Ibn al-Zarqālluh

Andalusian Astronomy in the Eleventh Century

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Astronomy was first cultivated in Al-Andalus, the part of the Iberian Peninsula under Islamic rule, during the early ninth century. This was mainly due to the fact that astronomy was necessary for the practice of astrology. The Muslim rulers relied on the predictive powers of a team of astrologers to provide them with useful information for decision-making. A group of poet-astrologers who served the courts of the emirs al-Ḥakam I (r. 796–822) and his son ʿAbd al-Raḥmān II (r. 822–852) are well attested in historical sources. The historian Ibn Ḥayyān recorded their names in his *al-Muqtabis fī tārīḫ al-Andalus*. A chapter titled "Anecdotes of the Astrologers with the Emir ʿAbd al-Raḥmān II," describes an attempt by the sovereign to test the accuracy of the predictions made by his astrologers. It is clear from this account that ʿAbd al-Raḥmān II and the members of his court were greatly interested in both astrology and astronomy. The emir himself is credited with the ability to calculate planetary positions, and a musician like Ziryāb is presented as having a deep knowledge of both disciplines. Ibn Ḥayyān also sheds light on the books brought to Córdoba from Baghdad by the astrologer ʿAbbās b. Nāṣiḥ (fl. ca. 800–850). Included is a list of what are presumably astronomical tables—known as *zījes* in Arabic—titled *al-Zīj*, *al-Qānūn*, *al-Sindhind*, and *al-Arkand*. The reference to *al-Zīj* is too general for the purposes of identification, but *Al-Qānūn* probably refers to Ptolemy's *Handy Tables*. *Al-Sindhind* is likely the Indo-Iranian *zīj* compiled by al-Khwārizmī in Baghdad during the first half of the ninth century; its use in Al-Andalus is well documented a century later. And *al-Arkand* is another set of Indian astronomical tables, introduced in Baghdad in the eighth century.

At the time, astronomy raised suspicions in orthodox circles due to its connections with astrology, and could only be cultivated under the rule of open-minded authorities. It is for this reason that there is little surviving information about astronomical and astrological practices following the death of ʿAbd al-Raḥmān II in 852. It was not until a century later that astronomy seems to have been revived, reaching maturity with the important figure of Maslama al-Majrīṭī (d. 1007). Maslama revised and adapted the coordinates of al-Khwārizmī's *Sindhind* tables to Córdoba. He also studied Ptolemy's *Almagest*, as well as the Ptolemaic tables compiled by al-Battānī (c. 858–929). Maslama was particularly interested in stereographic projection, as used in the making of the astrolabe and similar instruments, and improved Ptolemy's *Planispherium*, the classical work in which this type of projection was described. Two of his disciples, Ibn al-Ṣaffār and Ibn al-Samḥ, applied his findings in treatises on the construction and use of the astrolabe. These works were introduced in the Latin world through two compilations, *De compositione* and *De operatione astrolabii*, made during the twelfth and thirteenth centuries.[1] Through these compilations, Maslama's influence can be seen in treatises on the astrolabe written during the thirteenth and fourteenth centuries: one in Castilian by Alfonso X, another in French by Pèlerin de Prusse, and a third in English by Geoffrey Chaucer.

Orthodoxy returned to Al-Andalus under the leadership of al-Manṣūr ibn Abī ʿĀmir (981–1002), prime minister for the child emir Hishām II, who was too young to rule. Under the caliphate of Hishām's father, al-Ḥakam II (961–976), Al-Andalus had basked in one of the most accomplished periods of its cultural history. Al-Manṣūr destroyed this legacy, ordering selective manuscripts from the great library of al-Ḥakam II to be burned, including books on astrology and astronomy. Soothsayers and astrologers were arrested, tortured, and executed for predicting the end of al-Manṣūr's regime. Such predictions were still being made long after al-Manṣūr's death, during the period when his two sons held political power. Maslama, among others, predicted that the conjunction of Saturn and Jupiter in 1007 would portend the overturn of the regime, that the state would fall into other hands, and that there would be killings and famine. He was proved right. After the deaths of al-Manṣūr's sons in 1008 and 1009, a period of anarchy and civil wars followed. Between 1009 and 1031, seven different monarchs occupied the caliphate.

