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Astronomy in the Islamic world: a European perspective

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Mathematical and astronomical achievements of the Islamic world during its golden era are briefly exposed. The article is based on the invited talk delivered remotely at the ICRANET-Isfahan Astronomical Meeting, November 2–5, 2021, which, in turn, reproduces major parts of one of the chapters of my book "Our Celestial Clockwork", published recently (2021) by the World Scientific.

1 The spread and the golden age of Islam

At the end of the fifth century C.E. the Roman Empire was in shambles. It was divided into the Western and Eastern parts already in 395 C.E., and prone to steadily increasing barbarian invasions ever since. The last Roman emperor Romulus Augustulus was disposed of in 476 C.E. by Germanic war chief Odoaker, who proclaimed himself emperor.

The Eastern part of the Empire with its capital in Constantinople gradually transformed into Greek-speaking Byzantine Empire. All these territories, including Egypt and North Africa up to Spain were Christian since the Emperor Constantinus proclaimed Christianity to become state religion. However, since the fall of the Western Roman Empire, most of these territories were deprived of any organized army and statehood and prone to barbarian invasions, among which the Huns, the Goths and the Vandals were the most important and disastrous.

In the midst of the 7^{th} century C.E. a new religion was proclaimed by Muhammad in Arabia, derived from Jewish and Christian traditions, simplifying them and professing with great conviction the uniqueness of God. This was an important revolution, because it replaced the tribal principle by a more general religious and social unity.

While Europe entered the Dark Ages, an era of turmoil and invasions, lasting roughly from 500 C.E. until the 12^{th} century, the Arabs have conquered vast territories creating a buyoant Islamic Civilization, which spread from Moorish Spain in the West,

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through Western North Africa, through Egypt and Mesopotamia, touching India and even the most western parts of China. During first few centuries, they had to cope with the still mighty Eastern Roman Empire, and the powerful great Persian Empire of the Sassanides.

The main stages of this extraordinary politically-religious adventure can be represented as follows:

- Rightly Guided Caliphs 632–661
- Umayyad Expansion 661–750
- Abbasid Expansion 750–1258
- Moorish Spain 756–1162

The only precedent of as rapid expansion was the Hellenistic empire built by Alexander the Great. Like ancient Greek and Latin in the Roman Empire, the Arabic language became universal among Islamic scholars, with Persian and Turkish as subsidiary in the East. Ancient Greek science has been assimilated and developed further. Aristotle, Euclid and Ptolemy were translated and multiplied in countless copies. Medical science of ancient Greeks was also honored, and Hippocrates and Galen were translated, too.

The *Golden Age* of Islamic civilization covers the time span from 9^{th} till 13^{th} century C.E. in Baghdad under the *Abassid* dynasty, and in Moorish Spain until the fourteenth century; it lasted a little longer in Central Asia, falling under the Mongol conquest.

During the first 115 years of the Abbasid Caliphate (from 750 to 1258 CE), the Islamic State saw a record growth in the fields of the arts of literature and music, the sciences (especially astronomy), philosophy, mathematics, medicine, culture, commerce, and industry. Arabic, the language of the Quran became the language of international scholarship. In addition to the capital, Baghdad, many provincial centers competed with each other. A number of scientific terms of arabic origin are in use in Western science until today, and known to everybody: it is enough to cite a few, like *algebra*, *algorithm*, *zenith*, *azimuth*, *nadir*, *alcohol*, *alcali*.

In 751 C.E., with the help of a few Chinese prisoners, the Abbasid governor of Samarkand founded the paper industry. In 800 C.E. paper mills were established in Baghdad and Damascus; in 900 C.E. another one was established in Cairo. By 1150 C.E. several were established in Morocco and Spain. As a result, Islamic learning spread rapidly into Europe.

In 756 CE, Amir Abd ar-Rahman came to power in Spain. His term also contributed to the Islamic Golden Age. He organized a system of law and justice and was very fond of knowledge and learning. Scholars from all over Europe sought the knowledge and learning from Spain during his term. Islamic Universities were the only educational institutions free of charge.

In 830 CE the seventh Abbasid Caliph, al-Mamun, established the famous House of Wisdom in Baghdad. The Greek language gave way to Arabic as a form of expression of scientific and philosophical ideas. Classical Greek literature was translated into Arabic and Arabic speaking scholars wrote a number of renowned commentaries.

