

Chapter 2

Ancient Astronomical Instruments

With the developments of ancient astronomy, ancient astronomical mechanical instruments were extensively used for measurements, computation, and demonstration. These instruments represented the combinational achievements of astronomy and mechanical engineering technology at the subjects' eras. The investigations of the recorded ancient astronomical instruments not only give us a glimpse of their historical developments, but also provide overall concepts and knowledge about the mechanical characteristics for some designated functions and applications. Furthermore, the relevant craftsmanship is realized. This chapter presents a study of the ancient astronomical mechanical instruments and classifies them in accordance with their display functions. Some representative artifacts such as sundials, astrolabes, calendrical device and relevant compound instruments, astronomical (mechanical) clocks, and orreries are introduced. Focusing on a specific display function, the designs among different astronomical instruments are compared. In addition, the manufacturing technology and craftsmanship for generating some particular functions are analyzed.

2.1 Classifications Based on Functions

Designs of mechanical devices are advanced with the historical developments of diverse cultures, sciences, and manufacturing techniques along with numerous applications. Astronomy is one area much affected in ancient cultures. The characteristic of constrained motions of mechanical devices is widely used for the astronomical applications to produce complicated calculations, precise measurements, and ingenious exhibition. The development of ancient astronomy attaches to several ancient astronomical instruments with sophisticated designs and special applications. For examples, sundials, astrariums, astrolabes, planetariums, and

astronomical mechanical clocks are well-known devices with various knowledge of mechanisms and astronomy.

In what follows, the available ancient astronomical mechanical instruments, based on their functions, are classified into the applications of measuring time, measuring position, observation, computing, and demonstration [1–9].

2.1.1 Observation Application

These refer to the mechanical instruments used to assist in observing the phenomenon of celestial bodies in yonder universe. Observational astronomy is a division of modern astronomy. It is the practice of observing celestial objects by using telescopes and other astronomical apparatus. The observation of astronomical phenomenon is the leading work of ancient astronomy for recording and understanding what happened in the sky and their cycles by simple mechanical devices.

The changes of seasons are conscious natural phenomenon; however, it is closely constrained by the areas and climates the observers live in. Once the climate change of area is not obvious, the time cycle is not defined. Therefore, the revolutions of phenomenon of celestial bodies are regarded as the most popular and steady units of time. According to this requirement, the historical records about the astronomical observations existed in many ancient civilizations. Also, it is related to the developments of mechanical instruments for astronomical observation. Telescope is the representative work of observational astronomy. The first one was made in Holland around 1608 [5, 6]. In ancient Western civilizations, *cross-staffs* and *astrolabes* could be regarded as the instruments to assist the observation of astronomical phenomenon and events.

2.1.2 Measuring Position and Distance Application

These refer to the mechanical instruments for identifying positions of celestial bodies in the sky and the angles between each other, even to estimate the distances between these objects and the observers. Depending on the contribution of geometrical mathematics, the distance between measured objects could be estimated. In general, the application of measuring position or angle can be regarded as a part of astronomical observation work in ancient times.

The developments of measuring devices start with the study of geometry. For measuring distance, the measuring devices were usually used in the building of towers, temples, and towns [2, 6]. In addition, they can measure the distance with a wide range that was difficult to cross over such as a river, a mountain valley, or a sea inlet. For navigation, navigators used them to measure the elevation angle of the noontime Sun above the horizon, which allowed them to estimate their latitude. For astronomers, they were used to measure the angle between the directions

of two celestial bodies or position heavenly bodies in the sky before the invention of telescopes. The aspiration was to estimate the distance between the Earth and stars. *Cross-staffs* and *astrolabes* are two popular ancient astronomical mechanical instruments not only for observation, but also for measuring.

2.1.3 Measuring Time Application

These refer to the mechanical instruments for counting or indicating some time standards, which did not have obvious phenomenon (such as sunrise, sunset, and moon phase) to distinguish their time intervals.

Measuring position (angle or distance), measuring time, and observation can represent the first step in developing the combination of astronomy, mechanical design, and science and technology [2]. The work of measuring time starts with the definitions of a day, a month, a year, and other time cycles. These time definitions were based on the long-term observational records of cyclic astronomical phenomenon. Sunrises and sunsets are the basic standards to distinguish a day. For Egyptian and Romans, they further divided their day into 24 h, like we do today. Among these 24 time intervals, 12 h are for the day and another 12 h are for the night [1, 3, 5, 6]. Even though this definition resulted that an hour of the day is not the same as an hour of the night in some seasons, an hour was contributed to distinguishing and indicating the time much clearly in ancient times. Hence, the mechanical devices for measuring time were designed to distinguish the hours of a day.

