From Aristotle to Newton via Baghdad

The publication in 1962 of the seminal book "The Structure of Scientific Revolutions" by Thomas Kuhn introduced the idea of "paradigm shift" into the history of scientific development. Kuhn challenged the common view that the history of science proceeded by steady evolution, and suggested instead that science moves forward in significant stepwise revolutions, which departed from deeply ingrained concepts. He called these events "paradigm shifts". This paper aspires to give a brief glance at how one of these shifts changed our understanding of the solar system, and how much was due to contributions from the Arab world.

It was Aristotle's metaphysics, which placed the earth at the center of the universe, that dominated astronomy for a full 2,000 years after his death in the fourth century BCE. Aristotle's fundamental belief was that an unnamed Deity displayed His perfection by the neatness and order of His creation. Because of that, Aristotle posited that the only suitable geometric model for the cosmos was a perfect sphere. Also, his physics proposed that each body has its own "natural motion". Therefore the motion of a sphere must equally be perfect, and therefore it was in a circle, which has neither beginning nor end.

The concept of "natural motion" – that the heavens moved in natural ways which could be modeled geometrically, rather than by the whims of gods, was a major conceptual step forward. It also fit nicely with what could be easily observed – the roundness of the sun and moon, the diurnal arcs of the stars, the arc of the Earth's shadow on the eclipsed moon. But the observed motions of the sun, moon, and the five known planets were more complex. Even the word "planet" is actually derived from the Greek word for "wanderer".

Tonight I would like to describe the path leading to the point where twenty centuries after Aristotle, Johannes Kepler, using the exquisitely accurate naked eye observations of his mentor Tycho Brahe, broke with the Aristotelean paradigm of perfect circular motion by hypothesizing that the true motion of the planets was elliptical. By doing so, Kepler reduced the observational errors and simplified the models. Kepler's paradigm shift was both proved and eclipsed only 68 years later, when Isaac Newton published his gravitational theory, explaining the reasons for the elliptical motion that Kepler had intuited.

Returning then to the problem that ancient astronomers had: they struggled to describe the actual elliptical motion of the planets within the daunting Aristotelean constraint of using only constant circular motions centered on the earth. They observed significant anomalies from that constraint, the most obvious of which was the irregular retrograde motion of the planets. For example, since Earth circles the sun faster than Mars, Mars appears from the Earth to change direction with respect to the stars behind it, as Earth catches up and passes it.

To account for these anomalies, Aristotle assigned each planet to a spherical shell. He incorporated earlier theories to imagine that our solar system consists of multiple nested spheres, each made from a crystallized "first element", later called the "aether" or "quintessence", which were arranged like the layers of an onion surrounding the Earth. The outermost shell contained the fixed stars, and the inner ones contained the five known planets plus the sun and the moon. To explain all of the anomalies, Aristotle proposed a total of fifty-seven shells, each body requiring multiple shells, each rotating on separate axes. And since his physics postulated that all motion requires the application of a continuing force, (a concept which was held for nearly 2,000 years until Galileo discovered inertia), Aristotle theorized that the motion was due to the existence of what he called an “unmoved mover” which imparted motion to each shell. In Aristotle’s words; “For motion in space is the first of the kinds of change, and motion in a circle the first kind of spatial motion; and this the first mover produces.”(1)

To understand the origins of astronomical predictions, we need to go back centuries earlier to Babylon. The Babylonians had started keeping track of celestial events for their astrological and agricultural portent. The earliest records are of the intervals between the last and first visibilities of Venus, just before sunrise and just after sunset, from the 17th Century BCE. They used these types of observations to search for repetitive combinations of cycles of different bodies. An example of their discoveries was the Saros eclipse cycle of just over 18 years, when the circumstances of a solar eclipse closely repeat, due to a confluence of lunar and solar cycles. From observing these various cycles, the Babylonians were able to create tables which allowed recurring phenomena to be forecast, such as the dates of full and new moon, times and circumstances of eclipses, et cetera.

It is not known exactly how, but the ancient Greeks were influenced by Babylonian astronomy. For example, the Metonic cycle of 19 years, which tells when a new or full moon will repeat on the same day of the year, is known from

Babylonian cuneiform tablets dating from before 500 BCE, although its discovery is generally ascribed to the Greek Meton some 70 years later in 432. Another important influence was the adoption of the Babylonian measurement system using 60 as the base. This Babylonian system has come down to us through the Greeks as the 360 degree circle, divided into 60 minutes per degree and 60 seconds per minute, and the equivalent divisions of the hour. Perhaps more significant for simplified mathematical calculation was the invention of the place value notation we use today: for example "432" means 400 + 30 + 2. However, the fundamental concept the Babylonians developed was that numerical models could be devised to provide reliable predictions of complex astronomical phenomena.