No wonder that during the awakening of Medieval Western Europe, the scholars first turned to Arabic translations of ancient Greek science. In order to enrich Chris-

tian Europe in scientific, medical and philosophical studies, these works had to be retranslated into Latin. This was mainly done in Muslim Spain and Sicily and these books served as textbooks in universities for centuries.

However, recognizing the crucial role of Islamic Golden Age in in the transmission of ancient Greek science, we should not forget the fact that it was previously conserved and transmitted by Romans and Greeks themselves, especially during the early Christian era. The first Arabic translations were made no earlier than in the midst of the 8th century, 1100 years after Aristotle, 1050 years after Euclid and 900 years after Ptolemy published their scientific papers in Greek, which were written originally on a relatively fragile papyrus support. An average papyrus, especially if it was used for frequent reading, would last no more than a couple of centuries; this means that the papyri from which the Arabs translated the works of Aristotle, Euclid and Ptolemy were already copied many times and translated into Syriac by Christians of the Eastern Roman Empire. Before that, Latin translations were made in the West and conserved some remote monasteries, mostly in Ireland, and forgotten. The new impulse came from Baghdad and Spain during the Golden Age of Islam.

2 The sources

Islamic science took its sources on both sides of its geographical spread, namely in Greek scientific tradition conserved in Byzantium and in Hellenistic Egypt, both christianized since many centuries, and in Indian and Persian mathematical and astronomical traditions.

The Greeks owed much of astronomical knowledge to the earlier Babylonian and Egyptian civilizations; however, they enriched and extended them in unprecedented proportions.

In ancient Babylon, the observations were performed by Chaldeians from the top of pyramidal constructions called *ziggurats*. They were able to determine with astonishing precision the celestial coordinates of stars and planets, and follow the Sun's annual and the Moon's monthly motions. As in the ancient Egypt, timekeeping was one of their most important functions, as well as interpreting omens from planetary configurations and other noticeable celestial events, especially solar and lunar eclipses, some of which they came to predict quite successfully due to the comprehension of the so-called *saros* periodicity.

The earliest acquaintance of the Islamic world with mathematics and astronomy was due to Indian and Persian influences. From India, the Arabs took the decimal system with numerals and zero which we use today. The main Indian mathematical text by Brahmagupta (598–670 C.E.) was very early translated into Arabic.

It contained, among others, the idea of negative numbers and their algebraical properties. They were called "debts", in opposition to positive numbers called "fortunes". Not only was their algebraic addition defined, but also the multiplication, with well-known rules, including the fact that a product of two negative numbers is a positive one.

Brahmagupta owed much of his knowledge to his predecessor Aryabhata (476–550 C.E.), duly called the "father of Indian mathematics". Aryabhata was undoubtedly the greatest mathematician and astronomer of ancient India. His major work is

known as *Aryabhatiya*. It contained the elements of spherical trigonometry, quadratic equations, algebra, plane trigonometry, sums of power series and arithmetics.

On the western side of the Arabs' early advance were the vast territories of the christianized Roman Empire, heir to Latin and Greek culture and civilization. The three pillars of Greek science which were adopted by Arab and Islamic polymaths were: Aristotle for physics and all other natural sciences, Euclid for geometry, and Ptolemy for astronomy. Their major works were translated, copied, edited and commented upon by Muslim scholars for centuries to come.

Aristotle would assume the title of "First Teacher", vouching for all the intellectual heritage of the Greeks, viewed as a systematic knowledge compatible with the Muslim worldview. Together with Aristotle's own works, the Arabs translated an equally great amount of commentaries tracing back to late Antiquity, particularly to the School of Alexandria. Some of Plato's texts were translated at the same time.

Another great contribution to the development of science in the Islamic world came from ancient Greece via the translation of the totality of books written by Euclid. The great Greek mathematician Euclid united in the 13 books of his major work, "The Elements" the geometrical knowledge elaborated by his predecessors, Pythagoras (570–495 B.C.E.), Hippocrates of Chios (470–410 B.C.E), Eudoxus of Cnidos (406–355 B.C.E.). Euclid's merit was not only the systematization of all geometrical facts and theorems known in his time, but above all, the proof that they can be derived from only FIVE POSTULATES.

The "Elements" were copied many times in Greek in Byzantium, and later on translated in Syriac. The Arabic translation from Syriac and Greek appeared around 800 C.E. under the Khalif Haroun al-Rachid. In 1120, English monk Adelard of Bath translated Euclid's book from Arabic into Latin.