In 1031, the Córdoban caliphate came to an end. Political unity was lost, and the state was divided into a set of petty kingdoms. This arrangement lasted from 1031 to 1085, a period that could be considered the golden half-century of Andalusian science. The loss of political unity had two contradictory consequences. On the one hand, the number of patrons who fostered scientific research grew. Each sovereign was interested in having at his service physicians, astrologers, and poets who would enhance his glory and importance. On the other hand, Andalusian scientists of this period seem to have believed that an adequate scientific education could be obtained without the *riḥla*, or traditional journey, to the East, which completed the standard education of any young man belonging to a family who could afford it. None of the sovereigns of the petty kingdoms seem to have been able to afford the expense involved in receiving information about, let alone buying, new publications from Eastern capitals. The result was a long period of cultural isolation. As a result, a distinctive approach to astronomy developed in Al-Andalus during this period, one that differed markedly from its Eastern counterpart.

During the eleventh century, Toledo became well known as a center for astronomical activity. This reputation was maintained in the twelfth and thirteenth centuries by the ongoing process of translating Arabic scientific texts into Latin.[2] Yaḥyā al-Ma'mūn, who reigned between 1044 and 1075, was a member of the Banū Dhī l-Nūn, a Berber dynasty who ruled the kingdom of Toledo during the eleventh century. Yaḥyā's honorary name, al-Ma'mūn, was likely chosen to emulate an Abbasid caliph with the same name, who had patronized the first program of astronomical observations undertaken in Baghdad and Damascus in around 830. Al-Ma'mūn sponsored numerous technological marvels, contributing to Toledo's international reputation as the city of knowledge.[3] During his reign, the engineer Aḥmad or Muḥammad ibn Khalaf al-Murādī published his *Kitāb al-asrār fī natā'ij al-afkār* (Secrets of the Results of Thoughts),[4] which contains descriptions of 18 clepsydras, or water clocks. In the same period, Abū l-Qāsim b. ʿAbd al-Raḥmān, also known as al-Zarqāl, built a clepsydra-calendar that was used to mark the date of the lunar month.[5] According to a description by the geographer al-Zuhrī (d. 1137), al-Zarqāl built two large basins in a house outside Toledo on the banks of the Tagus, near the *Bāb al-dabbāghīn* (Door of the Tanners). The basins were filled and emptied in consonance with the lunar phases. When the new moon appeared, the water began to flow, and the water level rose by 1/14 of the total volume of the basin per day. On the fourteenth day of the lunar month, the basin was full and, on the fifteenth, the level of water began to fall at the same rate. By the end of the month the basin was empty. If anyone removed or added water to the basin, the system automatically compensated for the excess or shortfall.

Another patron of astronomy in Toledo, even more important than al-Ma'mūn, was the *qāḍī*, or judge, Ṣāʿid (1029–1070).[6] He became known as a historian and the author of the *Kitāb ṭabaqāt al-umam* (Categories of Nations), a world history of science containing abundant details about the development of science in Al-Andalus between the ninth and eleventh centuries.[7] The *Ṭabaqāt* reveals the astronomical sources that were available in Toledo toward the middle of the eleventh century: Ṣāʿid knew the Greek classics, particularly Ptolemy's *Almagest*, *Geography*, and *Tetrabiblos*, as well as Theon of Alexandria's commentary on the *Almagest* and the *Handy Tables*. References are also made to Eastern Islamic sources of the ninth and tenth centuries, especially al-Khwārizmī, al-Ḥasan ibn al-Ṣabbāḥ, Thābit ibn Qurra, Abū Maʿshar, Ibn al-Ādamī, and al-Hamdānī. The *Ṭabaqāt* gives no indication that Ṣāʿid knew of any Eastern Islamic books published after 950, confirming that Andalusian culture was isolated after the fall of the Córdoban Caliphate.[8]

Ṣāʿid was himself an astronomer and a patron of astronomical research. The fourteenth-century astronomer Isaac Israeli, in his *Yesod ha-'Olam*, recounts that Ṣāʿid gathered a team of about twelve people, mostly comprising Muslims, but also including some Jews. They consecrated their lives to scientific and astronomical research, while Ṣāʿid furnished them with adequate means for their living. Israeli notes that they used instruments built and adjusted by an astronomer called Ibn al-Zarqālluh.