200 years after Aristotle, by the 2nd century BCE, it appears that all earlier Greek and Babylonian knowledge of astronomy had become available to one of the greatest astronomers of antiquity, Hipparcus. He was able to devise a working mathematical model of the solar system by combining the Greek descriptive geometric with the Babylonian arithmetic methods and data. He is the inventor of trigonometry, and created the first known trigonometric table, a table of chord lengths equivalent to, but more unwieldy in use than a table of the sine function. He also excelled as an observer, producing the first comprehensive star catalog of about 850 stars, which is a substantial portion of the approximately 4,500 stars potentially visible on a dark night from one location. And from his study of the Babylonian records, Hipparchus is most famous for discovering the very slow rotation of earth's axis of rotation, like the wobble of a spinning top, known for its effect as the "precession of the equinoxes". He estimated a value of just 1 degree

per century, versus today's value of 1.4 degree, which is now known to be due to the pull of the moon's gravity on the earth's equatorial bulge.

Hipparchus adapted earlier explanations of planetary motion that had first been proposed by Apollonius of Perga in the 3rd century BCE. He used the concept of "epicycles" and "eccentric circles" to describe the observed motions of the planets. These approximated the then unknown elliptical orbits by using only circular motion. An epicycle can be visualized as a small rotating wheel whose axle rotates on the rim of a larger wheel, while each wheel is rotating at a constant speed. A different concept, but mathematically the same, is to offset the axle of the large wheel from the observer, therefore called eccentric motion. In either case, by choice of radii and rotation speeds, a point on the rim of the smaller wheel will show retrograde motion in accordance to observations, and move closer to and further away from the observer.

Most of what is known about Hipparchus comes from the writings of his great successor, Claudius Ptolemy, nearly three centuries later. Ptolemy lived in Alexandria, Egypt during the 2nd century CE. He was a Roman citizen, most likely of Greek ethnicity, and one of the greatest scientists of all time. He wrote eight treatises of applied mathematics on a variety of subjects, ranging from optics, mechanics, and geography to musical harmony and astrology. The most famous is his astronomical treatise, the Almagest, from the Arabic "al-megisti" meaning the greatest, but more modestly titled by Ptolemy as the *Syntaxis Mathematica*. It was the culmination of Greek astronomy and their geocentric model of the solar system.

The Almagest brings together in logical order all the necessary mathematical proofs, observational methods and instrument design, and using historical observational data then details how to create the tables necessary to calculate the position of the solar system bodies at any time in the past or future. It became the defining text on astronomy, improved upon but remaining the standard text for 14 centuries, up to and including the publication by Nicolaus Copernicus' of his heliocentric thesis in 1543 CE. Ptolemy probably had the resources of the great library at the Mouseion in Alexandria available to him, including all of Hipparchus' now lost writings, as well as Babylonian data going back to the lunar eclipse of 746 BCE, all of which is only known to us today from the Almagest.

Ptolemy elevated mathematical prediction of solar body positions to be the major focus of astronomy, and he developed and proved the mathematics to accomplish that end. But to attain the necessary accuracy to explain the observations, he had to stretch the imbedded view of an earth-centered solar system that was only in constant circular motion. He was less concerned that his model reflected physical reality, and more concerned that his predictions were accurate. And for this, later generations criticized him, even as they struggled to find a better model, while simultaneously continuing to improve the Ptolemaic model with new observations and mathematical innovations.

One of the major objections was to Ptolemy's concept of an "equant", in which the Earth is offset from the center of rotation, causing a body to appear to change speed and to move closer to and further from the Earth during its orbit.

This clearly violated Aristotle's dictum of geocentric constant motion, but the artifact was necessary in order to make his mathematical model fit the observational data.

Here we have to pause a moment, because much of what I have just related would not be known without the support of the Arab world. The remarkable truth is that we have to credit the "Translation Movement" and the "House of Wisdom" that flourished in Baghdad starting in the 8th century, for much of this history, and also for much of our knowledge of all ancient Greek philosophy and science.

Baghdad was the capital of the "Islamic Golden Age", which lasted until the 13th century CE, starting with the "Translation Movement" and the "House of Wisdom" in the middle of the 8th century, just a hundred years after the death of Muhamad in 632. The Translation Movement was to stretch over two hundred years. By 750 the Arabs controlled all the territory extending from Spain, across North Africa, and from Egypt to India, territory larger than either the Greeks under Alexander or that of the Roman Empire. An important result of this large empire was the breaking down of political barriers, and the introduction of Arabic as a common language, all of which generated increased trade and the exchange of ideas throughout the empire, resulting in greatly increased wealth.