However, ancient Greek mathematics was mostly geometry, which was conceived as more basic than arithmetics. In fact, Greeks made a clear distinction between "numbers", which were reduced to integers, fractions and rational numbers, and "magnitudes" such as the diagonal of a square, which was proven to be not expressible as ratonal number (fraction). Greek calculus was marred by the absence of adequate notation system including the extremely useful concept of zero, present in Indian mathematics. The Arabs were able to merge the two notions into a single one, including negative numbers and incommensurable quantities like square roots.

Astronomy, which in these times was synonymous with astrology, was given great importance by Muslim rulers since the advent of Islam. The main bulk of astronomical knowledge was contained in Ptolemy's "Magna Opus", translated into Arabic from Syriac and Greek versions conserved in Christian libraries that survived the fall of Roman Empire.

Claudius Ptolemy lived in the Egyptian city of Alexandria from 100 till 170 C.E. or even till 178 C.E. according to some Arab commentators and translators of his writings. At that time Egypt was a Roman province ruled by the Greek dynasty bearing the same family name, *Ptolemaios*.

Ptolemy was the last great representative of Greek science, heir to a tradition eight centuries old. Ptolemy lived and worked 400 years after Euclid, 600 years after Pericles and 700 years after Anaximander of Miletus who was the first to suggest the idea of the celestial sphere and to produce a map of the inhabited world known in his time. Little is known about Ptolemy's life except that he probably spent it all in

Alexandria, where he observed two solar eclipses: one in the ninth year of Hadrian's rule (125 C.E.) and in the fourth year of Antoninus' rule (141 C.E.). Besides his *Syntaxis Mathematicus*, known also as "Magnum Opus" due to its importance for astronomy, and mostly under the name of its arabic translation *Almagest*. Ptolemy was also a renowned geographer in his time.

The geocentric system elaborated in *Syntaxis* was universally accepted during Hellenic and Roman antiquity, and later on by medieval Christian and Muslim civilizations alike, and was used to describe and predict motions of celestial bodies by astronomers and astrologists.

3 Islamic science and scholars

Mathematics and astronomy in the Islamic world developed in a larger context of cultural, philosophical, religious and scientific development, due to remarkable thinkers, physicians and polymaths, among whom the greatest ones were the following:

- **Al-Farabi** (...?–950) known in the Christian world under the latinized name *Alpharabius*. He spent most of his life in Baghdad. A prolific writer, he authored comments on Platonic and Aristotelian philosophy, and original works on physics, alchemy, psychology, astronomy and music. His authority was so great in the Islamic world, that he was often called "The Second Teacher" – meaning second after Aristotle. His comments paved the way to the philosophical synthesis by Ibn Sina (Avicenna) and Ibn Rushd (Averroes). In his late years he moved to Damascus, where he died in 950 C.E.

- **Avicenna (Ibn Sina)** (...?–1037), renowned physician and philosopher, called "The Third Teacher". His most appreciated work was the *Canon of Medicine*, a manual of medical science in many volumes, which became the authority for European doctors after it was translated into Latin. Among his lasting contributions was the drug testing method and the discovery of the infectiousness of tuberculosis.

- **Averroes (Ibn Rushd)** (1126–1198). Considered as one of the greatest Muslim scientists, he was born in Andalusia, then ruled by the Almoravid dynasty, later passed under the Almohads. He studied diligently the writings of Aristotle, Al-Farabi and Ibn-Sina (Avicenna). He became the most influential Islamic scientist among the Europeans; his writings were studied in Padova, Salamanca, Oxford and Sorbonne.

In 1189 the Almohad caliph al-Mansour prohibits practicing music, poetry, and overall, philosophy. Averroes is accused of heresy and banished first from Cordoba, then from Andalusia to Morocco; his books are burned and prohibited. Although partly pardoned, he died in Morocco, never being permitted to come back to his hometown Cordoba.

- **Omar Khayyam** (1048–1131), a renowned mathematician, astronomer, philosopher and poet. Born in Nishapur, of Persian origin, he received an excellent education in his native Nishapur, and afterwards moved to Samarkand (now in Uzbekistan). His mathematical reputation rests principally on his *"Treatise on Demonstration of Problems of Algebra"*. He made such a name for himself that the

Seljuq sultan Malik-Shah invited him to Isfahan to undertake the astronomical observations necessary for the reform of the calendar. To accomplish this an observatory was built there, and a new calendar was produced, known as the Jalali calendar. Based on making 8 of every 33 years leap years, it was more accurate than the present Gregorian calendar, and it was adopted in 1075 by Malik-Shah.

