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THE ISLAMIC INFLUENCE ON WESTERN ASTRONOMY

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Abstract. Within one hundred years of the Prophet's death in 632, Islam had conquered the lands from the Indus to the Atlantic. The new culture was eager to assimilate what was best in the heritage of the conquered. Science, and in particular astronomy and astrology, were given very high priority. Islamic scholars soon realized that Ptolemy represented the scientifically most advanced aspects of ancient astronomy. Islamic scientists critically developed Ptolemy's theories, they constructed new astronomical instrumentation, improved observations, and created algebra and spherical trigonometry for the interpretation of the observations. From India they introduced the positional decimal system including zero, which from Northern Africa and Spain found its way to Europe. Astronomical knowledge in the Christian West was at the same time stuck at a very primitive level. This began to improve when towards the end of the 10th century contacts between the Islamic and Christian cultures, particularly in Spain, began to multiply. In the 11th and 12th century intellectual centres, Toledo housing the most important one, translated all the available astronomical works from Arabic into Castilian or Latin. Up to the days of Copernicus these works formed the basis on which European astronomy was building and developing.

Key words: History of astronomy, Islamic astronomy, Middle Ages

1. Introduction

The Prophet died in the year 632 A.D. Immediately after his death the Islamic movement succeeded in becoming a world power, a universal religion, and a new civilization, stretching from India to the Atlantic Ocean.

The Islamic conquest was different from what we usually associate with conquest and domination. There was respect for the cultural heritage of the conquered and a keen wish to assimilate what they deemed worthy. This was particularly true in respect to the old Greek civilization. The Islamic civilization emerged from a melting pot of Greek, Indian, Persian, Mesopotamian, and North African heritages growing on a fertile Arabic ground. This new Islamic civilization had first an indirect and from the 11th to the 14th century a very direct influence on the history of Europe.

2. The remains of former glory

What was the scientific environment of the lands conquered by Islam? Let us have a brief glance at history.

In 338 Phillip of Macedonia conquered Greece. His son, Alexander the Great, extended the Empire to reach from Egypt to the Caspian sea and from the Mediterranean to the Indus. Greek culture was spread to all these places, after all, Alexander had been a pupil of Aristotle. He founded Alexandria in 331 B.C. as a new centre of the Empire. With the establishment of the Museion around 295 B.C. the successors of Alexander intended to create an Academy along the one of Aristotle. Euclid, Apollonius, and Erathostenes worked in Alexandria, and in 150 A.D. Ptolemy published the Almagest.

In the meantime Egypt and the whole Mediterranean had become a Roman dominion and Christianity was spreading. With the advent of Christianity science became increasingly suspect. The assassination of Hypatia is a testimonial of the Christian fight against science. Hypatia was a learned woman of high reputation who is reported to have taught mathematics and astronomy. She was brutally killed in 415 by a Christian fundamentalists mob. For those who killed her, knowledge was not to be gained through scientific research, but was granted through divine revelation, and the Church had the monopoly on that divine transfer.

However, in some places like Alexandria in Egypt, Antioch in Syria, Edessa in Mesopotamia, or Byzantium the Hellenistic culture was still present, either in academies or half forgotten in libraries.

3. The beginning of Islamic science

Shortly after 640 the Sasanide empire was conquered by Islam. Baghdad was founded in 762 as the new capital by the second Abbasid caliph al-Mansur. And here in Baghdad we see the first important impetus of Islamic science. It began with al-Mansur, who was much interested in astrology, and it continued with his successors, e.g. Harun al-Rashid, who was Caliph from 786 to 809. It must have been a truly refined society. The splendour of the stories of Thousand and One Night bear witness. Caliph al-Mamun, the son of Harun al-Rashid, was particularly keen on collecting ancient sources. Much has been said about the Bayt al-hikma, the House of Wisdom. Its roots lie probably in the archive of al-Mansur, where many Persian documents were translated into Arabic. Particularly at the times of al-Mansur it may also have functioned as a gathering place for intellectuals, and a kind of academy (Gutas, 1998; Kennedy, 2005). In that place and in the households of the upper social classes Christian, Jewish, Muslim and Pagan intellectuals worked and translated from Greek, Syriac, and Persian into Arabic all that had survived of the philosophical and scientific traditions. The biggest treasure for astronomy was Ptolemy's Almagest. An excellent mathematical background was provided by the works of Euclid, Archimedes, and Apollonius. These translations became part of the Islamic culture. Arabic became an international language of science, and the dissemination of knowledge was further facilitated by the use of paper which around 750 was introduced from China.

