1

General survey of Arabic astronomy

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Interest in astronomy has been a constant feature of Arabic culture since the end of the second century AH (eighth century AD), and it is the quantity of study which strikes us first when we begin exploring this subject: the number of scientists who have worked on theoretical astronomy, the number of treatises which have been written in this field, the number of private or public observatories which have been successively active and the number of precise observations recorded there between the ninth and the fifteenth centuries.

This chapter is exclusively concerned with astronomy as an exact science, without considering the question of astrology. In fact, although the same authors sometimes wrote treatises in both disciplines, they never mixed purely astronomical reasoning and purely astrological reasoning in the same book and in most cases the titles of the works indicate unambiguously whether their contents relate to one discipline or the other.

The science of astronomy is chiefly defined by two terms: *ʿilm al-falak,* or 'science of the celestial orb', and *ʿilm al-hay'a,* or 'science of the structure (of the universe)'; the second term can be translated in many cases as 'cosmography'. In addition, many astronomical works are identified by the word *zij,* a term of Persian origin corresponding to the Greek *kanôn;* in its proper sense it denotes collections of tables of motion for the stars, introduced by explanatory diagrams which enable their compilation; but it is also often used as a generic term for major astronomical treatises which include tables.[1]

The astronomical term which is generally used to refer to the stars is *kawkab, kawakib,* while a word of similar meaning, *najm, nujum,* has a more astrological connotation, and astrology is described with the aid of expressions based on the latter term: *ʿilm ahkam al-nujum, sinaʿat al-nujum,*

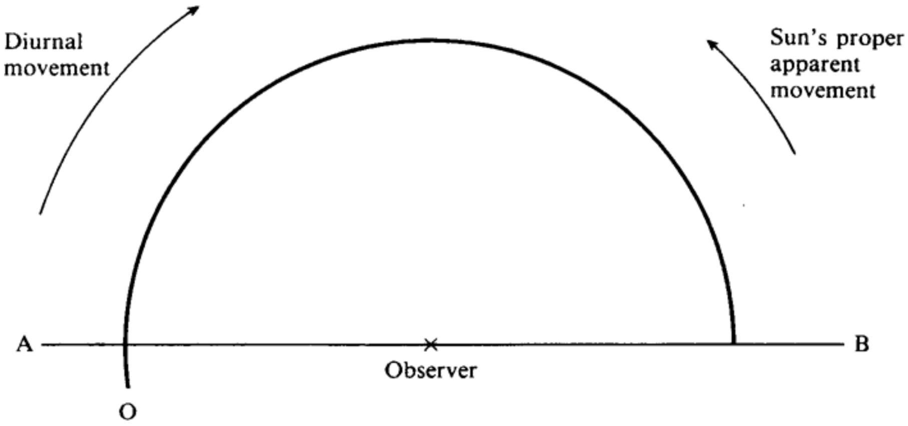

Figure 1.1

tanjim...;[2] however, *'ilm al-nujum,* 'the science of the stars', can include both astronomy and astrology, as two different approaches to the same reality.[3]

In the Arabian peninsula, as in all of the ancient Near East, traditions of observing the heavens went back a very long way; one of these traditions is of particular note, having become well-known through its revival in what Arab astronomers called the *Treatises on the Anwa'*.

The term *anwa'* is the plural of *naw'*; it describes a system of computation associated with observation of the heliacal risings and acronycal settings of certain groups of stars, permitting the division of the solar year into precise periods. The appearance of stars on the horizon at a given time of year was considered to be a sign of meteorological phenomena signalling a change of weather, so much so that the term *naw'* acquired the meaning of rain or storm. A brief reminder of the heliacal risings and acronycal settings of the fixed stars is contained in Figure 1.1, which shows a rough projection on the prime vertical of the apparent trajectory of the sun.

AB is the line of the horizon and O is the position of the sun under the horizon before sunrise, so that a star at A, next to the ecliptic, is at the limit of visibility when it rises, and a star at B is at the limit of visibility when it sets, according to the luminosity of the sky on the horizon just before sunrise. This situation shows the heliacal rising of star A and the acronycal setting of star B. The next day, because of the 'apparent movement of the sun' (approximately one degree per day), the sun will be further away from the horizon when A and B are in the same situation, and these two stars will be more visible since the horizon will be less luminous. About six months later, A and B will have exchanged their positions and B will be rising with A setting.

Originally the observation of these phenomena for definite groups of stars allowed the solar year to be divided into fixed periods, probably twenty-eight in number. After the eighth century, under the influence of Indian tradition, this system of calculation became combined with that of the twenty-eight 'lunar mansions' *(manazil al-qamar),* groups of fixed stars close to the ecliptic, delineating the zones of the sky in which the moon is found night by night during the lunar month. The *Treatises on the Anwa'* which have been handed down—in written form from the ninth century— are like a series of almanacs giving the solar calendar dates for the heliacal risings and acronycal settings of stars which correspond to the lunar mansions, together with the meteorological phenomena that are traditionally associated with them. Under this system the year was divided into twenty-eight periods of thirteen or fourteen days.[4]

This ancient tradition, empirical in origin, was revived as a scientific procedure by Arab astronomers within the framework of their studies concerning the appearance and disappearance of stars on the horizon at the moment of the rising or setting of the sun, which were based in part on the *Phaseis* by Ptolemy, discussed below.[5]

SOURCES OF ARABIC ASTRONOMY

The first scientific astronomical texts translated into Arabic in the eighth century were of Indian and Persian origin, and in the ninth century, Greek sources took precedence. We shall discuss them in chronological order, starting with texts in Greek.