Although he became known as Ibn al-Zarqālluh, his full name was Abū Isḥāq Ibrāhīm ibn Yaḥyā al-Naqqāsh al-Tujībī.[9] He had been born near Toledo and trained as a metalsmith, becoming an instrument maker for Ṣāʿid, al-Ma'mūn, and, in 1048, the young ʿAbbādid prince of Seville, among others.[10] Ibn al-Zarqālluh's patrons in Toledo lent him the necessary literature to teach himself astronomy. He soon assumed a prominent position in the group assembled by Ṣāʿid, who mentions him in his *Ṭabaqāt* as belonging to the younger Toledan generation. Israeli reports that precision instruments were used by the group, but there is otherwise little further information about them.[11]

Ṣāʿid's group had begun making observations by at least the early 1050s, leading to the compilation of a set of astronomical tables known as the *Toledan Tables*. These were adapted to the coordinates of Toledo using tabular information derived from al-Khwārizmī's (fl. ca. 800–950) and al-Battānī's Eastern *zījes*.[12] The set survives through three Latin translations or adaptations, one of which has been attributed to Gerard of Cremona (d. 1187), and through a Greek translation made ca. 1330–1340. More than 128 manuscripts of these translations have survived, an indication of the compilation's success throughout Europe.[13] Chaucer mentions the *Toledan Tables* in his *Canterbury Tales*:

His tables Toletanes forth he broght,
Ful wel corrected, ne ther lakked noght,
Neither his collect ne his expans yeres,

Ne his rotes ne his othere geres,
As been his centres and his arguments,
And his proporcionels convenients
For his equacions in every thing.[14]

As can be seen from the work of the Toledan astronomers, Western Islamic medieval astronomers developed original and highly influential treatments of the precession of the equinoxes. Precession had been discovered by Hipparchus of Rhodes in the second century BCE. He became aware that the so-called fixed stars had a slow motion, from west to east, of about one degree per century. This parameter was confirmed four centuries later by Ptolemy. When Muslim astronomers began making observations in Baghdad and Damascus around the year 830, they discovered that the motion was considerably faster: one degree every 66 years. This was confirmed by their successors in the ninth and tenth centuries. The Toledan astronomers of the eleventh century were inclined to trust the validity of the observations made by all their predecessors. When faced with this discrepancy, the Toledan astronomers concluded that the motion of precession was not uniform.

This assessment meant that a new geometrical model was needed that could justify variable precession and remain in agreement with past observations. At least three scholars in the Toledan team worked on this problem and recorded their observations: Ṣāʿid himself, Ibn al-Zarqālluh, and Abū Marwān al-Istijī.[15] The earliest known results of this work appear in the *Liber de motu octave spere*, extant in a twelfth-century translation from a lost Arabic original. Among its contents is a description of the model (Figure 1).[16] The *Liber de motu* also contains a set of tables, designed for the computation of precession on a given date, which were included in the *Toledan Tables*.

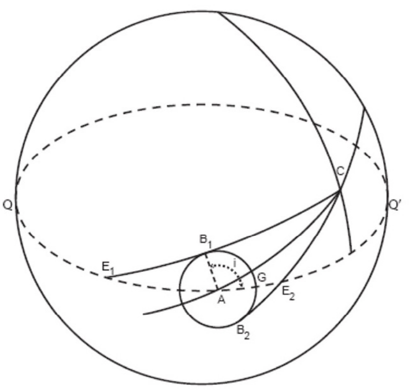

Figure 1. Model of precession, as described in the *Liber de motu octave spere*.

As shown in Figure 1, the mean equinox, point A, is determined by the intersection of the equator QQ′ and the mean ecliptic AC. Point B rotates uniformly on the small equatorial epicycle B_1B_2 with center A. Its motion drags the ecliptic, whose point of intersection with the equator, or equinox, moves back and forth, always keeping the common point C at 90º from A. As shown in Figure 1, there are two positions for the moving ecliptic: E_1B_1C and B_2E_2C. E_1 and E_2 are the equinoxes corresponding to the moments at which point B occupies the positions B_1 and B_2. The arcs of the moving ecliptic E_1B_1 and B_2E_2 determine the increase in longitude due to precession at the two moments in question. Angle *i* is an arc GB, measured from the equator, which determines the position of point B on the equatorial epicycle. In this model a second equatorial epicycle must also exist, one whose center is located at a distance of 180º from point A. Precession will increase when point B rotates in the upper half of the equatorial epicycle, and it will decrease in its lower half. This is why the sources refer to an accession and recession motion.

After the deaths of his patrons *qāḍī* Ṣāʿid in 1070 and al-Ma'mūn in 1075, Ibn al-Zarqālluh's life in Toledo likely became increasingly difficult. Historical sources indicate that he left Toledo either at the beginning of the reign of al-Ma'mūn's successor, Yaḥyā II al-Qādir (1075–1085), or as a result of the conquest of Toledo by Alfonso VI, king of Castile, in 1085. He moved to Córdoba, which belonged to the kingdom of Seville, where al-Muʿtamid (r. 1069–1091) reigned. Ibn al-Zarqālluh had already worked for this ruler in 1048, who was at the time the young ʿAbbādid prince of Seville.