4. Islamic contributions to astronomy

4.1. Observations

The classical astronomical observations of Aristarch, Hipparchos, and Ptolemy were critically repeated by Islamic observers. To mention just a few: Al-Battani (850-929) looked at the length of the year, he found changes in the inclination of the ecliptic and the rate of precession. In contrast to Ptolemy, who thought that the solar apogee was fixed, al-Biruni (973-1048) found that it slowly moves. Al-Sufi (903-986) published in 964 the 'Book of Fixed Stars'. It was an update of Ptolemy's list, with a more accurate determination of the brightness of the stars. It was widely used, and served as source of information when the Alfonsine Tables were set up in the 13th century. - It is strange that the Islamic astronomers did not discover the supernova of 1054, whereas plenty of observations are recorded from China.

Islamic scientists were the first to create astronomical observatories as scientific institutions. Maraghah in Persia was established by al-Tusi in 1262. That observatory was much more than a mere centre of observation. It possessed a fine library with books on a wide range of scientific topics. Theoretical work in mathematics, astronomy, and philosophy was vigorously pursued. The Samarkand observatory of Ulugh Beg was in operation from 1420 to 1449. Ulugh Beg's Catalogue of stars, is the first comprehensive stellar catalogue since that of Ptolemy.

Istanbul observatory functioned from 1575 to 1580, thus practically at the same time as the one of Tycho Brahe. However, there are no indications that they knew of each other. It was built 1575-1577 for Taqi al-Din by the Sultan Murad III. The reason for its closure is uncertain. Did religious leaders persuade al-Din that prying into the secrets of nature would only bring misfortune, or did he fail with his astrological predictions? Tycho Brahe lost his observatory because the new Danish king was not interested in astronomy.

4.2. Instrumentation

In addition to the usual astronomical instruments like sun dials, the astrolabe (Figure 1) became a particularly privileged instrument. Some of them are works of art. The astrolabe is a projection of the sky onto a plane. The most popular is the planispheric, where the celestial sphere is projected onto the plane of the equator. A typical astrolabe was made of brass and was between 10 and 20 cm in diameter. It consists of a hollow disk, called the mater, which is deep enough to hold one or more flat plates called tympans, or climates. A tympan is made for a specific latitude and is engraved with the stereographic projection of lines of equal altitude and azimuth representing the portion of the celestial sphere which is above the local horizon. The astrolabe serves in solving problems relating to time and the position of the Sun and stars, and to measure their altitudes. They were introduced to Europe from Islamic Spain at the end of the 10th century, and were in use until about 1650, when they were replaced by more specialized and accurate instruments.

4.3. Theory

4.3.1. *Arabic numbers*

The first great advance on the inherited Greek mathematical tradition was the introduction of "Arabic" numerals, which actually originated in India and which simplified calculations of all sorts and helped the development of algebra. The introduction of this system is attributed to al-Khwarizmi (780-850), who is also an important figure in the invention of algebra.

4.3.2. *Trigonometry and algebra*

To measure angles Ptolemy had used the chord (Figure 2). In India they invented the sinus. The other trigonometric functions and trigonometry itself, including spherical geometry, are important original contributions of Islamic astronomers and mathe-

Fig. 1. The astrolabe serves in solving problems related to time and the location of the Sun and stars. They were introduced to Europe from Islamic Spain at the end of the 10th century, and were in use until about 1650, when they were replaced by more specialized and more accurate instruments. Photo: Institut du monde arabe, Paris / Philippe Maillard.

maticians, the same is true of Algebra. Calculating with the sinus instead of the chord and working with the newly discovered trigonometric relations greatly simplified astronomical research on the celestial sphere.

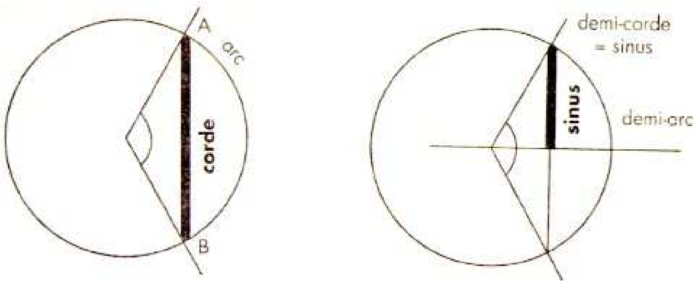

Fig. 2. Chord and Sinus. If the circle has a radius of length 1, then the sinus of half the angle from A to B is half the chord of the angle from A to B.