His years in Isfahan were very productive ones, but after the death of his patron in 1092 he fell in disgrace, and returned to Nishapur where he taught and served the court as an astrologer. Omar's fame in the West rests upon the collection of robaiyat, or quatrains, attributed to him.

4 Mathematics

One of the most often repeated claims is that Muslims invented algebra. This is largely true, even if initially they took source in ancient Greek and Indian mathematics. The word "algebra" comes from the arabic *al-jabr* and means "restoring" or "putting parts together".

It was coined by Persian mathematician and astronomer al-Khwarizmi (ca. 780 – ca. 850 C.E.) who lived in Baghdad, in his treatise *"llm al-jabr wa al-muqabala"*, which means "Science of putting parts together and balancing". In modern algebraical terms, the first word referred to the possibility of replacing terms from one side of an equation to another, and adding or substracting the same quantity from both sides. Al-Kwarizmi's name refers to the city of Khorezm (today in Uzbekistan) and was known in the West in its latinized version *Alkorizm* or *Algorithm*, and became the name of a general prescription in mathematics.

Al Khwarizmi's book contained plenty of examples of how to solve problems involving commerce, trade, inheritance, marriage and redemption of slaves. The examples did not involve any algebraic symbols yet, using geometrical figures modelling the relations between numbers. But in other Arabic mathematical treatises symbols, numbers and words tended to replace geometrical constructions. This was a major revolution in mathematics, with enormous impact on its further development.

For the mathematicians of ancient Greece a major difference existed between *numbers* and *magnitudes*, the second ones meaning measurable lengths, areas or volumes. Numbers were used as long as they could be expressed as integers or their ratios, e.e. fractions. These quantities were called "rational numbers", in contrast with "irrational ones", which could be constructed geometrically, but not algebraically, like the most famous square root of 2, which is simply the diagonal of a unit square, but no finite fraction exists whose square would be equal to 2.

The new approach to mathematics made possible simple and elegant proofs in place of sophisticated geometric constructions. For example, while the well known geometrical theorem saying that the area of a square with sides $a + b$ is equal to the area of a square with side a plus the area of another square with side b plus the area of two rectangles of sides a and b can be proved with no effort by an obvious geometric construction, the proof of another formula, that the area of a rectangle with sides $(a + b)$ and $(a - b)$ (with $a > b$) is equal to the difference between the areas of squares with sides a and b, i.e. $(a + b) \cdot (a - b) = a^2 - b^2$, needs a more sophisticated geometrical construction, Among the shortcomings of the purely geometrical approach

of the ancient Greeks was the lack of interest in the possibility of negative numbers and arithmetical operations involving negative entities, which were known in ancient China since 300 B.C.E. Islamic mathematicians not only incorporated negative numbers in algebraic operations, but also started to treat rational and irrational numbers in the same way making no distinction when adding, subtracting or multiplying them.

The advantage of the algebraic approach is that it can be easily generalized beyond its usefulness in describing geometrical constructions in two and three dimensions.

Nevertheless most of Muslim authors did not consider negative numbers on the same footing as the positive ones. They knew how to solve linear and quadratic equations, but whenever there was a negative solution, they rejected it as "absurd".

An important step forward due to Muslim mathematicians is the establishment of new arithmetic algorithms: the extension of root-extraction procedures, known to Hindus and Greeks only for square and cube roots, to roots of higher degree and by the extension of the Hindu decimal system for whole numbers to include decimal fractions as computational devices. Omar Khayyam (1148–1131 C.E.), Persian mathematician, philosopher, astronomer and poet (remembered more for his beautiful poetry than for mathematical achievements) considered the general problem of extracting roots of any desired degree. He also closely approached the general solution of cubic equations, and elaborated a unifying approach to geometry and algebra.

Islamic algebraists of the 10^{th} century made substantial progress, generalizing al-Khwarizmi's quadratic polynomials to the algebra of expressions involving arbitrary positive or negative integral powers of the unknown. Several algebraists explicitly stressed the analogy between the rules for working with powers of the unknown in algebra and those for working with powers of 10 in arithmetic.