Returning to the patronage of al-Muʿtamid, Ibn al-Zarqālluh continued working on astronomical instruments, including an armillary sphere,[17] a universal astrolabe, and an equatorium. The astrolabe is the standard instrument for solving problems of spherical astronomy in relation to the motion of the sun and the stars. It is easy to use, but has one major drawback: a specific plate is required for each latitude. If the appropriate plate is not available, time-consuming calculations are required that yield only approximate results. During his stay in Toledo, Ibn al-Zarqālluh and his colleague ʿAlī ibn Khalaf invented two astrolabes that were not latitude dependent (Figure 2). The instrument was called a *ṣafīḥa*, or *saphea* in Latin and *azafea* in Castilian. It contains two sets of coordinates. The most complete set is equatorial, the equator itself represented by the diameter which goes from the upper ring, used to hang the instrument, to the bottom of the instrument. A second diameter represents the ecliptic and forms an angle with the equatorial diameter, known as the obliquity of the ecliptic, of approximately 23º 30′. A second, incomplete set of coordinates corresponds to the great circles of ecliptical longitude passing through the beginnings of the zodiacal signs. A ruler that rotates around the center of the instrument (not shown in Figure 2) corresponds to the local horizon. Moving the ruler until its end forms an angle with the northern equatorial pole equal to the local latitude yields a perfect representation of the three basic astronomical planes—equator, ecliptic, and horizon—that can be used to solve all manner of problems in spherical astronomy. Ibn al-Zarqālluh made different versions of his *saphea*. Two of them were dedicated to his royal patrons: *al-ṣafīḥa al-ma'mūniyya* to al-Ma'mūn of Toledo and *al-ṣafīḥa al-ʿabbādiyya* to al-Muʿtamid of Seville, of the ʿAbbādid dynasty.

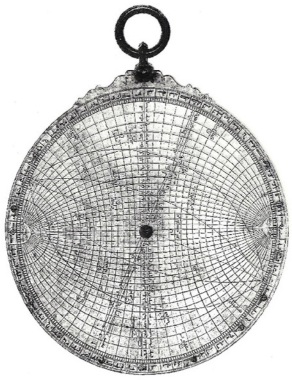

Figure 2. Ibn al-Zarqālluh's *saphea*.

Ibn al-Zarqālluh also designed another astronomical instrument for al-Muʿtamid. The equatorium, as it was known, allowed for a graphical determination of planetary longitudes using very little computation. It was based on a series of Ptolemaic planetary scale models. Computing the longitude of a planet using a standard set of astronomical tables requires about 30 minutes' work for a competent astronomer. If asked to cast a horoscope, the astronomer must then compute the longitudes of the sun, moon, Mercury, Venus, Mars, Jupiter, Saturn, and the ascending lunar node—the intersection of the moon's orbit with the ecliptic. This process requires about four hours of cumbersome computation. Further time is required to divide the ecliptic into twelve unequal astrological houses using complicated mathematical procedures. Finally, there is also the time needed for the analysis of the horoscope and the elaboration of a prediction. This lengthy process made horoscopes an expensive product to prepare. These overheads could be reduced by computing devices: an astrolabe made the division of the houses fairly simple, while the equatorium facilitated the determination of planetary longitudes.

This was not the only instance in which Ibn al-Zarqālluh simplified the work of astrologers. He also compiled a perpetual almanac using the goal-year cycles developed by Babylonian astronomers to predict planetary motion.[18] These cycles are characterized by the number of solar years during which a planet makes a particular number of synodic and zodiacal revolutions. Both figures are expressed as integers. These goal years have an obvious advantage for the astronomer. Assuming that a high degree of precision is not required, they allow for the computation of planetary positions for whole cycles—for example, eight years for Venus. In the following cycles, these positions will be repeated on the same dates. In the case of Venus, its longitude will be the same on January 1 of the first year as it is on January 1 of the ninth year, January 1 of the seventeenth year, and so on.

Ibn al-Zarqālluh wrote two short treatises on the construction and use of an equatorium. The former is only known through the Alfonsine Castilian translation, while the latter is extant in the original Arabic.[19] It seems that both works were written during Ibn al-Zarqālluh's time in Córdoba. The latter treatise mentions the year 474H of the Hegira, which is 1081–82 CE. The Alfonsine text mentions year 473H, or 1080–81.