Greek sources

Greek texts were of two types: 'physical' astronomy, in the old sense of the word, and 'mathematical' astronomy.

The aim of 'physical' astronomy was to arrive at a global physical representation of the universe by means of purely qualitative thought; this astronomy was dominated by the influence of Aristotle, with his coherent organization of the world into concentric moving spheres, ranging from a common centre, the earth, and stable at that point. The first celestial sphere was that of the moon—the sub-lunar world being one of generation and corruption, the supra-lunar world one of permanence and uniform circular motion, the only motion that could befit the perfection of the celestial bodies —while each star had its own sphere to move it, and so on out to the sphere of the fixed stars which enclosed the universe.

‘Mathematical’ astronomy sought a purely theoretical, geometrical representation of the universe, based on precise numerical observations, disregarding if necessary its compatibility with a coherent world of the ‘physical’ type: to find the geometrical parametric models capable of accounting for measured celestial phenomena, enabling the calculation of the position of the stars at a given moment and the compilation of tables of their movements.

The history of ancient scientific astronomy is built in part on the tension between these two approaches to the same science.

‘Mathematical’ astronomy developed within the framework of Hellenistic astronomy—especially from the time of Hipparchus (*fl.* 160–126 BC), adapting the work of Apollonius from the previous century —but it was the work of Ptolemy in the second century AD which represented its crowning achievement in the Greek language.

Ptolemy is the scientist whose works have been the most studied, revised, commented on and criticized by later astronomers, until the seventeenth century. His four works on astronomy, in the order of their composition, are the *Almagest,* the *Planetary Hypotheses,* the *Phaseis* and the *Handy Tables.* The first two are the most important.

The *Almagest,* or *Great Mathematical Compendium,* handed down in the original Greek and in several Arabic translations, is regarded as the standard manual, which has served astronomy in the same way as Euclid’s *Elements* served mathematics. Suffice it to say that within this monumental work of thirteen volumes Ptolemy synthesized the research of his predecessors, modifying it according to his own observations, and refining the old geometrical models or creating others. It was no accident that the word ‘mathematical’ was included in the title of the work, because Ptolemy made little reference therein to the ‘physical’ situation of the universe, even though he took this implicitly into account; he established and detailed the geometrical procedures capable of accounting for observed phenomena, on the basis of two postulates of ancient astronomy: the earth is stable at the centre of the world, and all celestial motion must be explained by a combination of uniform circular movements. He defined his method thus:

1. To collect the greatest possible number of precise observations
2. To identify anomalies in the movements thus observed in relation to uniform circular motion
3. To determine experimentally the laws governing the periods and the magnitudes of the anomalies
4. To combine uniform circular motions with the aid of concentric or eccentric circles and epicycles to account for the observed phenomena

5 To calculate the parameters of these movements in order to compose tables for calculating the positions of stars.

Ptolemy's method was therefore defined very precisely, but his desire to 'save the phenomena' led him in practice to infringe certain of his basic principles and to allow empiricism to intrude on some of his demonstrations, as he states himself in the last volume of his work: 'Each of us must endeavour to make the simplest hypotheses agree with the celestial movements as best he can, but if this is not possible he must adopt the hypotheses which fit the facts'.

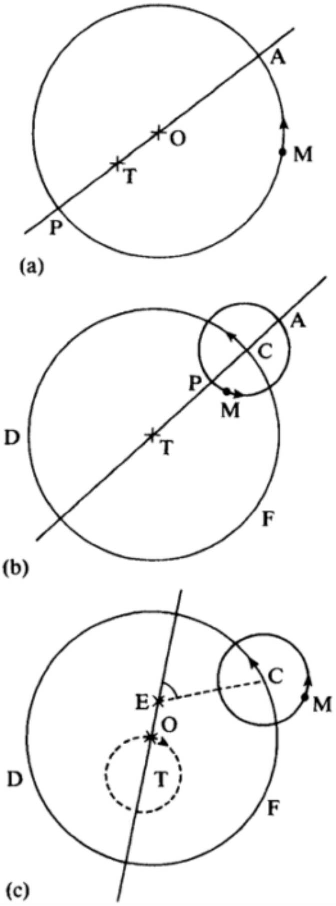

Figure 1.2

Ptolemy based the research for his geometrical models on work carried out by Hipparchus—drawing in turn from Apollonius—when he had developed the system of epicycles and eccentrics. Let the earth be stationary at T, the position of the observer. In the simple eccentric system (Figure 1.2(a)) a star at M travels on the circle MAP in uniform circular motion about the centre O, but the observer notices a different apparent speed when the star is at the apogee A or the perigee P. This geometric model can be applied to account for the apparent movement of the sun. In the simple epicycle system (Figure 1.2(b)), we imagine the observer at T, the centre of a circle CDF (the deferent), on which there travels a small circle with centre C (the epicycle), on the circumference of which moves a star M, the two circular motions being uniform and the angular speed of the centre C corresponding to the mean motion of the planet. This epicycle system, like that of the eccentric, can explain the difference in distance to the earth, but, above all, it can account for the apparent retrograde motion of the planets in a much more convincing way than a pure system of concentric physical spheres: when the planet is at P and its apparent angular speed on the epicycle is greater than that of C, it has an apparent retrograde motion; on the other hand, when it is at A, the two speeds sum and, to the observer at T, it appears to move faster than C.