Similar progress was made in geometry. The Islamic mathematicians Thabit ibn Qurrah (836–901), his grandson Ibrahim ibn Sinan (909–946), Abu Sahl al-Kuhi (died c. 995), and Ibn al-Haytham (965–1040), known in Europe as Alhazen, solved problems involving the geometry of conic sections, including the calculus of areas and volumes of plane and solid figures formed from them. They also investigated the optical properties of mirrors made from conic sections, which became of crucial importance centuries later, for the construction of optical devices.

5 Astronomy

During the "Golden Age" of Islam, astronomy was one of the most important sciences. Muslim religion had imposed several requirements which needed important astronomical skills to improve the time-keeping and space orientation. Exact timing of five obligatory prayers a day, beginning and the end of fast during the holy month of Ramadan, linked to the first and last crescent of the Moon, establishing times of islamic holidays – all that created the need for astronomical observations.

Newly constructed Mosques had to be oriented towards Mecca in the Arabian Peninsula, and so should be positioned a Muslim during his prayer – this alone needed improved geographical and astronomical knowledge, too.

Finally, vast territories of Islam, with flourishing terrestrial and maritime trade, made necessary the emergence of practical astronomy, improving observational devices like sextants and astrolabiums, to be used on land or in the open sea.

Astronomy became the chief amongst the sciences in which Muslim scholars excelled. Success was built upon mastery of mathematics, geometry in particular, as much as the philosophical inheritance of the ancient Greeks and other early civilizations through translation into Arabic. Observatories founded in the most important centres of learning such as Baghdad and Cairo required specialized instruments for observation and instruction. These included celestial globes, quadrants, and armillary spheres, but the most sophisticated instrument adopted and developed by Muslim astronomers was the *astrolabe*.

How great was the impact of the Arabs on European astronomy that took the lead after 16^{th} century can be easily seen in any modern stellar atlas. Here are a few among the best known bright stars whose names are of the Arab origin:

Aldebaran, α Tauri, from arabic *Al-Dabaran*, the "Follower";

Algol, β Persei, from arabic *Al Ghoul*, the "Demon", or "Scary monster" (named so probably because its periodical blinking in the matter of hours could be easily seen by the naked eye).

Altair, α Aquilae, from arabic *an-Nisr ut-Ta'ir*, the "Flying Eagle";

Betelgeuse, α Orionis, from arabic *Yad al Jawza*, the "Hand of Al-Jawza", a mythical character;

Deneb, α Cygni, from arabic *Dhaneb ud-Djadjab*, "Hen's tail";

Dubhe, α Ursae Majoris, from arabic *Dubb*, "Bear";

Fomalhaut, α Piscis Austrini, from arabic *Fum al-Hul*, the "Mouth of the Whale".

The Arab astronomers continued observations using the techniques inherited from Greeks and incorporating other ancient traditions, e.g. from Persia and India. They were often able to improve and enrich the data collected by Ptolemy in his *Almagest*. An example: following Hipparchus, Ptolemy estimated precession of the equinoxes to be of 1° per 100 years, which would correspond to completing the full cycle in 36000 years. Egyptian astronomer Ibn Yunus (850–1009 C.E.) has corrected this estimate, reducing it down to 1° in 70 years, which corresponds to the full cycle of 25200 years, very close to the presently accepted value. Let us present the most remarkable astronomers and their contributions.

- **Al-Khwarizmi** (ca. 786–850 C.E.), of Persian origin, was appointed by al-Mamoun, the son of Harun-al-Rashid of the Abbasid dynasty, as the chief astronomer and head of the library in the "House of Wisdom" in Baghdad.

Al-Khwarizmi's important strides in astronomy and geography include the measurement of the length of a degree of a meridian in the plain of Sinjar, improving Erastothenes' evaluation of Earth's circumference, the creation of a world map based on the geography of Ptolemy, providing more accurate coordinates of approximately 2 400 sites in the known world. These results were contained in his book "Kitab surat al-ard" ("The Image of the Earth") .

Another al-Khwarizmi's treaty that made it into the Western canon of mathematical studies was a compilation of astronomical tables including a table of sines, and this was translated into Latin. He also produced two treatises on the sundial, on the astrolabe, and one on the Jewish calendar. Around 1110 the Englishman Robert of Chester, who was then in Spain, translated into Latin Al-Khwarizmi's al-Jabr (Algebra) and introduced into Europe Arabic numerals, including the figure zero, which

the Arabs themselves had borrowed from the Indian mathematicians.