The ruling caliphate at the time was the Abbasid. They captured the Umayyad capital of Damascus in 750, starting a dynasty that endured for 500 years, until it was finally toppled by the Mongol invasion in 1258.

The Abassids from the beginning recognized the necessity of inclusion, particularly due to the large debt they owed the Persians for their help in overthrowing the Umayyads. They built a new capital in Baghdad, which was in a very different demographic area from the previous capital in predominately Greek Damascus. It was a multi-ethnic city, with its population made up of Aramaic speaking Christians and Jews, both Zoroastrian and Muslim Persian speakers, Christian Arabs, and Arab Muslims, with the latter a minority. While Arabic was the lingua franca, it remained a polyglot community, in which all were considered near equals.

To help legitimize their rule, the Abassids undertook to incorporate Persian culture into theirs. Al-Manṣūr, the second Abassid caliph and the founder of Baghdad, was the initial architect of this uniquely open society, which he established through three routes: First, he legitimized Zoroastrian astrology through his own deep belief in it and charged his three astrologers not only to choose the date for starting the construction of his new capital in Baghdad, but to develop an astrological history legitimizing his rule. Secondly, he placed Persians in high positions in his administration, and third, he began the translation movement, drawing on the cultural history of translation into Persian from Greek and Hindu sources. Over the century since the initial Arab conquest of Persia, there had been a continuing decline of the Persian language in favor of Arabic, thus creating a demand for Arabic versions of Persian writings, particularly about Zoroastrian ideology, but also for Greek and Hindu works that had been translated into Persian.

While the Translation Movement began under the caliph al-Manṣūr, the greatest credit for it is generally given to his great-grandson, al-Ma'mūn, who also is credited with the founding of the "House of Wisdom". There are differing views of what the "House of Wisdom" really was, ranging from it being a loose agglomeration of scholars working in Baghdad, to a building compound housing international scholars together with a great library supported by the state. What is certain is that Baghdad became a great intellectual center under al-Ma'mūn, and that there must have been an important palace library, among many others.

Al- Ma'mūn belonged to the Mutazalite school of Islam. Importantly, Mutazalites celebrated the power of reason and the human intellect[(2)], reflecting their reading of the Quran, which encourages learning. Al- Ma'mūn himself practiced *kalām*, which is a formal science of discourse, and regularly invited scholars to his palace for discussion of scientific and philosophical subjects, setting an example for open scholarly debate.

With the active support of the caliph, the Translation Movement also gained support from the upper echelons of social, military, and political society, who would hire their own translators, maintain libraries, and search for books to translate. The great wealth that flowed to Baghdad from all over the empire supported the movement: Al- Ma'mūn reportedly required some of his defeated enemies to pay him in books rather than gold, and he was willing to pay a book's weight in gold for a particularly desirable item. Due to the widespread support of Baghdad's elite, libraries containing thousands of manuscripts were created.

The skills of the translators grew as the Translation Movement matured. Good translations required competence in the subject matter, as well as specialized vocabulary, so study of the translations led to improved translations. Most of the focus was on science and mathematics, such as astronomy, geometry, astrology, logic, and medicine. As scholarship improved, commentaries were written on the translated works in order to teach others, so that Baghdad's reputation grew, attracting even more scholars, turning Baghdad into the intellectual capital of the world, and Arabic into the language of science. Top scholars and translators earned incomes that were among the highest in Baghdad and they held honored status in society.

Mathematical astronomy was of particular importance, since it both under-pinned astrological calculations, and was important to the practice of Islam. For example, spherical astronomy allowed calculation of the *quibla*, or direction of prayer towards Mecca, as well as the orientation of mosques. Also, the months of the Islamic calendar began with the Imam's first sighting of the new moon, which was aided by astronomical tables. Even the determination of the five times of daily prayer relied on astronomy. Every mosque employed a timekeeper for that purpose, and he needed to be versed in astronomy to do his job.