This system of epicycles is very versatile and lends itself to a more complex combination of the elements concerned: the deferent CDF can be considered as eccentric with respect to the earth (Figure 1.2(c)), and makes in its turn a circular movement around T. One can thus arrive at highly complicated models, such as that of the moon or Mercury. For the larger planets (Mars, Jupiter, Saturn), Ptolemy takes an eccentric deferent CDF, with centre O, with the observer still situated at T, but he asserts that the uniform motion of the centre C of the epicycle is not around O but around the point E such that O is in the middle of TE; the point E is called the ‘equant point’. This expedient leads to a better agreement between the theoretical model and the observations but contradicts the basic principle of uniform circular motion.[6]

It is thus possible to find the position of different planets in the heavens; it only requires calculation, based on observations, of the different parameters in each case: eccentricities, relative size of the radii, and angular velocities on the different circles.

The *Planetary Hypotheses* has been preserved partly in Greek (a little less than a quarter of the work) but there is a complete Arabic version.[7] It is much shorter than the *Almagest,* and its general tone is very different. First, Ptolemy calculates the maximum and minimum distances of the stars in terms of the data in the *Almagest* and thus divides the universe into concentric zones, each corresponding to the area in which a given star could move, placing the spheres of fire, air, water and earth under the sphere of the moon, in accordance with Aristotle. Thereafter, his point of view becomes 'physical' in the Aristotelian sense of the term rather than 'mathematical'. He seeks to describe the form of the physical bodies within which the circles which account for the various movements can be conceived, as an expression of the constitution of the real physical universe. He divides the 'ether' into thick globes tangential to one another, recalling the Aristotelian system of homocentric spheres; but Ptolemy also uses eccentric spheres and adds a further arrangement of tori and discs. The result is a kind of highly complex compromise between a purely geometrical system and a coherent physical system such as that defined by Aristotle. Ptolemy had thus attempted to embody his theory in a concrete 'physical' system, but the *Planetary Hypotheses* was to have less influence than the *Almagest,* apart from his calculations of the distances and sizes of stars which would be largely accepted by later astronomers.

The *Phaseis* treats of the appearance and disappearance of fixed stars just before sunrise or just after sunset (heliacal rising and acronycal setting). This work is in two parts, only the second of which is preserved in Greek and which contains a calendar of appearances and disappearances of stars on the horizon in the course of the year. The contents of the first part, a purely theoretical analysis of this particular phenomenon, is only known through an Arabic text.[8]

The *Handy Tables* has been handed down in Greek in Theon of Alexandria's fourth-century *Commentary on the Handy Tables.* It represents a rethinking in practical form of the theoretical results of the *Almagest* through the creation of detailed tables, with modification of certain parameters in accordance with the results in the *Planetary Hypotheses* and in the *Phaseis.*

All these works are cited by Arab astronomers as far back as the ninth century, together with the commentaries on the *Almagest* composed by Pappus and by Theon of Alexandria, and also a series of Greek treatises known as the 'Small astronomy collection' because it was regarded as an introduction to the reading of the *Almagest:* the *Data,* the *Optics,* the *Catoptrica* and the *Phenomena* of Euclid;[9] the *Spherics, On Habitations* and *On Days and Nights* of Theodosius;[10] *On the Moving Sphere* and *On Risings and Settings* by Autolycus;[11] *On the Sizes and Distances of the Sun and Moon* by Aristarchus of Samos;[12] *On the Ascensions of Stars* of Hypsicles;[13] and the *Spherica* by Menelaus.[14]

Indian and Persian sources

Three Indian astronomical texts are cited by the first generation of Arab scientists: *Aryabhatiya,* written by Aryabhata in 499 and referred to by Arab authors under the title *al-arjabhar; Khandakhadyaka* by Brahmagupta (d. after 665), known in Arabic under the title *zij al-arkand;* and *Mahassidhanta,* written towards the end of the seventh or at the beginning of the eighth century, which passed into Arabic under the title *Zij al-Sindhind.*[15]

These texts are based on the yearly cycles corresponding to Indian cosmology, and their scientific tradition is linked with an earlier period of Hellenistic astronomy than that of Ptolemy; they thus preserve a certain number of elements that can be traced back to the time of Hipparchus. They contain few theoretical developments but methods of calculation for creating tables and numerous parameters of the movement of stars. The major scientific innovation of the Indian scientists in this field is the introduction of the *sine* (half-chord of the double arc) in trigonometric calculations, which makes these much less cumbersome than the chords of arcs used in Greek astronomy since Hipparchus (see vol. II, chapter 15).

In Persia, under the Sasanids (AD 226–651), some activity in scientific astronomy developed in the Pahlavi language, under both Indian and Greek influence (Ptolemy's *Almagest* was translated into Pahlavi in the third century). This work seems to have been primarily oriented toward astrology, and the only traces which remain are found in Arabic texts from the end of the eighth century onward; these refer in particular to the 'Royal tables' *(zij al-Shah),* several successive versions of which are reported: from 450, 556 and 630 or 640 (under Yazdegerd III). These tables depended principally on Indian parameters.[16]

The chapters which follow detail how the Arab astronomers worked with these different sources.