4.3.3. *Trepidation*

Trepidation is a concept and theory that formed an essential part of medieval astronomy. Copernicus dedicates a whole section of De Revolutionibus to trepidation. Tycho Brahe finally did away with it. What is it? When Islamic astronomers compared their observations with those of Ptolemy, they made two discoveries. The obliquity of the ecliptic was smaller and the precession rate was faster than it had been in Greek antiquity.

Thabit ibn Qurra (836-901) came to the conclusion that this change varied in time. This led to the theory of trepidation. For Ptolemy the 8th sphere, with the ecliptic inscribed, belongs to the fixed stars. Thabit then adds a 9th sphere. It is the sphere of diurnal motion and therefore contains the celestial equator. He then introduced a small circular movement of the 8th within the 9th sphere that would produce what he thought was a cyclic movement. He thought of a period of about 4000 years. From the 12th century onward it was realized that precession was going in only one direction, but that the plane of the ecliptic had a small wobble.

4.3.4. *Criticism on Ptolemy*

Although Ptolemy's Almagest remained the basis of Islamic astronomy, that work was attacked since the 9th century. This culminated in a first major critique by Nasir al-Din al-Tusi (1201-1274) and his students, especially Qutb al-Din al-Shirazi (1236-1311). One of the main points of attack was the equant in the theory of the planets and the moon, because it violated the principle of regular circular motion.

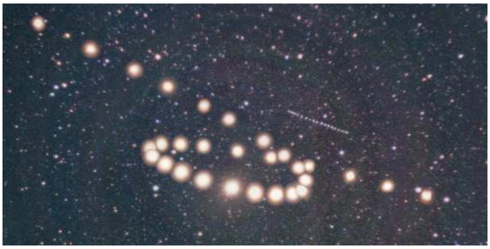

Fig. 3. Retrograde motion of the outer planets. The path of Mars from June to September 2003.

This was not just a technical point. It was an essentially philosophical question about the nature of the universe. According to Aristotle the heavenly bodies are immune to changes in their nature, and there is only one kind of motion fit for them, this is the steady circular motion, because this kind of movement has no beginning and no end, and any position on a circle is as good as any other position on this circle. Thus, Ptolemy had been confronted with the problem of describing the observed varying speed of a planet by a model of constant circular velocity. For this he invented the equant. The centre of the epicycle moves on a circle - the deferent. To better reproduce observations, this circle is not centred on the earth and the centre of the epicycle moves with varying speed along the deferent. However, he found a point, the equant (Figure 4), from which the centre of the epicycle is seen to move with constant angular velocity. But the philosophers saw this as an artifice and inadmissible violation of the Aristotelian principle. Ibn Rushd (1126-1198, latinized

Averroes) criticized eccentric spheres and the epicyclic sphere as contrary to nature. He reproached the Ptolemaic system, that it hold no deeper truth, but was simply a mathematical tool to describe celestial movements.

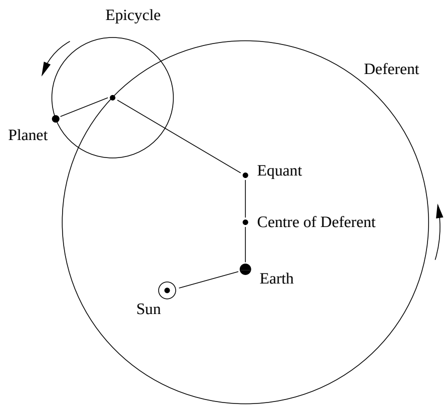

Fig. 4. The Equant. Seen from the Equant, the centre of the epicycle moves with constant angular velocity.