In ancient times, the hours of a day were identified based on the position of the Sun in the sky. For instance, *sundial* is the ancient measuring device that used the shadow of object, *gnomon*, to reflect the position of the Sun. In addition, the users could understand the time according to the time graduation that the shadow indicated. Nevertheless, the operation of the device is determined on the appearance of the Sun. It was useless on days when there was no Sun, and it could not measure the nighttime. The appearance of clocks overcomes the above constraints of the sundials.

Clocks were an important invention for measuring time. The precursor of clocks was the water clock [1, 3]. It depended on the flow of water from a tank to indicate the hours, as shown in Fig. 2.1 [10]. Because of the different duration of hours of the day and the night, the tank could be designed to coincide with the duration of the day by varying the quantity of a scale. Afterward, the *mechanical clock* was invented based on the redefinition of hours, and its service depended on the accurate motions by gearing. Many early mechanical clocks were not a separate instrument for measuring time. They were *astronomical clocks* for measuring time, displaying astronomical motions, and showing astronomical information. Such a sophisticated device was regarded as a combination of outstanding manufacturing technique and advanced astronomical achievement. It could continuously demonstrate the cyclic astronomical motions according to the clockwork.

Fig. 2.1 Virtual imitation of ancient Egyptian water clock



2.1.4 Computing Application

The astronomical mechanical instruments for computing applications refer to the devices with mathematical gearings for calculating the astronomical cycles. For mechanical devices, the power output or transmission was not the only required application. This type of instruments focused on using the kinematic characteristics of mechanisms to generate specific rate of transformations. Generally, such an output function was achieved by gear mechanisms. The resulting mechanical instruments could calculate some astronomical cycles or calendars based on the known mechanism characteristics. In addition, these astronomical mechanical devices seemed to be the precursor of computation devices [4].

In fact, the ancient astronomical mechanical devices with computing applications were used for calendrical devices. According to available historical records, they were mostly not formed as independent instruments, but usually associated with other astronomical instruments, such as *sundials* or *astrolabes*.

2.1.5 Demonstration Application

The astronomical mechanical instruments for demonstration application are defined as the devices used to simulate relevant academic and science theories by mechanical designs, such as planetariums, *armillary spheres* (*concentric spheres*), and *orreries*. Simultaneously, their displays could be regarded as the computation results to show the attitude, latitude, and/or longitude of designated positions.

As mentioned in Chap. 1, it is understood that the ancient astronomy had developed the hypothesized geometrical models of the universe and the orbits for describing the motions of heavenly bodies based on the observational records.

These geometrical models in writing form were applied on the physical mechanical devices that generated the motions satisfied their corresponding astronomical geometrical models, owing to the development of manufacturing technique and the advanced understanding of mechanism characteristics. Some complete mechanical devices referred to the embryo of the universe that was opinioned at that time. Like the astronomical computing devices, they sufficiently applied the kinematic characteristics of mechanisms for generating appropriate rate ratios and built by gear mechanisms. Furthermore, they were the essence of astronomy in their eras.

2.2 Jacob's Staff

Jacob's staff was a widely used ancient measuring device. It, also called *baculum*, *cross-staff*, or *radius*, consists of a main staff with a perpendicular crosspiece, which was attached to the staff at its middle and was able to slide up and down along the staff, as shown in Fig. 2.2 [2, 5, 8, 9, 11–13].