OBSERVATIONS AND OBSERVATORIES

Small portable instruments and sundials are described in Chapters 4 and 5. Here we shall confine ourselves to a brief presentation of observatories and their large-scale instruments.[17]

Ibn Yunus reports that astronomical observations were carried out at Gundishapur at the end of the eighth century by al-Nihawandi (d. AH 174 (AD 790)), whose work has been lost.[18] But the earliest precise observational results to have come down to us were recorded first in the al-Shammasiyya quarter in Baghdad, and then on Mount Qasiyun at Damascus, in the final years of the reign of Caliph al-Ma'mun (813–33) and through his impetus. They involved a precise programme dealing particularly with the sun and the moon, and at Damascus there was a complete year of continuous observation of the sun in AH 216–17 (AD 831–2). The work does not appear to have continued at these two sites after the death of al-Ma'mun.

Apart from the numerical results found in later texts, we know little about these two observatories—their functioning, their size, etc.—except that Yahya b. Abi Mansur, who was in charge of the observation work at Baghdad, belonged to the famous 'house of wisdom' *(bayt al-hikma),* and that the caliph himself had demanded that the instruments used should be the most precise possible. There is no explicit mention of the type of instruments used, but the form of the results and the kind of observations carried out are the same as Ptolemy's, which indicates that the instruments were similar to those described in the *Almagest,* i.e. the equatorial or equinoctial armilla, the meridian armilla, the equatorial quadrant (the plinth), the parallactic rods, the large gnomons, the dioptra of Hipparchus for measuring apparent diameters, and the armillary sphere (Singer *et al.* 1957: III, 586–601); these were the classic instruments of ancient astronomy and were gradually improved by Arab scientists, who sought in particular to construct larger and larger circles to achieve greater precision.[19]

In the wake of the first series at Baghdad and Damascus, a number of other observations were recorded during the course of the ninth century by Habash al-Hasib, the Banu Musa, al-Mahani, Sinan b. Thabit, etc. In the majority of cases only the place is mentioned (Baghdad, Damascus, Samarra or Nishapur, for example) with no indication of the setting in which these observations were made, which indicates that they were carried out from private observatories, outside any collective structure.

All these accumulated observations had not yet been organized systematically, but, by way of comparison, it should be noted that Ptolemy based all the work in his *Almagest* on ninety-four observations made between 720 BC and AD 141, the oldest having been recorded in Babylon and the latest (thirty-five in all) being due to Ptolemy himself (Pedersen 1974:408–22). It is therefore evident that, from the ninth century, the Arabic astronomers had at their disposal the results of a far greater number of recent observations than those available to Ptolemy when creating his work.

At the turn of the ninth and tenth centuries, al-Battani emerged as one of the major observers of the first period of the history of Arabic astronomy. For a period of about thirty years he followed a systematic programme of observations at Raqqa in the north of present-day Syria, and in the context of locating the first crescent moon on the horizon, he made what appears to be the first reference to 'observation tubes' in an astronomical treatise in the Greco-Arabic tradition.[20] These tubes, without lenses, enabled the observer to focus on a part of the sky by eliminating light interference.[21] Al-Battani only mentions them, but the work of al-Biruni includes an exact description of this type of apparatus, in a section that is also dedicated to verifying the presence of the new crescent on the horizon:[22]

> This tube is fixed on a column and is capable of two movements: the first is the movement of the column itself, enabling one to turn the tube in all directions; the other is around an axis so that the tube moves in the plane of the circle of elevation in which it lies. The tube must be not less than five cubits in length and one cubit in section. The view is concentrated and strengthened because of the shadow of the tube and its darkness, augmented by its internal blackness. When the column is placed at the centre of the Indian circle, it can be turned round until the plumbline fixed at the end of the tube is in line with the azimuth of the crescent; then the other movement is used until the tube makes an angle with the surface of the earth equal to the height of the crescent; this is simple with a quadrant divided into 90 degrees attached to the column and turning with it parallel to the tube.

This observation tube, whose use is thus attested in the Arabic world from at least the end of the ninth or the beginning of the tenth century, passed into the medieval Latin West where it became a standard astronomical instrument.[23]

Numerous other observations were recorded in the East in the course of the tenth century. Let us briefly mention in particular the work carried out at the end of that century by al-Quhi and Abu al-Wafa’ al-Buzjani from the large observatory built in the gardens of the royal palace at Baghdad under Sharaf al-Dawla (AH 372–9 (AD 982–9)); that of ʿAbd al-Rahman al-Sufi (d. AH 376 (AD 986)), who systematically observed the fixed stars at Isfahan, measured their position, and published as a result his famous catalogue of stars, which was a complete revision of Ptolemy’s;[24] and that of Ibn Yunus at Cairo, at the turn of the tenth and eleventh centuries.[25] But let us look more closely at the observatory of Rayy.

It was at Rayy (12 km south of Teheran), in the reign of Fakhr al-Dawla (AH 366–87 (AD 977–97)) who subsidized it, that al-Khujandi (d. *c.* AH 390 (AD 1000)) devised and built a very large sextant for solar observations, based on the principle of the black box: a dark room with a small opening in the roof (Bruin 1969).