Islamic scientists developed mathematical tools to replace the equant. The most prominent are al-Urdi (d.1266), al-Tusi (1201-1274), and al-Shatir (ca.1304-1375) Saliba (1994, 2005). Al-Tusi and his group discovered, that by combining two uniformly revolving epicycles, they could generate an oscillation along a straight line. Today, this is called the Tusi-couple (Figure 5). They devised a model that produces a linear back and forth motion out of two circular motions, which allowed them to do away with Ptolemy's equant point by adding two additional small epicycles to the excentric planetary orbit. Al-Shatir of Damascus (ca.1304-1375) eliminated the equant as well as the excenter by minor epicycles. This made it possible to explain the non-uniform motion of the epicycle around the deferent in terms of purely uniform motions.

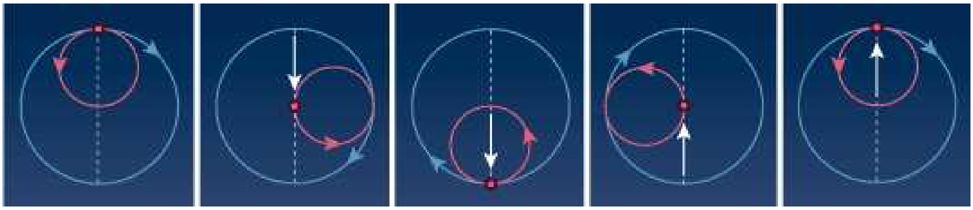

Fig. 5. The Tusi couple. The combination of two steady circular motions results in a back and forth movement along a straight line. Having a circle of half the radius of the epicycle turn tangentially in the epicycle can replace the equant.

But why did Islamic astronomers not challenge the geocentric system? Well, there was no observational evidence against it. Even such a clever observer as Tycho Brahe refused the Copernican idea and developed his own geocentric system. One of the main objections was the absence of yearly stellar parallaxes. The first observational proof that a planet was circling the sun and not the earth came in 1613, when Galileo Galilei discovered the changing phases of Venus.

4.4. Astrology

Astrology was rejected by both Islamic and Christian religious leaders. On the other hand, philosophers looked to Aristotle and his analogy between the macrocosmos of the universe and the microcosmos of the human body. Ordinary people as well as the caliphs and kings were always much interested in what astrology had to tell them. Astrology is one of the most important historical contexts in which astronomy developed. In the West astronomy and astrology went closely together up to the beginning of the 17th century.


Leonis parthi parsqꝫ mesopotamie deinde valles cum rippis amnibus metallorumqꝫ loca. Tum regia palatia atqꝫ oppida inuicta coclee quoqꝫ ⁊ satum cum celsis ⁊ speluncis.
¶ Uirginis iudea ⁊ gallilea cum confinio eufratis atqꝫ insula quadam persie. Deinde omnia sata genezea ⁊ externes cantorum numorum et musicorum mansiones.
¶ Libre roma cũ grecia istria ⁊ italia. Indeqꝫ vsqꝫ ad affricam ⁊ mesim: inde ⁊ barckan keremen atqꝫ balach deinde pedes montiũ culti locaqꝫ pomifera forisce. na locaqꝫ venationũ asturcorum ⁊ insidiarum.
¶ Scorpionis assiria nobothea tingis deinde vineta moreta hisqꝫ similia post hec loca fetida carceres domus planctus ⁊ luctuũ cum cauernis scorpionũ.
¶ Sagittarij hisplen om̃esqꝫ agri allum⁹ post hec loca eliebaelhei beida ⁊ ramrãia atqꝫ loca p̃teriti temporis plene petre boumqꝫ loca ⁊ curruum.
¶ Capricorni ethiopia orientalis tingria cum media eius maris: mariaqꝫ duo ad indiã ⁊ ethiopiã cum orientalibus italie ⁊ grecie partibus: deinde castra cũ portis atqꝫ vbi rigat cum portis aquã rigentibus ⁊ lacunis aquã recipientibus cũ qua naues applicant. Tũ loca canũ vulpiũ ⁊ ferarũ ⁊ serpentũ tum hospitalia pegrinorum pauperum ⁊ seruorum postremo lares ⁊ ignitabula.
¶ Aquarij nigellorum turcorumqꝫ regio versus montes ⁊ alkufam: egyptus cũ ethiopia occidẽtali. Deinde loca infima cũ fluuijs ⁊ canalib⁹ puteis ⁊ pelago atqꝫ salo loca altiliũ vinee cuz cupis metretis cistis ⁊ tabernis.
¶ Pisciũ india ⁊ mare rubrũ insule italie ⁊ grecie versus siriã cuz alexandria deinde maritima lacus ⁊ stagna cum suis littoribus atqꝫ piscibus tum angulorũ habitacula cum templis pulpitis ⁊ cenobijs