Not surprisingly, one of the Translation Movement's first and most often translated works was Ptolemy's Almagest. Not only was it translated, but commentaries and summaries and simplifications of it were written. New observations were made, causing adjustments to Ptolemy's data, and tables were recalculated, as he had foreseen. Improved methods of calculation were developed, such as using the Hindu sine function in place of the clumsier chord function, and the invention of the additional trigonometric functions of cosine and tangent. To quote one historian, they "corrected, completed, criticized, and brought the contents up to date both theoretically and practically". [3]

But Arab astronomers in the 11th century began to have doubts about the Almagest. These doubts were mainly philosophical, and were focused on objections to Ptolemy's violation of Aristotle's notion of perfectly circular and constant earth-centered motion. These doubts caused Arabic astronomers working from the 11th through the 14th centuries to come up with ingenious devices to overcome these concerns. One of the most brilliant was al-Tūsi who developed in the 13th century what is known today as the "Tūsi couple", which allowed linear motion to be created via rotating circles at constant speed. Then around 1350, Ibn al-Shātir used a version of the Tūsi couple to make a completely concentric model, which resolved the doubters' issues, although it did not improve the accuracy.

The cultural fruits of the Golden Age also made their way into Islamic Spain, or al-Andalus, and the intellectual centers that had developed there. The initial capital of Toledo, which competed with Baghdad for cultural ascendancy, had a royal library reported to contain nearly 400,000 books by around 970. In 1085 the so called Christian Reconquista conquered Cordoba. Fortunately, it was declared an open city, in return for a promise to protect Muslims' religious rights, and to support its continuation as a center of learning.

Thus the stage was set for a new translation movement in Christian Toledo, known as the Toledo School of Translators. This was a polyglot group of scholars; Jews, Christians, Christian Arabs, and Islamic Arabs, who worked together during the 12th and 13th centuries to translate many of the classical works from Arabic, first into Latin, and later into Castilian in the 13th century. The Greek classics, as well as Arabic scientific works, had been inaccessible to the Latin West before then. Archbishop Raymond of Toledo led the first translation program of the philosophical and religious portion of these works from Arabic into Latin. Much of the work was done in teams, for example, one person translating from Arabic to Castilian, and then another into Latin, or else using Hebrew as the intermediate language.

Scholars from other parts of Europe heard of the intellectual activities in Toledo, and came to participate in either learning or translation. One of the most productive translators there was one Gerard of Cremona, credited with seventy-one works. He had come to Toledo around 1144 in search of Ptolemy's Almagest, and learned Arabic in order to create, over ten years, what would become the standard Latin translation. He also translated works of the great mathematician al-Kwarizmi, who invented algebra and incorporated the Hindu number system, thus causing our so called Arabic numbers, along with decimal notation and algebraic methods, to become available to the Latin West.

Ptolemy's Almagest continued to be the major text for advanced astronomy. In particular, a remarkable German known as Regiomontanus undertook to finish the work of his teacher, Georg Peurbach, in writing a Latin commentary on the

Almagest designed to supersede all others. This treatise, *Epitome of the Almagest*, succeeded admirably, becoming the standard textbook for Ptolemaic astronomy in 50 editions over three hundred years.

Regiomontanus was a prodigy, entering Leipzig University in 1447 at the age of 11. Exhausting the resources there, he entered the University of Vienna at 14, where he studied under Peurbach, receiving his B.A. at 16. While he lived only a short life, dying at age forty, he accomplished a great deal. He was the first to apply the new invention of moveable type to the mathematical sciences. He undertook the massive job of calculating and printing accurate and extensive trigonometric tables, and then, using Ptolemaic methods, ephemerides of the sun, moon and planets covering the 32 years from 1475 to 1506, and of lunar and solar eclipses from 1475 to 1530. The latter tables were used by Christopher Columbus and later explorers to establish longitudes in the Americas, although with varying accuracy.

Nicolaus Copernicus published his seminal work, *De Revolutionibus*, on his deathbed in 1543, and ushered in what is now known as the Copernican Revolution. He proposed a heliocentric solar system which simplified the physical explanations for many phenomena, such as the changing of the seasons and the retrograde motion of the planets.

But how indebted was Copernicus to Islamic astronomy? Certainly, about some of that debt there is no doubt. He directly references five Islamic astronomers, and it is known that he studied Regiomontanus' *Epitome* and had a firm understanding of Ptolemaic theory. That being said, we know that although he was accomplished in Greek and Latin and several other languages, he had no knowledge of Arabic. Still, his mathematics closely mimics that of al-Shātir a couple of centuries earlier, who had found ways to modify Ptolemy so it didn't conflict with Aristotle's insistence on geocentric uniform circular motion. However, there is no evidence that a Latin translation of al-Shātir was ever made, or that his writings were otherwise available to Copernicus. Similarly there is no evidence of how he would know about the al-Tūsi couple which he clearly used in *De Revolutionibus*. But in this case there is a "smoking gun". The diagram of the proof published by Copernicus is virtually the same as that published by al-Tūsi, with even the same lettering of the vertices. Some scholars believe Copernicus could have invented these on his own, while others find the circumstantial evidence too compelling that he must have known of the Arabic astronomy, but from a yet undetermined source.