The building was oriented north-south along the meridian; it was composed of two parallel walls, 3.5 m apart, about 20 m in length and 10 m high (see Figure 1.3); it was devoid of light, but a small opening was made in the southern corner of the roof of the building. The ground was partially excavated between the two walls so that a sextant of 20 m radius could be drawn with the opening in the roof as its centre. The interior of the arc of the sextant was covered in copper plate where the image of the sun formed when it was at the meridian, and the markings permitted measurement of its height above the horizon or its distance at the zenith. Each degree measured

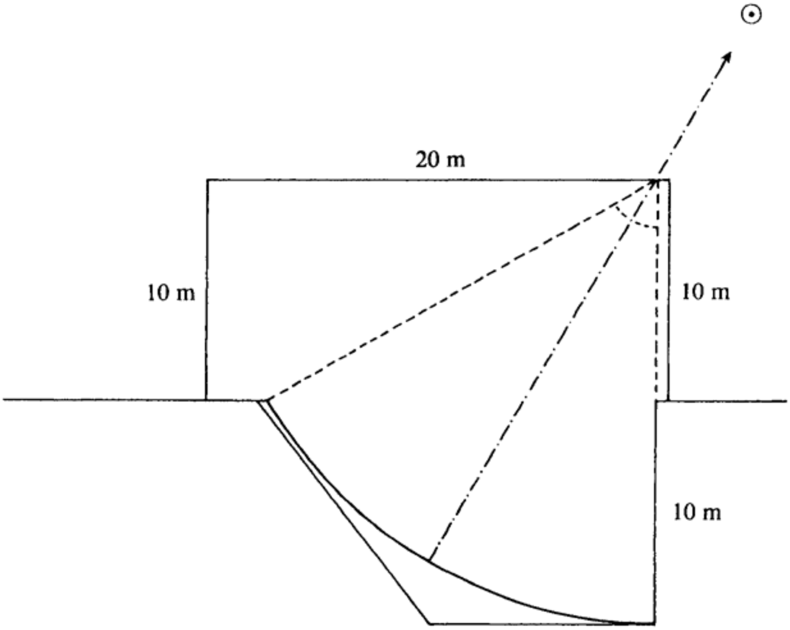

Figure 1.3

approximately 35 cm; it was divided into 360 parts of 10 seconds each, and the image of the sun passing at the meridian formed a circle about 18 cm in diameter; by finding the centre of the circle, a precise angle could be read off the copper surface. In 994, al-Khujandi measured the obliquity of the ecliptic as 23; 32, 19 and the latitude of Rayy as 35; 34, 39, but we have no other point of reference to indicate for how long a period this sextant was used.

There are several allusions to large-scale instruments in various earlier observatories—for example, a construction of spherical shape, 12.5 m in diameter, in the observatory of Sharaf al-Dawla at Baghdad, for following the path of the sun—but the description of the great sextant at Rayy is the first to be given in such precise detail about a large-scale structure within the environment of a permanent observatory; most instruments of Hellenistic design were portable or could be made in one place and transported to another for ongoing use there, including large-sized copper circles or tubes like those of al-Battani.

One other instrument of great size, cut into a permanent base of masonry, is described by Ibn Sina (AH 370–428 (AD 980–1037)) in his treatise *Maqala fi al-alat al-rasadiyya.*[26] On the top of a circular wall about 7 m in diameter lay a completely horizontal graduated circle. At the centre of the

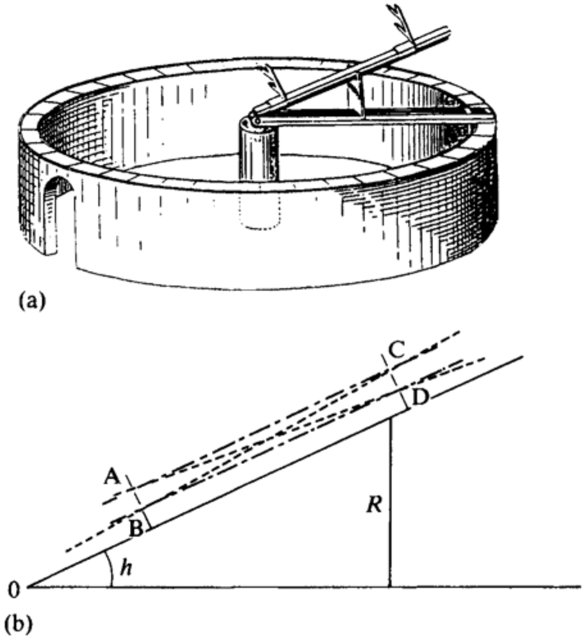

Figure 1.4

circle was a pillar bearing a double, vertically jointed rule, which could pivot horizontally around the centre. The lower rule lay on the graduated circle and allowed measurement of the azimuth; the upper rule carried a sighting system, and the angle between the two rules gave the height of the object observed. This construction was therefore based on a similar principle to that of the ‘observation tube’ described by al-Biruni. About two centuries later, at Maragha, Ibn Sina’s instrument was further developed by the addition of a second set of jointed rules—or by an analogous arrangement of two vertical sighting devices pivoting independently around the centre of the large stone circle—enabling simultaneous measurement of the height and azimuth of two celestial objects.

The instrument described by Ibn Sina—and probably invented by him —is of particular interest because its new sighting system was much more precise than that of earlier instruments, giving independent readings of degrees and minutes. The upper rule was equipped with two identical movable sights, each comprising two superposed aligning grooves (Figure 1.4(b)), A and B on the first sight, and C and D on the second, so that AB=CD. Calling the angle CAD *a* and the angle CBD *b,* we know these two angles by the respective positions of the two sights, read from the upper rule. If we focus on a star through the two grooves A and C—or B and D—the required height of the celestial object being observed will be the angle h, determined by the position of the smaller rule R on the lower rule. If we observe the same object through the two grooves A and D, the position of R will need to be altered to give an angle at O of value h_1 such that $h=h_1-a$; if we sight through grooves B and C, we must again modify the angle at O to a value h_2 such that $h=h_2+b$. It is therefore possible in this way to bring the small rule R to a position corresponding to the whole number of degrees that is closest—h_1 greater or h_2 less—to the true height of the observed object, and then to manipulate the position of the two sights to observe the star through A and D or B and C, so that one only has to subtract an angle a or add an angle b, according to the particular case, these angles being less than a degree and being accurately determined on the upper rule. The position of the scale small rule R thus gives the number of degrees, and the position of the sights AB and CD the number of minutes. This procedure represented a major advance in the precision of recorded measurements.