In his equatorium design, Ibn al-Zarqālluh concentrated all the circles corresponding to each planet on both sides of the same plate. This forced him to use different scales for each planet. For each planetary deferent, he placed the center of the epicycle in a position corresponding to the planet's mean longitude. The situation was more complicated in the case of Mercury, for which the Ptolemaic model established that the center of the planet's deferent rotates on a small circle whose center is located in the apse-line—a straight line that connects the planet's apogee and perigee and passes through its center. As a result, Mercury's deferent is not circular, but instead forms an undefined curve.

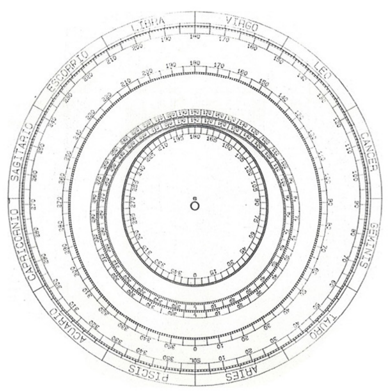

Figure 3. Circles for Mercury, the moon, and the sun in Ibn al-Zarqālluh's equatorium according to a reconstruction by Mercè Comes and Honorino Mielgo. Note the oval shape of Mercury's deferent.

In a paper published in 1955, Willy Hartner established that the curve described by the center of Mercury's epicycle becomes practically identical with an ellipse according to the parameters provided in the *Almagest*. This configuration is not affected by Ibn al-Zarqālluh's slight modification to Ptolemy's parameters. Hartner also noted that the Alfonsine translation of Ibn al-Zarqālluh's lost Arabic original was the first explicit description of Mercury's true deferent.[20] This curve is identified as an ellipse in the Castilian translation of Ibn al-Zarqālluh's Arabic text on the construction of the instrument. In an English approximation of the enigmatic Castilian text, "The deferent circle will have the shape of the *deficient section* [ellipse], of those sections which appear in the *pineal figure* [cone]."[21]

This is likely the first use of such a conic section in astronomy. Ibn al-Zarqālluh had no theoretical pretensions in his use of an ellipse and employed it only to simplify the design of an equatorium.[22] Similar developments took place in the Islamic East during the fifteenth century, in which al-Kāshī's equatorium used an oval curve for Mercury's deferent, as well as in Europe. Georg von Peuerbach (1423–1461) was the first European scholar to identify the oval curve of Mercury's deferent in Ptolemaic theory. Erasmus Reinhold (1511–1553) subsequently found that this was not only the case for Mercury, but also for the moon.[23]

Beginning around 1050, Ibn al-Zarqālluh made observations of the sun for the following 25 years and the moon for 37. He started in Toledo, probably while working with Ṣāʿid's team, and continued during his stay in Córdoba where, according to his own account, he was helped by one of his disciples, likely Ibn al-Kammād. He used the mid-seasons method, observing the sun in the midpoints between equinoxes and solstices. In his *Yesod ha-ʿOlam*, Israeli offers some details about Ibn al-Zarqālluh's determination of the autumn equinox which took place in Toledo on September 17, 1075, at 4 hours and 18 minutes after noon. The modern calculated value for this particular equinox is September 17, 1075, at 5 hours, 30 minutes, and 40 seconds after noon. The year 1075 also seems to have been when Ibn al-Zarqālluh made crucial observations that allowed him to determine the solar parameters. Observations of stellar longitudes made in 1063 and 1080 are mentioned in his *Treatise on the Motion of the Fixed Stars*. This task was continued until at least 1087 or 1088.

Ibn al-Zarqālluh wrote several important works based on these long periods of observation. One of them, not extant, was entitled *On the Invalidity of Ptolemy's Method to Obtain the Apogee of Mercury*. The title implies that he was aware that Ptolemy's apogee for Mercury, 190°, was inaccurate by about 30°. In his *Treatise on the Motion of the Fixed Stars*, Ibn al-Zarqālluh improved the trepidation model that was likely designed by Ṣāʿid with other members of the Toledan team. He introduced a secondary model that allows for the calculation of the obliquity of the ecliptic, the angle between the ecliptic and the equator. The model implies that the changes in the obliquity are cyclical between a maximum of 23° 53′, attained near Ptolemy's time,[24] and a minimum of 23° 33′, obtained in the time of Ibn al-Zarqālluh. This finding reappeared in all his theoretical efforts, in which his geometrical models justified historical changes to astronomical parameters.