Fig. 6. Albumasar (787-886): Introductorium in astronomiam. Printed 1489 in Augsburg and 1506 in Venice, it proves the influence of Islamic astronomy and astrology on Renaissance Europe. (Zentralbibliothek Zürich)

Important Islamic astrologers had a high social standing. The court astrologer of Harun al-Rashid was supervisor of the royal library, which shows, that these personalities had a profound knowledge of the classical texts available at the time. To the Medieval West the most important representative of Islamic Astrology was the Persian Abu Ma'shar (latinized Albumasar, 787-886). His works (Figure 6) were translated into Latin in 1133 by John of Seville and circulated widely in manuscript form. He exerted a powerful influence on the development of Western Astrology. And we should never forget, that these astrologers were scholars of a wide culture, who wrote on philosophical and astronomical subjects as knowledgeable as about astrology.

5. What did the Christian culture at the time of Charlemagne know about astronomy?

Very little, is the most concise answer. When during the decline of the Roman Empire the Völkerwanderung upset in Europe the old order of values, the cultural heritage of antiquity was practically lost. Some books were preserved in monasteries, but their content was hardly understood. Religion became the all dominating factor. Charlemagne lived at the same time as Harun al-Rashid; they had political contacts, but the difference in the scientific levels of the two cultures was enormous.

Ambrosius Theodosius Macrobius lived in the early 5th century and wrote a comment about the "Dream of Scipio". This comment contains a section on astronomy. An outermost sphere is heaven itself, the Supreme God, enveloping and comprehending everything in existence, including all the fixed stars. Inside this one lie the spheres of Saturn, Jupiter, Mars, the Sun, Venus and Mercury, the Moon, and innermost the sphere of the Earth. The movement of the spheres creates the heavenly music. However, there is no detailed astronomical information in that work. Of course, the Christian Church needed some astronomy to set the Easter date. This kept the interest in astronomy alive, though on a very low level.

Another, well known source about the heavens was Martianus Capella of Carthage who lived about 365-440. For his son's wedding he wrote an allegory "De nuptiis Philologiae et Mercurii (The Nuptials of Philology and Mercury)". In this encyclopedia on the seven liberal arts we find a treaty on astronomy. It is a qualitative narrative about the geocentric system, without any detailed description or prescription how to find the paths of the planets. However, it contains the interesting statement, that Venus and Mercury circle the sun - Copernicus (1543) mentions that passage. But compared to the Almagest, the astronomical information in Martianus Capella is very primitive. This was the status throughout the first millennium.

The development of cathedral schools in the eleventh and twelfth centuries, as part of the reform program championed by the papacy, brought renewed interest in the heritage of classical antiquity. At Chartres, for example, there was extensive study of Plato's cosmological work, the Timaeus, along with Chalcidius'(4th century) commentary, Martianus Capella, Macrobius, Seneca's "Natural Questions", Cicero's "On the Nature of the Gods", along with works by Augustine, Boethius, and John Scotus Eriugena. Timaeus was particularly important in that it contained the most systematic discussion of questions in cosmology and physics. Thierry of Chartres (d. after 1156) was especially influential in his attempt to use Platonic cosmology in his reading of the creation account in the Genesis. But, schools established at cathedrals and monasteries, as well as at secular courts, were much more preoccupied with grammar, logic, theology, and biblical exegesis, rather than with scientific questions.

6. Contacts with the Islamic culture and translation centres

In the 10th century contacts between Islamic and Christian intellectuals were still rather sporadic, but becoming more frequent. One example is Gerbert of Aurillac who was born between 940 and 950. He entered the Church, was interested in natural sciences, traveled to Spain where he studied in Ripoll and Vic, and possibly with Islamic teachers in Cordoba and Sevilla. He was interested in astronomy, and learnt the Arabic number system. On his return he became teacher at the school of the cathedral of Reims. It is likely that he brought from Spain the knowledge of the astrolabe to the cathedral school of Reims. He was far superior to anyone else in doing mathematics. Thus, with the astrolabe and with a new system of numbers, he was watched with suspicion, and even suspected of being a magician in touch with the devil. He was later elected Pope Silvester II (999-1003).