His revolution took a very long time to become accepted. As far back as the 3rd century BCE the Greek Aristarchus had proposed a sun centered system, but it never achieved any traction. Even sixty years after Copernicus only fifteen astronomers supported heliocentrism, but importantly, one them was Galileo Galilei. Part of the reason for its slow acceptance was not only extreme Catholic opposition and the entrenchment of the earth centered view, but also that Copernicus continued to use the complexity of Ptolemy's epicycles (those small wheels rotating on the rim of a larger one), and he used even more of them in his mathematical model. Further, his model produced no better results than the geocentric ones, nor was there any way to discriminate between the two models by observation. In addition, supporters of geocentrism pointed to the fact that when you throw a ball straight up, it falls straight down. They believed that if the earth were truly rotating under it, it should land further away.

The first proof of heliocentrism was provided by Galileo's telescopic observations in 1610. Through his telescope he was able to discern Venus cycling through phases similar to those of the moon, and he realized that this could only happen if Venus was circling the sun. His observations of four moons circling Jupiter provided further evidence that not all bodies revolve around the earth, and his discovery of craters on the moon disproved the Aristotelean ideal that all heavenly bodies were perfect spheres of crystalline aether.

Now the bases for the final paradigm shift from geocentrism to heliocentrism and elliptical orbits were nearly all in place. Tycho Brahe was a Danish noble who, in 1576, with support from his King, built a castle with the finest observatory in Europe, named Uraniborg. Here he designed and built instruments enabling the most accurate astronomical measurements to date, and with the help of many assistants, carried out extensive observing programs of the planets.

A new Danish king reduced the royal support for Uraniborg, so in 1598 Tycho set up an observatory in Prague, under the patronage of the Holy Roman Emperor. By good fortune he invited a young German to join him in order to help calculate orbits based on his observations. His name was Johannes Kepler. Only a year later, in 1601, Tycho died, but he left the legacy of his extensive observations in the very capable hands of his 30 year old assistant.

Kepler had grown up a Copernican, never doubting heliocentricity. Tycho's measurements of planets were accurate to within only 2 minutes of arc, equal to the width of a dime viewed from 100 feet, a remarkable achievement without a telescope. This accuracy allowed Kepler to refine his evolving theories, which had previously undetectable errors of as little as 9 minutes of arc, in order to deduce his three laws of motion.

In 1609 Kepler published the first two of his three laws: first, that the planets move in elliptical orbits, and second that they sweep out equal areas in equal time, thus moving fastest when closest to the sun. The third law was published ten years later, which related the orbital velocity to the distance from the sun. Kepler's three laws sealed the end of support for Aristotle's view of the solar system, and of Ptolemaic mathematics. 68 years later, Newton's publication of his revolutionary theory of gravitation in 1687, provided the explanation of why Kepler's laws worked, and marked the start of the Age of Reason. The paradigm of geocentric circular motion had finally shifted.

By focusing selectively within the field of astronomy, this paper can only hint at the Western world's debt to Islamic scholarship. Similar stories can be told about medicine, chemistry, mathematics, philosophy, and so forth. Our awareness of Islam's Golden Age, the Translation Movement, and the House of Wisdom is limited. Partly this is due to the West's colonial view of the Middle East from the

19th century: we find it hard to credit conquered colonies for our cultural roots in ancient Greece. Partly this results from a lack of scholarly research: it is estimated that only 10% of extant Arabic materials are available to the West. A larger part may be the view represented by the thesis of Pierre Duhem, an influential French philosopher and scientist working at the end of the 19th century, and author in 1913 of a 10 volume *History of the Cosmological Doctrines from Plato to Copernicus*. He claimed "that the Arabs were incapable of scientific thought and that whatever merits their science may have had were due to the intellectually superior Greeks"[(4)] Research since then has led most people to a less xenophobic conclusion, and particularly in the last twenty years, to a growing awareness of Muslim contributions to Western science.

Presented to the Chit-Chat Club of San Francisco on 11 September 2018 by Peter B. Dunckel

Notes:

(1) Aristotle, *Metaphysics* XII, Part 7

(2) al-Kahlili, 2011, p. 125

(3) Saliba, 1997, p. 148

(4) Walker, 1996, p. 171

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