Ibn al-Zarqālluh's book on the sun is also lost, although most of its contents have been recovered from quotations found in later Andalusian and Maghribi sources, as well as in the *Tractatus super totam astrologiam* by the thirteenth-century Franciscan Bernard of Verdun and in the *Epitome of the Almagest* by Regiomontanus in the fifteenth century.[25] Ibn al-Zarqālluh's book contained two original contributions. First, he discovered that the solar apogee had a motion of its own. While Ptolemy believed that the solar apogee was fixed and that its longitude was invariably 65° 30′, observations made by Islamic astronomers in 829 and 831 yielded two different values of its position: 82° 39′ and 82° 45′, respectively. To reconcile these different measurements, astronomers concluded that the apogee advances 1° over 66 years, a parameter identical to the Ma'mūnī estimation of the precession of equinoxes. This was the origin of a general belief among Islamic astronomers that the solar and planetary apogees were sidereally fixed—that is, each was always pointing to a particular star, moving slowly with it as a result of precession.[26] Even though this assumption resulted in disparities between calculated positions and solar observations, no Eastern Islamic astronomer dared to formulate an alternative. Ibn al-Zarqālluh established that the solar apogee moved faster than the stars, and suggested that its rate of motion was 1° in 279 years. His figure is close to the modern value: 1° in a little more than 310 years. Tables for the motion of the solar apogee based on Ibn al-Zarqālluh's determination appear as part of later Andalusian and Maghribi astronomical tables.

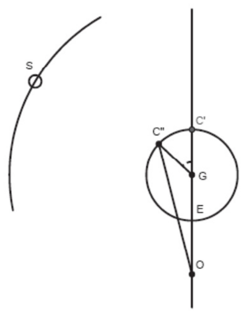

Figure 4. Ibn al-Zarqālluh's solar model with variable eccentricity.

Ibn al-Zarqālluh's second original contribution was the design for a solar model with variable eccentricity. This was a work motivated by the fact that the eccentricity used by Ptolemy and Hipparchus was 2.5 parts, or $2;30^p$ in sexagesimal notation, assuming that the radius of the solar orbit was 60^p. Thābit ibn Qurra's (d. 901) figure was $2;6,40^p$, while Al-Battānī and the *Toledan Tables* used an eccentricity of $2;4,46^p$. Ibn al-Zarqālluh had found a figure of $1;58^p$ in observations made around 1075. In his solar model with variable eccentricity (Figure 4), S is the sun, which rotates uniformly about C, the center of its eccentric. C rotates very slowly, but also with uniform velocity, around the center G of the small circle C′C″E. O is the center of the earth. The solar eccentricity, OC, attains its maximum value (2;29,30^p) when C is in C′, and its minimum (1;50,56^p) at E.

The Maghribi *zījes* based on Ibn al-Zarqālluh's work contain tables from which the value of eccentricity can be calculated for a given date. Ibn al-Zarqālluh thought that the maximum value had been attained in the time of Ptolemy and that it was near its minimum in the second half of the eleventh century. This model passed into the medieval European astronomical literature and reappeared in *De revolutionibus* by Nicolaus Copernicus.[27]

A further innovation by Ibn al-Zarqālluh is mentioned in the testimony of Ibn al-Hā'im, an Andalusian astronomer of the early thirteenth century. In his *Kāmil zīj*, he states that he had read, in Ibn al-Zarqālluh's own handwriting, a modification to a Ptolemaic lunar model: the center of the moon's mean motion in longitude was not the center of the earth, as in Ptolemy, but was placed on a straight line linking the center of the earth with the solar apogee. The maximum correction in the lunar mean longitude amounted to 24′. Ibn al-Zarqālluh had reached this conclusion after a careful examination of Ptolemy's lunar model, checking its results

> in relation to many eclipses which took place in all parts of the ecliptic, during a long period of time of about thirty-seven years, according to what we found [in a text] written by his own hand. [He reached results] which did not disagree at all with [what] the Ancients said on this topic, with the only exception of the mean [lunar] motion in longitude.[28]

No other details have survived about this correction, other than it was introduced in later Andalusian and Maghribi *zījes*. The authors of these books recommend its use when a high degree of precision is required, particularly in relation to the computation of eclipses.

Ibn al-Zarqālluh was one of the most important astronomers of the Islamic West. He was fortunate to be born in a time when the astronomical knowledge inherited from the Indo-Iranian and Greek traditions, as well as that produced in the Middle East during the ninth and tenth centuries, had been fully assimilated. The eleventh century was also a period in which Al-Andalus was culturally isolated. As a result, Andalusian science developed independently from Eastern Islam. The work of Ibn al-Zarqālluh is a case in point.