The gates really opened after the conquest of Toledo in 1085 by Alfonso VI. The large scale re-conquest had started with Fernando I in the middle of the 11th century. A scholarly community, “The School of Toledo”, grew under the leadership of Archbishop Raymond of Toledo who guided that institution from 1126 until his death in 1152. Raymond knew about the wealth of scientific expertise of the Islamic culture. He created a “Translation Centre”. The purpose was to translate into Latin all the Greek and Arabic manuscripts. Raymund’s centre employed Jewish, Christian, Muslim, Latin, and Greek scholars.

The centre attracted renowned thinkers from all over Europe such as Robert of Chester, Adelard of Bath, and David Morley from England; John of Brescia, Plato of Tivoli, and Gerard of Cremona from Northern Italy. Every available work on astronomy and astrology was translated. Robert of Chester traveled from England to Toledo to learn Arabic, and in 1145 completed a translation of al-Khwarizimi’s treatise on calculation. Around 1175 Gerard of Cremona came to Toledo to translate the Almagest from Arabic into Latin. This version was copied by hand, until in 1515 it was printed in Venice. It was only at that time that translations were made directly from the Greek text which had come to Rome after the Turks had conquered Constantinople in 1453. After the death of Raymond in 1152 the school of Toledo continued into the 13th century. It worked for a while in parallel with the new translation centre of Alfonso X (1221-1284), called “el Sabio” (the Learned).

Two astronomical works gained particular importance: The Toledan Tables and the Alfonsine Tables. They give the recipe for determining the astrologically all important positions of sun, moon and planets. Azarquiel or Arzachel (al-Zarkali 1028-1087) worked in Toledo and produced the Toledan Tables in Arabic. Already in 1140 they were translated by Raymond of Marseille and adapted in the “liber cursuum planetarum” to the meridian of Marseille. They had a wide circulation because they allowed to calculate planetary positions for any time. However, in order to really work with them, an understanding of the Almagest was needed. At the request of Alfonso X (1221-1284) the Toledan Tables were translated around 1255 into Castilian and again around 1277.

The best known and influential work through the later Middle Ages are the Alfonsine Tables (Figure 7). Alfonso X had inherited a vastly extended kingdom. In addition to Toledo it included Cordoba and Seville. This gave the Christian scholars access to the Andalusian culture that had been flourishing during the previous centuries. Happily the kings of the re-conquista, Alfonso VI, Ferdinand III, and Alfonso X were similarly open minded as the Califs of Baghdad in the 8th and 9th century. They showed great interest in culture and a high regard for what they found in their newly conquered places. Alfonso X gathered around him a large group of scientists, mainly astronomers, who translated from Arabic mainly into Castilian, but occasionally also into French and Latin.

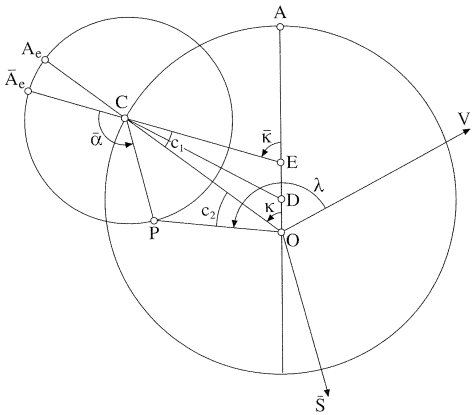

Fig. 7. The Alfonsine Tables of Toledo (Chabas & Goldstein, 2003). The Tables give procedures to calculate the longitude of the sun and the planets on the ecliptic.

However, they not only translated, they also created original works. The Alfonsine Tables are such a creation. They are not the work of a single author, but of a whole group. The members of the group mastered more than one language and their members had different cultural backgrounds being Christians or Jews or coming from Islam. The Tables contain the technique of trigonometry, daily rotation, latitudes, planetary visibility and retrogradation, planetary and lunar velocities, Syzygies (three bodies found along a straight line) and eclipses, visibility of the lunar crescent, astrology, mean motion, the equation of time which gives the deviations from the mean motion, trepidation. The Alfonsine Table take as starting point the year 1252, 1252 was the coronation date of Alfonso X.

