philosopher of the early twelfth century. There are indications that some of his thinking did aid medieval Europeans[1]. But after him historians of science have failed to find any successors of his caliber. Neither the Ottomans nor the Mughals wrote significant treatises on the science of motion in the years between Ibn Bajja and Galileo or Kepler[2]. A major reason for this is that none of Aristotle's

(1) For an analysis of Ibn Bajja's work and its influence on medieval European natural philosophers, see Marshall Clagett, The Science of Mechanics in the Middle Ages (Madison: University of Wisconsin Press, 1959); and the essays of Ernest Moody, "Laws of Motion in Medieval Physics," Scientific Monthly, 72 (1951):18-23; idem, "Galileo and Avempace: The Dynamics of the Leaning Tower Experiment," in Roots of Scientific Thought, edited by Philip P. Wiener and Aaron Noland (New York: Basic Books, 1957), pp. 176-206; as well as John E. Murdoch and Edith D. Sylla, "The Science of Motion" in Science in the Middle Ages, edited by David C. Lindberg (Chicago: University of Chicago Press, 1978), pp. 206-264.

(2) For an overview of Ottoman science, see Ekmeleddin Ihsanoglu, "The Introduction of Western Science to the Ottoman World: A Case of Study of Modern Astronomy (1600-1800)," ibid. Apart from some histories of astronomy in the Mughal Empire in the sixteenth and seventeenth centuries, no studies of fragments of the science of motion or magnetism in India in this period seem to exist. For aspects of the history of seventeenth astronomy in India see S. M. Razaullah Ansari, "Introduction of Modern Western Astronomy in India During the 18-19 Centuries," in History of Astronomy in India, edited by S. N. Sen and K. S. Shula (New Delhi: Indian National Science Academy,

natural books on physics and the science of motion were taught in the madrasas. Ibn Bajja's contribution to the science of motion, that was actually rejected by Averroes, was the notion that if you take away the force of the surrounding air, the speed of the propelled object would *not* be instantaneously infinite, but would reveal the *natural motion* of the object. But that realization is a long way from Galileo's law of inertia as well as his law of free fall.

The Making of Newton's Synthesis

It is now evident that very little of the Arab-Islamic scientific tradition had a significant impact on the great innovators who crafted the core of the scientific revolution of the seventeenth century. Copernicus, Galileo, Kepler and Newton each contributed unique elements to the grand synthesis put forth by Isaac Newton in 1687. Moreover, what has often been portrayed as the most advanced part of the Islamic scientific tradition, namely mathematics which in Aristotle's view is *not* a natural science, added undetectable elements to the advances of the four great architects of the scientific century revolution mentioned above.

What was needed to get to Newton's grand outcome was the synthesis of Kepler's 3/2 law, Galileo's law of inertia and free fall, and the proof that if an object falls toward the earth, its trajectory would be an ellipsis; secondly the *force* involved would *vary inversely with the square of the distance between the centers* of physical

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1985); and Rajesh Kochhar, "Pre-Telescopic Astronomy in India" in History of Indian Science, Technology and Culture AD 1000-1800 (Oxford University Press, 2000).

objects, whether they be planets, stones or particles. Sir Christopher Wren, Robert Hooke, and the young Edmund Halley all knew this result must be right, but only Newton could prove it. Moreover, Newton *achieved his great synthesis*, not by using algebra, trigonometry, or calculus, but by using *geometry*.

Neither the Mughals, Ottomans, or Persians – nor the Chinese for that matter- were on that path to a new *unified science of celestial and terrestrial* motion[(1)].

(1) I have reviewed the scientific traditions in those other cultural areas in Why the West? Science, Education and Economic Development (forthcoming: Cambridge University Press, 2010).