Together with his Toledan colleagues, Ibn al-Zarqālluh accepted the figures from earlier periods of observation, and developed models compatible with both old and new results. This approach yielded trepidation theory, the cyclical changes of the obliquity of the ecliptic, the discovery of the motion of the solar apogee and a solar model with variable eccentricity. His astronomical ideas and results proved extremely influential not only for astronomers in Al-Andalus and the Maghrib during the twelfth and the fifteenth centuries, but also in Europe where his work was passed on in Latin and Romance translations produced in twelfth-century Toledo. Ibn al-Zarqālluh's innovations in instrument design and astronomical theory remained popular until the time of Copernicus.

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1. Both had been attributed to Māshā'allāh, an Eastern astrologer of the second half of the eighth century, but research has shown that they are the works of Maslama and his disciples.
2. José Martínez Gázquez, *The Attitude of the Medieval Latin Translators towards the Arabic Sciences* (Florence: Sismel Edizioni del Galluzzo, 2016).
3. Among these marvels was the pavilion al-Ma'mūn had built in the center of his palace where he sat. In the middle of a large pool, a kiosk with a dome-shaped covering was made in colored glass. Water was brought up to the top of the dome and descended by the outer walls. By night the kiosk was lit by candles, whose light, refracted by the water curtain, produced marvelous visual effects. Henri Pérès, *La Poésie andalouse en arabe classique au XI^e siècle* (Andalusian Poetry in Classical Arabic in the Eleventh Century) (Paris: Adrien Maisonneuve, 1933), 150.
4. Although many of the devices were ingenious toys rather than practical instruments, two were yearly astronomical calendars of the kind that can still be seen today in European cities like Prague. The only extant manuscript describing these calendars (Florence, Medicea-Laurenziana 152) was copied in Toledo in 1266 during the reign of Alfonso X. See the facsimile of the manuscript, edition, and translation published by Massimiliano Lisa, Mario Taddei, and Edoardo Zanon, *The Book of Secrets in the Results of Ideas: Incredible Machines from 1000 Years Ago, Ibn Khalaf al-Murādī* (Milan: Leonardo3, 2008).
5. José María Millás-Vallicrosa, *Estudios sobre Azarquiel* (Studies on Azarquiel) (Madrid & Granada: CSIC, 1943–50), 7–9.
6. Also called Ṣāʿid al-Andalusī or Ṣāʿid al-Ṭulayṭulī. The most complete study of his life and works is Eloísa Llavero Ruiz, "Al-Ṭulayṭulī, Ṣāʿid," in *Biblioteca de al-Andalus*, vol. 7 (Almería: Fundación Ibn Tufayl de Estudios Árabes, 2012), 484–98.
7. I have consulted, among others, the French translation by Régis Blachère, *Livre des catégories des nations* (Paris: Larose, 1935), and the English translation by Semaʿan I. Salem and Alok Kumar, *Science in the Medieval World: "Book on the Cat-*

egories of Nations" (Austin: University of Texas Press, 1991).