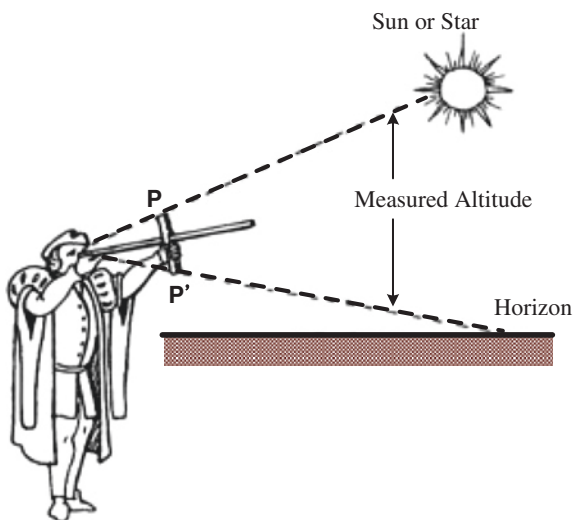
In navigation, this apparatus was used to determine angles or distances: The angle between the horizon and Polaris (or the Sun) can be determined to estimate the latitude at which a vessel is located. The angle between the top and bottom of an object can be measured to determine the distance to the object, based on geometric mathematics, if its height is known, or to determine the height if its distance is known. Furthermore, the horizontal angle between two positions can be measured to determine the other position on a map [2, 9, 11, 12].

When Jacob's staff was used for astronomical observation, it was referred to as a *radius astronomicus*. Figure 2.3 shows a schematic introduction of application method of a staff. In order to measure the angle between two stars or the altitude of a star, astronomers would place the staff below one of his eyes. Since the cross-piece would have a pair of open sights (sticking out perpendicular to the scheme)

Fig. 2.2 Virtual imitation of Jacob's staff



Fig. 2.3 Application illustration of Jacob's staff [11]



at symmetric locations such as P and P', they slide the crosspiece up and down until sight P covered one of the stars and sight P' the other. Moreover, Jacob's staff was workable at night because of the convenient slits on the sights [9, 11, 12].

2.3 Astrolabe

An *astrolabe* is an astronomical instrument used for measuring altitudes of celestial bodies, displaying the positions of stars, and finding the time of a day and the time of celestial events, such as sunrise and sunset [14]. Its origin was in the classical Greece (lasting from the fifth through the fourth century BC). The astrolabe was introduced to the Islamic world until the mid-eighth century and was highly developed and extensively spread during the early centuries of Islam. With the popularization of Islam, it moved through North Africa into northern Spain and was introduced into Europe in around eleventh century [15–19].

The stereographic projection is the most important theory for building an astrolabe. It was as if Apollonius had studied the theory. Afterward, Hipparchus refined the structure of the theory. He redefined and formalized the concept of projection to build a method for solving complex astronomical problems. Hipparchus is regarded as the most influential individual in the discovery of the stereographic projection theory, but he did not invent the astrolabe [11, 16]. The earliest evidence for applying the stereographic projection theory in a mechanical device was an anaphoric clock in around the first century. Nevertheless, exactly when the stereographic projection theory was turned into the astrolabe, we known today remains a mystery.

A traditional astrolabe was composed of several members, as shown in Fig. 2.4 [15]. Its major members were rete, mater, and plate. A rete is a skeletal plate that

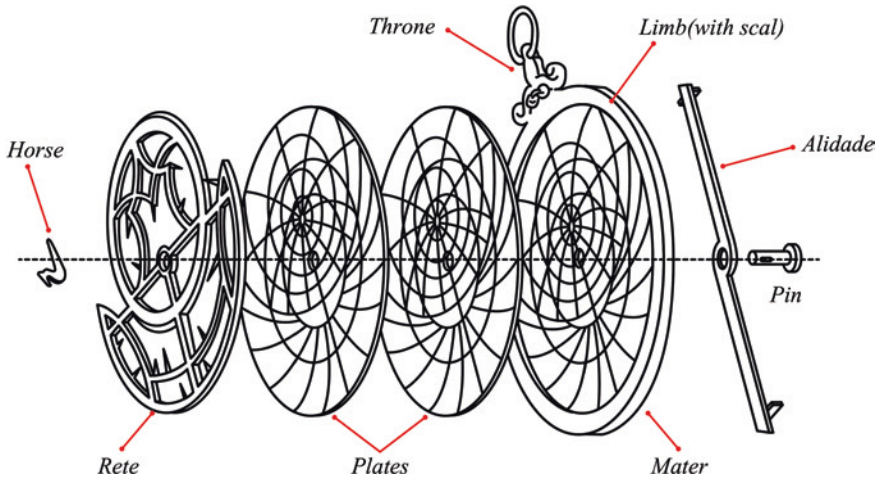


Fig. 2.4 Members of astrolabes; reprinted from Ref. [15]