• **Al-Battani** (died in 929), known to Europe as Albategni or Albatenius was the author of the *Sabian tables* (al-Zij al-Sabi), a work which had great impact on his Muslim and Christian successors. His improved tables of the orbits of the sun and the moon comprise his discovery that the direction of the sun's eccentric as recorded by Ptolemy was changing. This, in modern astronomy, means the Earth's line of apsides is slowly moving. He also worked on the timing of the new moons, the length of the solar and sideral year, the prediction of eclipses, and the phenomenon of parallax.

Al-Battani was also a pioneer in the field of trigonometry. He was among the first, if not the first, to use trigonometric ratios as we know them today. During the same period, Yahya Ibn Abi Mansour had completely revised the Zij of Almagest after meticulous observations and tests producing the famous Al-Zij al Mumtahan (the validated Zij). In al-Zij al-Sabi (known as the Sabian Tables), Al-Battani plotted the Sun's orbit more accurately than Ptolemy did. In his *"De Revolutionibus"*, Copernicus refers to Al-Battani's calculations no fewer than 23 times.

• Belonging to the same era, **Abd-al Rahman al-Sufi** (903–986) made several observations on the obliquity of the ecliptic and the motion of the sun (or the length of the solar year). He became renowned for his observations and descriptions of the stars, their positions, their brightness and their colour, setting out his results constellation by constellation. For each constellation, he provided two drawings, one from the outside of a celestial globe, and the other from the inside (as seen from the sky). Al-Sufi also wrote comments on the astrolabe, finding numerous additional uses for it (including one's location, measuring distances and heights, etc.)

• Egyptian astronomer **Ibn Yunus** (died in 1009), in his observation endeavours included, amongst others more than 10, 000 entries of the Sun's position throughout the years using a large astrolabe of nearly 1.4 m in diameter. His work in the French edition, was centuries later an inspiration for Laplace in his determination of the "Obliquity of the Ecliptic" and the "Inequalities of Jupiter and Saturn".

The famous European astronomer Newcomb also used his observations of eclipses in the motions of the moon.

• **Al-Biruni** (973–1050) claimed that the Earth rotated around its own axis. He calculated Earth's circumference, and fixed scientifically the direction of Mecca from any point of the globe. Al-Biruni wrote in total 150 works, including 35 treatises on pure astronomy, of which only six have survived. In addition, in the late 10^{th} century Abu-al-Wafa and the prince Abu Nasr Mansur stated and proved theorems of plane and spherical geometry that could be applied by astronomers and geographers, including the laws of sines and tangents. Al-Biruni was Abu Nasr's pupil; he produced a vast amount of high-quality work, and was one of the masters in applying these theorems to astronomy and to such problems in mathematical geography as the determination of latitudes and longitudes, the distances between cities, and the direction from one city to another.

• **Al-Farghani** was one of Caliph Al-Mamun's astronomers. He wrote on the astrolabe, explaining the mathematical theory behind the instrument and correcting faulty geometrical constructions of the central disc, that were current then. His most famous book on cosmography, *Kitab fi Harakat Al-Samawiyah wa Jaamai Ilm al-Nujum*, contains thirty chapters including a description of the inhabited part of the

Earth, its size, the distances of the heavenly bodies from the Earth and their sizes, as well as other phenomena.

• **Al-Zarqali** (Arzachel) (1029–1087) prepared the Toledan Tables and was also a renowned instrument maker who constructed a more sophisticated astrolabe: a *safiha*, accompanied by a treatise explaining how to use it.

• **Jabir Ibn Aflah** (died in 1145) was the first to design a portable celestial sphere to measure and explain the movements of celestial objects. Jabir is specially noted for his work on spherical trigonometry. Al-Bitruji's work "*Kitab-al-Hay'ah*" was translated by the Sicilian based Michael Scot, and bore considerable influence thereafter.

• **Nur ad-Din al-Bitruji** (ca. 1150–1200 C.E.), known in Europe as *Alpetragius*, is the author of *Kitab fi al-haya*, "A Book on Cosmology". He lived in Moorish Spain, in Andalusia, at the end of the Islamic Golden Age. He was probably a disciple of astronomer Ibn Tufayl. The problem faced by al-Bitruji was that faced by all Aristotelians who were reading Ptolemy's Almagest. Aristotle clearly stated that the planets must move with circular motions and implied that the center of these motions must be identical with the center of the Earth; he further desired a mechanism to transfer the motion of the prime mover to the planetary spheres.

Al-Bitruji followed the suggestion of Ibn Tufayl, as did the latter's other pupil Averroes, and attempted to adjust the Aristotelian solution in such a way that it would correspond to observed reality. The attempt failed owing to the inherent inadequacy of the homocentric system to describe the phenomena.