8. Julio Samsó, "Al-Andalus, a Bridge between Arabic and European Science," *Alhadra* 1 (2015): 101–25.
9. Spelled variously Zarqiyāl, Zarqāl, and Zarqālī or, in Latin transcriptions, Azarquiel and Azarchel. The name Al-Zarqālluh may have been derived as a result of combining *zarq*, which means "blue" in Arabic, and the Romance diminutive suffix -*ello*. This man should not be confused with the aforementioned al-Zarqāl, who built the Toledan clepsydra-lunar calendar.
10. The prince was only eight or nine years old at the time. He would later become King al-Muʿtamid and resume patronage of Ibn al-Zarqālluh after the deaths of Ṣāʿid and al-Ma'mūn.
11. An anonymous contemporary Toledan source mentions an instrument that had problems with stability, which implies that the instrument may have been large, in the tradition of Eastern Islamic observatories which employed enormous instruments in order to achieve better precision.
12. The *Toledan Tables* are usually considered to be the result of the collective work of the Toledan team, in which Ibn al-Zarqālluh had an important role. The leadership of this project should be ascribed to *qāḍī* Ṣāʿid, yet a difficulty in accepting this interpretation lies in the facts that Ṣāʿid did not mention the *Toledan Tables* in his *Ṭabaqāt*, written in 1068, and he died in July 1070. If he actually was the patron and promotor of the tables, they must have been compiled hurriedly between 1068 and 1070, or otherwise, after his death, based on observations made before it. Lutz Richter-Bernburg, "Ṣāʿid, the *Toledan Tables* and Andalusī Science," *Annals of the New York Academy of Sciences* 500, no. 1 (1987): 373–401, doi:10.1111/j.1749-6632.1987.tb37212.x.
13. Critical edition in Fritz Pedersen, *The Toledan Tables: A Review of the Manuscripts and the Textual Versions with an Edition*, Historisk-filosofiske Skrifter 24:1–4 (Copenhagen: Kongelige Danske Videnskabernes Selskab, 2002).
14. Geoffrey Chaucer, *Canterbury Tales*, "The Frankeleyns Tale," lines 545–52.
15. These authors wrote about the issue in the following works: Ṣāʿid in his *Iṣlāḥ ḥarakāt al-nujūm* (Correction of the Motion of Heavenly Bodies); Ibn al-Zarqālluh in his *Treatise on the Motion of the Fixed Stars*, only extant in a Hebrew translation; and Abū Marwān al-Istijī in *Risālat al-iqbāl wa-l-idbār* (On Accession and Recession).
16. This was later improved in Ibn al-Zarqālluh's treatise.
17. His treatise on the construction of this instrument has been preserved in a Castilian Alfonsine translation.
18. Millás-Vallicrosa, *Estudios sobre Azarquiel*, 75–134.
19. Mercè Comes, *Ecuatorios andalusíes: Ibn al-Samḥ, al-Zarqālluh y Abū-l-Ṣalt* (Andalusian Equatories: Ibn al-Samḥ, al-Zarqālluh, and Abū-l-Ṣalt) (Barcelona: Facultat de Filologia, Universitat de Barcelona; Instituto de Cooperacíon con el Mundo Arabe, Agencia Española de Cooperacíon International, 1991), 203–36, 79–138.
20. Willy Hartner, "The Mercury Horoscope of Marcantonio Michiel of Venice: A Study in the History of Renaissance Astrology and Astronomy," in *Oriens-Occidens* (Hildesheim: Georg Olms Verlagsbuchhandlung, 1968), 440–95.
21. Translated in Julio Samsó and Honorino Mielgo, "Ibn al-Zarqālluh on Mercury," *Journal for the History of Astronomy* 25 (1994): 289–96, doi:10.1177/002182869402500403.
22. S. Mohammad Mozaffari has analyzed a passage of al-Bīrūnī's *al-Qānūn al-Masʿūdī*, in which the great Eastern astronomer studies the oval-shaped curve described by the center of the lunar epicycle and proves that it is not an ellipse. "Bīrūnī's Examination of the Path of the Centre of the Epicycle in Ptolemy's Lunar Model," *Journal of the History of Astronomy* 45 (2014), doi:10.1177/002182861404500107.
23. The history of European equatoria has been studied by Emmanuel Poulle, *Les Instruments de la théorie des planètes selon Ptolémée: Equatoires et horlogérie planétaire du XIII*[e] *au XVI*[e] *siècle* (The Instruments of the Theory of the Planets according to Ptolemy: Equatorials and Planetary Clocks from the Thirteenth to the Sixteenth Century) (Geneva: Droz; Paris: Champion, 1980).
24. The value given in the *Almagest* is 23º 51' 20".
25. Gerald Toomer, "The Solar Theory of az-Zarqāl: A History of Errors," *Centaurus* 14 (1969): 303–36, doi:10.1111/j.1600-0498.1969.tb00146.x; Gerald Toomer, "The Solar Theory of az-Zarqāl: An Epilogue," in *Annals of the New York Academy of Sciences* 500 (1987): 513–19, doi:10.1111/j.1749-6632.1987.tb37222.x; Julio Samsó and Eduardo Millás, "Ibn al-Bannā', Ibn Isḥāq and Ibn al-Zarqālluh's Solar Theory," in *Islamic Astronomy and Medieval Spain*, ed. Julio Samsó (Hampshire: Aldershot; Brookfield: Variorum, 1994).
26. S. Mohammad Mozaffari, "Limitations of Methods: The Accuracy of the Values Measured for the Earth's/Sun's Orbital Elements in the Middle East, AD 800–1500, Part 2," *Journal for the History of Astronomy* 44, no. 4 (2013): 389–411, doi:10.1177/002182861304400402.
27. Toomer, "The Solar Theory of az-Zarqāl: A History of Errors" and "The Solar Theory of az-Zarqāl: An Epilogue." Emilia Calvo, "Astronomical Theories Related to the Sun in Ibn al-Hā'im's *al-Zīj al-Kāmil fī l-taʿālīm*," *Zeitschrift für Geschichte der Arabisch-Islamischen Wissenschaften* 12 (1998): 51–111. Mozaffari, "Limitations of Methods."
28. Roser Puig, "The Theory of the Moon in the *Al-Zīj al-kāmil fī l-taʿālīm* of Ibn al-Hā'im (circa 1205)," *Suhayl* 1 (2000): 71–99.

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