The book on stars of al-Sufi had a lasting influence on stellar toponymy in European languages. It was translated into Spanish by Alfonso X el Sabio. Many of our star names, such as Aldebaran, still recall their Arabic origin.

The intellectuals gathered in Toledo gained access to new ways of thinking, and were able to incorporate into their own writing what they found in the Islamic culture. Thus, Adelard of Bath wrote his “Questiones Naturales” as a summary of ideas he collected from Arab sources. Adelard, who translated al-Khwarizmi’s Astronomical Tables and “Liber Ysagogarum” (About Arithmetic), later wrote books such as the “Rule of the Abacus” and the “Usage of the Astrolabium”, which were strongly influenced by al-Kwharizmi’s teachings.

7. The impact of Islamic astronomy

European philosophy, science and medicine received an enormous impetus from the contact with the Islamic world in all branches of culture: Medicine, philosophy, literature, music, mathematics, astrology, astronomy, geography and others. We concentrate on astronomy.

The Arabic numbers came to Europe through several channels. The first one was probably Gerbert of Aurillac (ca. 940-1003), whom we already mentioned. He studied in Islamic Spain and later became Pope Silvester II. Then we have the 12th century translation al-Khwarizmi by Adelard of Bath. The use of Arabic numbers became more widespread when the Italian Fibonacci (ca. 1170-1240) published his "Liber Abaci" in 1202. Fibonacci had lived near Algiers for several years, where his father was ambassador for Pisa. His book was meant to help commerce. But Roman numbers were used up to the time of Georg Peuerbach (1423-1461), who wrote the first German book on calculations, using Arabic instead of Roman numbers.

Islamic culture did not simply hand over what it had inherited from Ptolemy. They created new mathematics, trigonometry and algebra, they improved the Ptolemaic methods and tables, and thoroughly criticized Ptolemy on philosophical grounds.

Many Islamic authors were translated into Latin and influenced European thinking. One of them is al-Farghani who between 830 and 860 wrote "Elements of Astronomy" which is a non-mathematical summary of Ptolemaic astronomy. In Toledo it was translated into Latin first by John of Seville in the first half of the 12th century, and later by Gerard of Cremona (ca. 1114-1187). From this source Dante learnt about Ptolemaic astronomy for the "Divina Commedia", where the poet ascends through the spheres. From the translation of John of Seville Sacrobosco got his information about the Ptolemaic universe. Sacrobosco (d. 1256) is famous for his textbook "De Sphaera" (ca. 1230) which was a watered down edition from al-Farghani, explaining spherical astronomy. According to Gingerich (1986) this book went through 200 editions before it was superseded in the early 17th century.

Al-Battani (850-929, latinized Albategnius) wrote with "Kitab al-Zij" one of the early important works. It contains 57 chapters and begins with a description of the division of the celestial sphere into the signs of the zodiac and into degrees. The necessary mathematical tools are then introduced such as the arithmetical operations on sexagesimal fractions and the trigonometric functions. Chapter 4 contains data from al-Battani's own observations. Chapters 5 to 26 discuss a large number of different astronomical problems, some already treated in the Almagest. The motions of the sun, moon and five planets are discussed in chapters 27 to 31, where the theory given is that of Ptolemy. Al-Battani covers in Chapters 49 to 55 astrological problems, while chapter 56 discusses the construction of a sundial and the final chapter discusses the construction of a number of astronomical instruments. The "Kitab al-Zij" was translated into Latin as "De motu stellarum" (On the motion of the stars) by Plato of Tivoli in 1116 while a printed edition of this translation appeared in 1537 and then again in 1645.

Al-Battani's work was very influential in the West. Tycho Brahe knew it, and Copernicus mentions him. Let us come back to trepidation and equant. Tables of trepidation were included in the Toledan Tables, finalized by al-Zarqali in about 1080. But then it was realized, that precession was not periodic, but continuous. The makers of the Alfonsine Tables introduced a steady precession with a period of 49'000 years and an oscillation of +/- 9 degrees which is completed in 7'000 years.

This became the standard theory from the 14th to the end of the 16th century. But this steady precession needed an additional 10th sphere. The 8th sphere is the firmament, the 9th sphere is occasionally (Apian) called crystalline, it is responsible for the trepidation of the 8th. The 10th sphere is called the first movable, it gives the daily rotation and is responsible for precession of the 9th sphere. Copernicus blamed the periodic component of precession and trepidation on the movement of the Earth's axis. However, Tycho Brahe came to the conclusion, that precession was a steady process and that trepidation is probably a periodic wobble of the plane of the ecliptic.