• **Al-Tusi** (1201–1274), was the last great astronomer of Islamic Golden Age, and without exaggeration can be given the title of "Hipparchus of Islamic Astronomy". Of Persian origin, he studied in his native town Tus, then in the nearby town Nishapur, educated in philosophy, medicine and mathematics. Already in Nishapur al-Tusi acquired a reputation as an oustanding scholar, and became a member of Ismaili Court invited by the shi'ite ruler Abd ar-Rahman.

Al-Tusi stayed and worked in the Alamut castle until it fell to the troops of Dzhengis Khan's grandson Hulagu. Al-Tusi's reputation was so great that Hulagu named him his own advisor, and took him along to Baghdad, which was conquered by the Mongols in 1258. Hulagu made Maragheh (in northwestern Iran) his capital, and the Observatory of the same name was built there.

Al-Tusi is mostly known for his geometric decomposition of linear motion into a sum of two circular motions, called "the Tusi couple", shattering the established Aristotelean view on exclusivity of circular motions in heaven. The same construction was used by Copernicus 250 years later, probably re-invented independently.

Al-Tusi published the *Ilkhanic Tables*, relating his astronomical observations made during 12 years. Using his geometrical findings, he improved substantially the model of lunar motion. He also determined the almost exact value of precession of the equinoxes, establishing it at $51'$ per century. *Commentary on the Almagest* contained excellent trigonometric tables with values of chords calculated to three sexagesimal places for each half degree of argument.

• **Ibn al-Shatir** (1394–1375) was a prominent astronomer and mathematician in Damascus, during his life under the rule of the Ummayad dynasty. After completing

studies in Cairo and Alexandria, he was appointed the *muwaqqit* at the great Ummayad mosque. His most important book was an astronomical treatise entitled *"The Final Quest concerning the Rectification of Principles"* which contained new lunar, solar and planetary models, seriously departing from the Ptolemaic scheme, although firmly geocentric in principle.

Ibn al-Shatir was not concerned with adhering to the theoretical principles of natural philosophy or Aristotelian cosmology, but rather to produce a model that was consistent with empirical observations. His concern for observational accuracy led him to eliminate the epicycles in the Ptolemaic solar model and all the eccentrics, epicycles and equant in the Ptolemaic lunar model. Shatir's new planetary model consisted of new secondary epicycles instead of equant, which improved on the Ptolemaic model.

6 Medieval islamic observatories

- **The Maragha Observatory**

At the time of decline of science in medieval Islam, when Baghdad ceased to be the flourishing cultural center after the Mongols sacked it in 1258 thereby ending the reign of the Abbasides and a new influential institution called the *Maragha Observatory*, was created in northern Persia under the patronage of Hulagu, Gengis Khan's grandson. Hulagu appointed Nasir al-Din Tusi (1201–1274), to be the observatory's director as well as his personal advisor.

The Maragha complex was much more than just an astronomical observatory: it became a unique center of scientific research, endowed with a library containing more than 100 000 volumes, the main building surrounded by auxiliary ones, including accomodation quarters for visitors. Astronomers and mathematicians from all parts of the vast Islamic world participated in the design and construction of astronomical instruments, many of which were genuinely new inventions. Al Tusi appointed Mu'ayyad al-Din al-Urdi (who died in 1266) as chief astronomer and instrument designer.

An anonymous treatise in Persian named *al-Risala al-Ghazaniyya fi 'l-alat al-raadiyya*, Ghazan's (or Ghazanid) treatise on the observational instruments, describes the structure, construction, and functions of twelve "new" observational instruments in the medieval period that appear to have been proposed and invented during the reign of Ghazan Khan, the seventh Ilkhan of the Ilkhanid dynasty of Iran 1295–1304.

Such primary historical sources may contain interesting notes and claims concerning Ghazan Khan's astronomical activities and especially the new observatory that he founded in Tabriz. The fact is that at present there are hardly any sound and historically reliable accounts of the activities of the Maragha Observatory from around 1280 onwards.

The astronomical equipment of Maragha included a mural quadrant with a 40-meter large radius, a solstitial armilla, an azimuth ring, a parallactic ruler (called *triquetrum, (parallactic ruler) in Latin)*, and an armillary sphere with a radius of about 160 cm.