Around 1074, probably in the region of Isfahan, a large and highly organized observatory was founded by Malikshah (AH 465–85 (AD 1072–92)), counting al-Khayyam in particular among its scientists. Observations there were planned to take place over thirty years, the period of one complete revolution of Saturn, the planet then considered to be the most distant from the earth (Sayili 1960:160–6). In fact it only operated for eighteen years, until the death of its founder, but it was the first official observatory to have had such long continuous activity backed by such a precisely planned structure, and it was specifically in this tradition that the well-documented Maragha observatory was constructed in the second half of the thirteenth century, marking an important turning point in the history of Arabic astronomy (Sayili 1960:188–223; Vardjavand 1980).

The observatory at Maragha (in northwest modern Iran) enabled the creation of a new set of astronomical tables, known as the 'Ilkhanian tables' but above all it gave the scientists who worked there the opportunity of producing better geometrical models than those of Ptolemy to account for the movements of celestial bodies, thanks to the high quality of its instruments, the rigorous organization of the work and the number of extremely high-calibre researchers who were able to work there simultaneously. Nasir al-Din al-Tusi (AH 597–672 (AD 1201–74)) had chief responsibility for the work, and al-ʿUrdi (d. AH 664 (AD 1266)) undertook the design of the instruments. The building was financed by Hulagu Khan (d. AH 663 (AD 1265)), who assigned the observatory large sums of revenue from a pro tected legacy *(waqf)* for its maintenance. This is the first time, to our knowledge, that an observatory was accorded this privilege, and it explains how work was able to continue there following the death of its founder Hulagu, finances not having been abruptly terminated by the disappearance of the princely patron, as had happened with the observatory of Malikshah, for example.

Building began at Maragha in AH 657 (AD 1259) and seems to have been completed in AH 661 (AD 1263). The group of buildings was situated over an area of 280 m×220 m; in addition to the various instruments, it included a very important scientific library and a foundry for the construction of the copper apparatus. The instruments designed by al-ʿUrdi were those that were already known, improved in size and precision, except for one which seems to have been created for Maragha: the azimuthal circle equipped with two quadrants, permitting the simultaneous measurement of the height of two stars above the horizon.

A programme of continuous observations was intended by Nasir al-Din al-Tusi to last for thirty years, as at the observatory of Malikshah and for the same reason, but was reduced to twelve years, the period of rotation of Jupiter, and the 'Ilkhanian tables' were in fact published after this period. A great many scientists worked at Maragha—the most famous being Nasir al-Din al-Tusi and Mu'ayyid al-Din al-ʿUrdi themselves, and Muhyi al-Din al-Maghribi and Qutb al-Din al-Shirazi, who will be covered in the following chapters—all of whom participated in the task of extending the astronomy of Ptolemy. Thus a veritable 'school' grew up around Maragha which would have an important influence on all later developments in astronomy in the East.

Traces of activity at the observatory last until AH 715 (AD 1316), the date of the death of its last known director, Asil al-Din, who was in charge from AH 704 (AD 1304), but the buildings were in ruins by about 1350. We are therefore sure that Maragha functioned for more than fifty years, although it is not possible at present to date the ending of work at the site precisely.

This observatory had a marked influence, not only due to the importance of the scientific work that it nurtured, which will be explained below, but also because it acted as a model for the large observatories built later, of which the most celebrated, because of the quality of their instruments, were those at Samarkand and Istanbul. The observatory at Samarkand was founded in AH 823 (AD 1420) by the sovereign Ulugh Beg, who was also a scientist of high standing, and it remained active until nearly 1500 (Sédillot 1853). The one at Istanbul was built by the astronomer Taqi al-Din from AH 982 (AD 1575) and only functioned for a few years (Sayili 1960: 259–305). The last great observatories in the Maragha tradition were founded in India in the eighteenth century by Jaï Singh, notably the one at Jaipur (1740), most of whose instruments are still in place.

This brief survey has offered us some idea of the evolution of observatories in the East. In the Muslin West, Andalusia and the Maghreb, astronomical observation was far less developed; it did not form part of an ongoing tradition and there is no trace of organized public observatories. The only precise observations that have survived were carried out from private observatories, at the end of the fourth century AH (tenth century AD) by Maslama al-Majriti and in the fifth century AH (eleventh century AD) by al-Zarqallu, whose ‘Toledan tables’ had a marked influence in the medieval Latin West.[27]

PROBLEMS OF PRACTICAL ASTRONOMY

From the end of the eighth century, with the development of the exact sciences in the particular context of an organized Muslim society, scientists from various disciplines were called upon to resolve a number of practical questions relating to social or religious matters. It therefore fell to astronomers, for example, to respond technically to the demands of the astrologers, whose official social role was important; the astronomical tables for calculating the position of the heavenly bodies were set up in part for this purpose. But above all the astronomers were required to help solve practical problems of calendars, time, or bearings on land or sea. This is illustrated by Ibn Yunus at the start of his ‘Hakemite tables’ written at the beginning of the eleventh century:

> The observation of heavenly bodies is connected with religious law, since it permits knowledge of the time of prayer, of the time of sunrise which marks the prohibition of drinking and eating for him who fasts, of the moment when daybreak finishes, of the time of sunset whose ending marks the start of the evening meal and cessation of religious obligations, and moreover knowledge of the moment of eclipses so that the corresponding prayers can be made, and also knowledge of the direction of the Kaʿba (towards Mecca) for all those who pray, and equally knowledge of the beginning of the months and of days involving doubt, and knowledge of the time of sowing, of the pollination of trees and the harvesting of fruit, and knowledge of the direction of one place from another, and of how to find one’s way without going astray.[28]

All these subjects gave rise to important theoretical developments which went far beyond the bounds of the practical problems involved. They will be discussed in detail in the following chapters on gnomonics and the science of time, the question of the ‘qibla’ for determining the direction of Mecca from a given place, calculation of the visibility of the crescent, mathematical geography and the computation of the latitude and longitude of a place, nautical science for navigating at sea, etc. Let us give some attention here to the question of calendars.

In the Arab world, the official calendar is lunar. Year one of the Muslim era began on Friday 16 July AD 622, date of the Hijra (hence the European custom of referring to Muslim years as AH), and the lunar year is made up of twelve months of twenty-nine or thirty days; the change in date takes place at sunset, and the passage to the following month occurs when the first crescent moon is sighted on the horizon just after sunset. Ptolemy had passed on a very accurate value for the average length of the lunar month at a little over twenty-nine and a half days (by about forty-four minutes); a lunar year of twelve months is therefore equal on average to 354.367 days. This value was verified and re-adopted from the ninth century by Arab astronomers who then introduced a cycle of thirty years to create an official calendar with alternating months of twenty-nine and thirty days, eleven of the years in this cycle having an additional day in the last month (which normally consisted of twenty-nine days); these were the years 2, 5, 7, 10, 13, 16, 18, 21, 24, 26 and 29 of the cycle. The astronomic correspondence is thus closely respected in the long term, but the visibility of the first crescent on the horizon on the evening of the twenty-ninth day always brought in a change of month for the place where this observation was made, so that there could be a difference of one unit in the day of the month from one end of the Muslim world to the other. Although actual visibility of the crescent was required in principle by religious law, the question facing astronomers was how to calculate the visibility of the lunar crescent in advance at a given place on the evening of the twenty-ninth day of the month, whatever the reading on the official calendar (which is what Ibn Yunus meant by ‘days involving doubt’ in the earlier quotation). This is a difficult problem in view of the number of parameters involved—celestial co-ordinates of the sun and the moon, apparent relative speed of these ‘two luminaries’, latitude of the place, brightness of the sky on the horizon, etc. —and numerous astronomers studied the question, thereby producing important theoretical developments concerning the visibility of heavenly bodies on the horizon just after sunset.

In Persia the solar calendar was always used in parallel with the lunar calendar and corresponded at first to ‘the era of Yazdegerd’ which began on 16 June AD 632. As in the ‘Egyptian calendar’ used by Ptolemy in the *Almagest,* the year was divided into twelve equal months of thirty days, and five extra days—six every four years for leap years—were added at the end of the year; these were called the ‘epagomenes days’ and allowed the legal year to coincide with the astronomical solar year. This is the calendar which was adopted from the beginning by the astronomers of Baghdad, because the solar cycle is at the basis of astronomical measurements, and it was easier to create tables of the movements of heavenly bodies for months that always equalled thirty days. But the length of the solar year is a little less than 365. 25 days, and at the end of the eleventh century Jalal al-Dawla Malikshah—

founder of the great observatory described above—asked the astronomers whom he had appointed to review the composition of this calendar and make the necessary corrections to avoid accumulating the slight discrepancy with the apparent movement of the sun. Thus began 'the era of Jalali', instituted in AH 467 (AD 1075) and comprising eight leap years in thirty-three years—instead of the thirty-two years in the earlier computation—which corresponded well with the astronomical calculations. This correction was of the same order as the one which waited until 1582 in the West, when the Julian calendar changed to the Gregorian calendar.[29]

But, apart from what we have called practical astronomy, the most important contribution of Arab astronomers is found in the arena of pure theoretical astronomy, which is not unrelated to the above.

GREAT PERIODS IN THE HISTORY OF ARABIC ASTRONOMY

The history of Arabic astronomy can be broadly divided into two great periods, the eleventh century being at the turning point between the two.

From the ninth to the eleventh century, the work was almost exclusively in the area of geometrical models inherited from Ptolemy, reworked and criticized on the basis of new observations, and in the eleventh century Ibn al-Haytham (AH *c.* 354–430 (AD *c.* 965–1039)) made an evaluation of the scientific papers accumulated for two centuries in his work *al-Shukuk ʿala Batlamyus* ('Doubts concerning Ptolemy').[30] He drew up a catalogue of all the still unresolved inconsistencies to be found in three of Ptolemy's works, the *Almagest,* the *Planetary Hypotheses* and the *Optics*—but without proposing solutions.

This critical assessment led to a temporary impasse, since solutions could only be found outside the framework in which astronomy had confined itself. Solutions of two very different kinds were therefore sought, one in the Muslim West and the other in the East.