In the Christian Middle Ages, particularly during the scholastic period, the heavenly spheres were the subject of much speculation. The discussion was split into subjects of astronomical and religious relevance. Dante (1265-1321) in the "Divina Commedia" is led by Beatrice through the nine spheres of Heaven. They are: (1) The Moon, (2) Mercury, (3) Venus, (4) the sun, (5) Mars, (6) Jupiter, (7) Saturn, (8) the stars, (9) The Primum Mobile (the Prime Mover).

Copernicus was as unhappy with the equant as al-Tusi (1201-1274) and al-Shatir (1304-1375) had been before him. Copernicus (1514) wrote in the Commentariolus: "I often pondered whether perhaps a more reasonable model composed of circles could be found, from which every apparent irregularity would follow, while everything in itself moved uniformly, just as the principle of perfect motion requires." This same problem had been discussed and solved by al-Tusi, who showed that a combination of two circular motions can result in a straight line. Copernicus (1543) employed that procedure in De Revolutionibus, Chapter 4 of Book 3 which carries the title "How an oscillating motion in libration is constructed out of circular motion". There he tried to explain trepidation, the non-uniformity of precession. He explained the backward and forward motion by the Tusi couple, however, he does not mention al-Tusi. He also replaced the equant with epicycles in the way al-Shatir had done before him. It is very likely that the mathematical models he employed were inspired by these two scientists. (See also Swerdlow 1996, and Dobrzycki & Kremer 1996).

It is not known how Copernicus learnt about the models of al-Tusi and al-Shatir. But, because of the many similarities, historians have for some time been quite certain, that he must have known those models. He may have become acquainted with them through a 14th century manuscript of Ibn al-Shatir containing the Tusi couple, which was a translation of an Arabic text into Greek, made probably in Constantinople. It might have reached Rome after the fall of Constantinople in 1453, and is still in the Vatican library. Copernicus may have seen it during his sojourn in Rome in 1500 (Saliba, 1999).

8. Conclusions

The influence of the Islamic culture on Europe from the end of the 10th to the 13th century was very great in all domains, in poetry, music, philosophy, medicine, and science. Let us first summarize the conditions that favoured the emergence of the Islamic culture:

1) There was a strong economical basis. Conquests between 635 and 750 had resulted

in an immense empire, controlling essential resources and trade routes from the Indian Ocean to the Atlantic.
2) Arabic was the lingua franca for the entire cultural room. The arrival from China of the art of manufacturing paper at the time of Harun al-Rashid gave an enormous boost to the dissemination of knowledge.
3) An open mind for the values of other cultures. A spirit of religious tolerance allowed Muslims, Jews, and Christians to work side by side.
4) Education was wide-spread and touched all layers of society.

Astronomy had a very high social standing. It was very much an applied science. It delivered calendars, the techniques for exact geography, and it dealt with the high art of astrology. Islamic astronomy further developed the techniques inherited from Ptolemy.

Islamic astronomers did more than simply read Ptolemy. They provided astronomy with new mathematics. Their invention of algebra and trigonometry substantially changed the mathematical foundation of astronomy. They also questioned Ptolemy fundamentally. They created cosmological alternatives. However, they never questioned geocentricity.

Islamic astronomers were well known in the Christian Middle Ages. Copernicus (1543) mentions some in his De Revolutionibus, e.g. Ibn Rushd, al-Battani (his name I found 27 times), Al-Zarkali (mentioned 8 times), Thabit ibn Qurra, and al-Bitruji (latinized Alpetragius, died 1204 in Spain). The fundamental criticism on the Almagest by al-Tusi and others may have been instrumental in the work of Copernicus.

The revival of European learning which began slowly at the end of the 10th century, was strongly influenced by contacts with the Islamic world. These contacts, first a trickle and eventually a flood, radically altered the intellectual life of the West. They familiarized Europeans with the positional numerals and the zero. They acquainted European astronomers with Ptolemy's Almagest. Its translation from Arabic into Latin in the 13. century, combined with the additional work of the Islamic scientists brought scientific astronomy to Europe. It familiarized Europeans with scientific thinking. It gave in the 13. century the initial impetus to European astronomy.

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