The Maragha Observatory represented a new period of scientific activities in the Islamic world in the mid 13$^{\text{th}}$ century, A number of sophisticated pre-Copernican, but non-Ptolemaic systems were elaborated there, explaining the planetary motions with greater accuracy than ancient Greek astronomers were able to produce. Several

observatories in Persia, Asia Minor and Central Asia were built with Maragha serving as a model.

- **Ulugh Beg and the Samarkand Observatory**

Ulugh Beg was born in northern Iran in 1394, as the oldest son of Shahrukh, one of Tamerlan's sons. As a young prince, he was designed to rule over the vast province of Transoxania (today in Uzbekistan). He assumed his full responsibilities in 1411, although he continued to be subordinate to his father, who ruled the empire from Herat (today in Afghanistan). After his father's death in 1447, Ulugh Beg succeeded him, but survived only two years as an independent ruler before being overthrown and beheaded by his own son in 1449.

He is remembered mostly for his extraordinary achievements in astronomy, and the construction of the greatest and the most modern astronomical observatory and *madrasa*, a high school, a library and a research center combined. The first director of Ulugh Beg's observatory was Qazizadeh Rumi, a native of Anatolia, who was also one of Ulugh Beg teachers. After his master's death he left Samarkand for Istanbul, followed by other astronomers employed in the madrasa.

Ulugh-Beg's observatory was built from 1420 till 1430 on a hill to the north of Samarkand, and was in use until his death in 1447. Its exact location is unknown, because it was almost completely destroyed a few generations after his death. Ulugh Beg constructed the largest mural sextant (or it rather might have been a quadrant) in the 15^{th} century, which had a radius of 40.4 meters. He took inspiration from the first known mural sextant constructed in Ray, Iran, by Abu-Mahmud al-Khujandi in 994, to measure the obliquity of the ecliptic.

Housed in the main building, it had a finely constructed arc with a staircase on either side to provide access for the astronomers who performed the measurements. It would have been used to measure the angle of elevation of major heavenly bodies, especially at the time of the winter and summer solstices. Light from the given body, passing through a controlled opening, would have shone on the curved track, which was marked very precisely with degrees and minutes. Fainter objects were observed directly and the elevation angle reported to the sextant. Travelers and scientists who visited Samarkand and the observatory have described many astronomical instruments which were lost afterwards. There were several armillary spheres of various sizes and huge astrolabes, among others.

Ulugh Beg was certainly the most important observational astronomer of the 15^{th} century. The obliquity of the ecliptic measured by his astronomers was almost perfect, within half a minute discrepancy with what we know at present.

His permanently mounted astronomical instruments were the first of their kind in the world, and it was their firm position that ensured greater precision of observation. Among his great achievements was the star catalogue containing more than thousand stars (1018 precisely), with exact coordinates attributed to each of them.

Ulugh-Beg's masterpiece *"Chronology"* was translated into Latin and edited in Europe in 1650, and the publication of his star tables followed in 1675. The determination of the obliquity of the ecliptic was much better than those of Hipparchus and Ptolemy. His observations of planets remained unsurpassed until Tycho Brahe's observations more than a century later.

7 Concluding remarks

As Bernard Lewis (1916–2018) has put it in his book *What went wrong?*, for many centuries the world of Islam was in the forefront of human civilization and achievement. However, due to many interior and exterior factors, Islamic science stopped its development around the 15^{th} century; since then, European science took the lead.

Looking back at our sketchy summary of the history of Islamic science one can easily note the major qualitative difference between its achievements in Mathematics versus all other domains. As a matter of fact, it is in Mathematics that the Arabs and Persians produced a genuine breakthrough by adopting Indian system of notation and calculus, and by merging geometry and algebra together. This paved the way to the next revolutionary breakthrough performed by the Europeans, who enlarged the scope of algebra by discovering complex numbers. This could not be achieved without the algebraical basis led forth by the Islamic polymaths.

On the other hand, with all its remarkable achievements, the Arab and Islamic Astronomy, especially in the observational field, represents the last chapter of the science of Antiquity, a natural extension of Babylonian, Indian and, above all, Greek scientific heritages of a small world centered on the Earth, for which the sphere of fixed stars represented the utmost external limit.

Modern science germinated within the new university framework of Medieval Europe between the 13^{th} and 15^{th} centuries, openly born with the intellectual revolution brought by Copernicus in the 16^{th} century, pursued later on by Galileo, Descartes, Kepler, Leibniz, Newton and other European scientific luminaries.

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