In Andalusia there was a proposal to re-adopt Aristotelian principles by abandoning epicycles and eccentrics and returning to homocentric spheres, which would be much more consistent from a 'physical' astronomy point of view. The most characteristic representative of this school was al-Bitruji (end of the twelfth century), but his bases were almost entirely philosophical, and it was impossible to make any calculations from his conclusions or to verify them by numerical observations. This approach was therefore unproductive, even though the underlying philosophical processes remain interesting.

In the East the response was scientific and gave rise to what we have called the second great period of Arabic astronomy when the search took place to account for the movement of heavenly bodies by means of new geometrical models of epicycles and eccentrics that were geocentric but non-Ptolemaic. The essential part of that work was carried out by the team connected with the Maragha observatory, described above.

The history of the development of theoretical astronomy in the Arab world is therefore divided by the two following chapters in accordance with the two great Eastern periods, and the work of the astronomers in the Muslim West is described in the chapter on Arab science in Andalusia (chapter 7).

NOTES

1 For example, al-Battani's important work, *al-Zij al-Sabi*, or al-Biruni's *AlQanun al-Masʿudi*—where a transcription of the Greek term is retained—cited in the bibliography; see also the following chapter.

2 See Rashed's note on the term *munajjim* in Diophante (1984: vol. III, pp. 99–102).

3 See, for example, Abu ʿAbd Allah al-Khwarizmi, pp. 210ff.

4 For the *Anwa',* cf. C.A.Nallino (1911:117–40, conferences 18 and 19) and *The Encyclopaedia of Islam,* I, pp. 523–5. For the lunar mansions, cf. 'Manazil' in *The Encyclopaedia of Islam,* VI, pp. 374–6.

5 In particular Sinan b. Thabit b. Qurra (d. 331 AH (943 AD)) reproduced part of the second book of *Phaseis* in his *Kitab al-Anwa';* see Neugebauer (1971).

6 For a short and precise description of the geometrical planetary models proposed by Ptolemy in the *Almagest,* see Neugebauer (1957: appendix I, French translation, pp. 239–55).

7 See Ptolemy, *Planetary Hypotheses.* I have personally undertaken the edition of the Arabic version of this text (Morelon 1993).

8 The contents of this book were found described in a passage of the work by al-Biruni, *al-Qanun al-Masʿudi;* see Morelon (1981).

9 Euclid lived around 300 BC; his *Data* contains diverse definitions of the elements involved in geometry; his *Optics* develops a theory of vision and of perspective; his *Catoptrica* is a study on mirrors; his *Phenomena* contains a geometrical study of the celestial sphere.

10 Theodosius lived in the second century BC; his *Spherics* concerns the geometry of the spheres; in *On Habitations* he shows which portions of the celestial sphere are visible according to the regions of the earth; in *On Days and Nights* he determines the portions of the ecliptic traversed by the sun each day over the whole year.

11 Autolycus lived in the third century BC; in *On the Moving Sphere* he describes the different circles of the celestial sphere and the modification of their respective positions caused by the movement of the sphere; in *On Risings and Settings* he describes the phenomena of the visibility of the stars on the horizon at their rising or setting.

12 Aristarchus lived in the third century BC and is famous for having proposed a short-lived heliocentric hypothesis; in his treatise *On the Sizes and Distances of the Sun and Moon* he calculates their distance from the earth and their respective size based on their position in quadrature and on eclipses.

13 Hypsicles lived around 150 BC; in his *Ascensions* he determines the rising of the different signs of the zodiac for a given place in terms of the relation between the longest and shortest day at that place.

14 Menelaus lived in the first century AD; his book on the *Spherica* contains the fundamental formulae of spherical trigonometry used by Ptolemy in the *Almagest,* introducing equal proportions between the chords of arcs on a complete spherical quadrilateral (see the chapter on trigonometry in vol. II).

15 See al-Hashimi, *Book of the Reasons,* pp. 201–11.

16 See 'Astrology and Astronomy in Iran' in *Encyclopedia Iranica* (1987: vol. II, pp. 858–71) and Kennedy (1958).

17 On the question of observatories, see Sayili (1960).

18 See Ibn Yunus, *Le Livre,* pp. 140–1.

19 In particular at Baghdad and Damascus, from the time of the first observations.

20 See al-Battani, *Al-Battani,* vol. 3, pp. 137–8; vol. 1, pp. 91 and 272.

21 See Eisler (1949), 'The polar sighting tube'. These 'observation tubes' are not mentioned explicitly in any of the texts of Hellenistic astronomy that have come down to us, but they have been known in China since the sixth century; see Needham and Wang Ling (1959:332–4).

22 Al-Biruni, *Al-Qanun,* p. 964, treatise 8, chapter 14, 2nd section.

23 See Eisler (1949), 'The polar sighting tube'.

24 See al-Sufi, *Kitab suwar al-kawakib.*

25 See Ibn Yunus, *Le Livre.*

26 Arabic text edited and translated into German with notes by Wiedemann-Juynboll. The following two figures are taken from this publication; the drawing of the instrument was made by J.Frank from data in the text and from the author's knowledge of the instruments of the observatory of Maragha.

27 See the entries for these two scientists in the *Dictionary of Scientific Biography.*

28 Ibn Yunus, *Le Livre,* pp. 60–1.

29 See 'Djalali' in *The Encyclopaedia of Islam,* II, pp. 397–9.

30 Ibn al-Haytham, *Shukuk.*