fits into an astrolabe on top of the selected latitude plate and is freely rotatable over it. The rete is the stereographic projection of celestial sphere. It had star pointers and the stereographic projection of the ecliptic. The star pointers were placed at the positions of their stereographic projection to mark visible and bright stars [14, 15, 18, 19]. The form of the pointers could be simple indicators or patterns of vines and animals. The retia of the astrolabes are various. For early astrolabes, the number of star pointers varied from 10 or 12, and they increased to as many as 50 or 60 on later ones. They were regarded as the representative symbol of a family. Besides, a mater is the disk of an astrolabe which usually had a hollow section. A plate for representing the local latitude engraved with circles of altitude and azimuth for a certain latitude was inserted into the hollow section of the mater. It is the stereographic projection of the local sky based on the latitudes of builders' positions. Sometimes, the ancient astrolabes included several plates engraved on both sides, so the instrument could be used in various latitudes. For the astrolabe, the projection of the celestial sphere and the projection of the local sky are overlaid with a common point, the north celestial pole. Thus, the projection of the celestial sphere can be rotated with respect to the projection of the local sky to display a view of the sky for any combination of date or time [15, 19].

Whenever an astrolabe was used, the moveable members were adjusted to a specific date and time. After appropriately setting, much of the sky was represented on the instrument. The two faces of the astrolabe had their own functions. Most problems were solved by the front of the astrolabe which has fixed and rotatable parts. The fixed parts represent timescales and the stereographic projection of the sky. The rotatable parts were adjusted to simulate the daily rotation of the sky. As to the back of the astrolabe, it usually had scales for finding the longitude and the altitude of the Sun or a star for a specific date.

2.4 Sundial

A *sundial* is a device for measuring the hour of a day existed in many civilizations in the ancient world. The oldest sundials appeared around 3500 BC and were represented by obelisks and solar clocks by Egyptians and Babylonians [3]. In general, a sundial consists of the *gnomon* that is also called the *style* and the surface engraved with the timescale for indicating the time of a day, as shown in Fig. 2.5. The shadow of the gnomon is projected on the surface. When the Sun moves in the sky, the corresponding gnomon’s shadow moves in the surface. According to the position of the gnomon’s shadow, the hour of a day is identified.

The shape of gnomon might be that of a rod or an edge, which was not constrained, and the styles of the surface were diverse. Ancient sundials could be

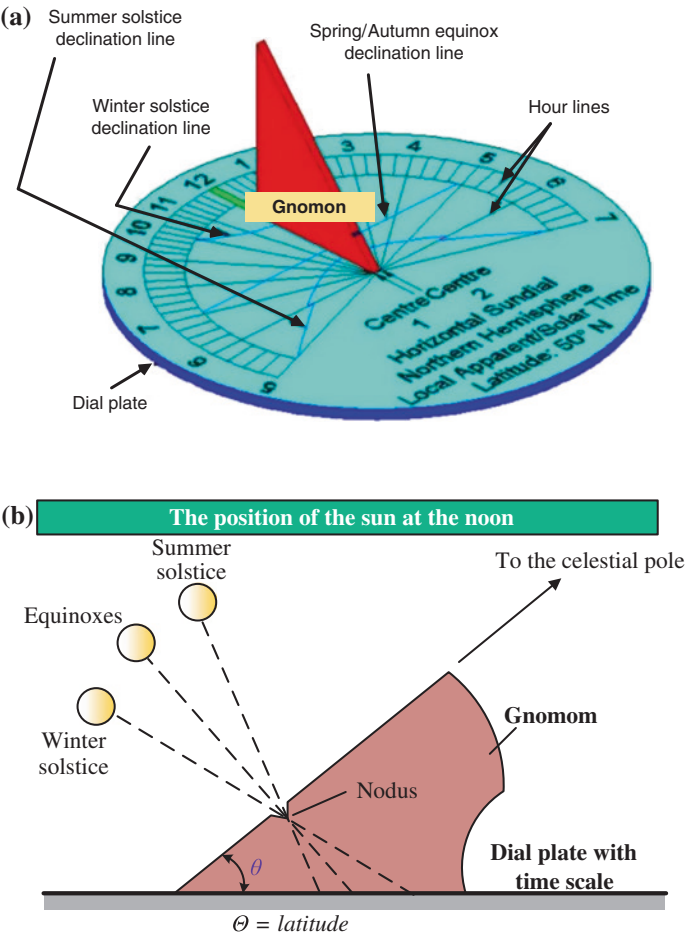


Fig. 2.5 Illustration of the sundial. **a** Members. Reprinted from Ref. [40], copyright 2015, with permission from Carl Sabanski. **b** Projection [41]

classified into two types: fixed sundials and mobile portable sundials. Fixed sundials refer to sundials that are mounted in a fixed structure. According to the styles of the sundials' surface, fixed sundials can be further divided into equatorial sundials, horizontal sundials, vertical sundials, and non-planar sundials, as shown in Fig. 2.6. The surface of equatorial sundials is an incline parallel to the equator, and its gnomon is parallel to the axis of the Earth. The surface of horizontal sundials is parallel to the ground, and the gnomon is parallel to the axis of the Earth. These

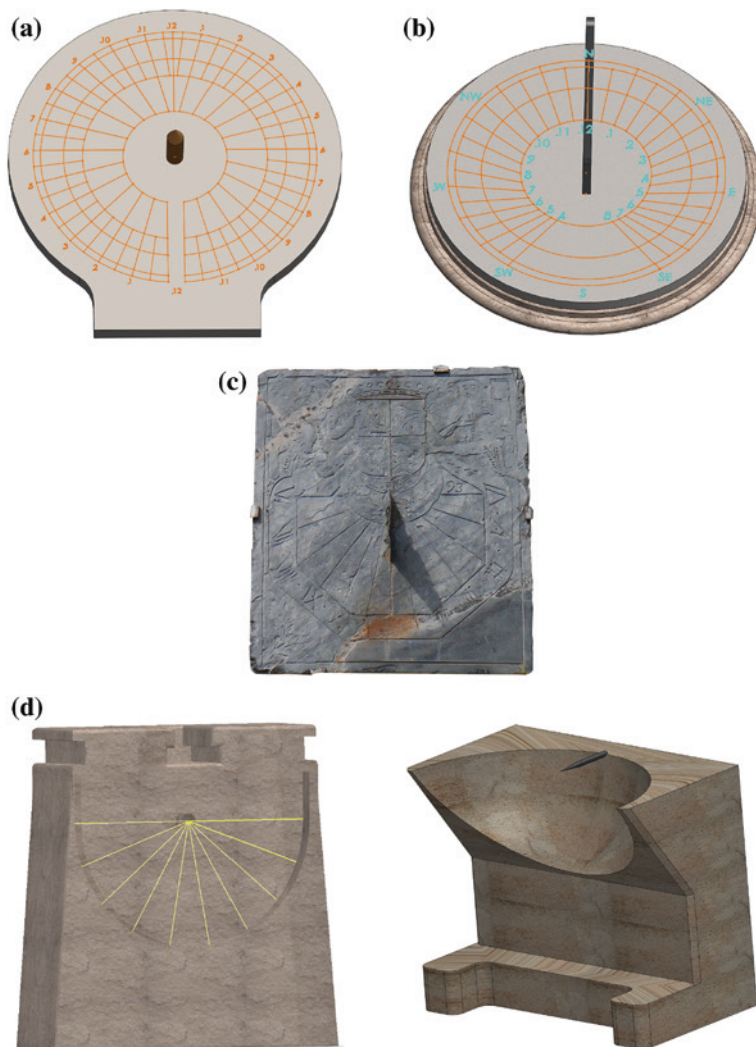


Fig. 2.6 Fixed sundials. **a** Equatorial sundial [42]. **b** Horizontal sundial. **c** Vertical sundial, reprinted from Ref. [43], copyright 2015, with permission from the Web site. **d** Non-planar sundial [44, 45]

two types of sundials were much popular in the excavated sundials. The surface of vertical sundials must be vertical to the ground, and their gnomon is still aligned with the axis of the Earth. As a result, this type of sundials was usually built on the wall. The final type is non-planar sundials with curved surface, like a part of inter-surface of a cylinder, a cone, or a sphere, to receive the shadow of the gnomon [3].

There were many styles of portable sundials developed in ancient times. The excavated fragment of an Egyptian portable sundial for example [19], in general, this type of sundials still had a gnomon that was a perpendicular block rising at the foot of the sloping face, as shown in Fig. 2.7. The height and width of the gnomon and the sloping object were the same. Whenever the instrument was to be used, it must be put down on a flat surface and be turned so that it faced the Sun directly [20, 21]. Thus, the shadow of the gnomon could fall upon the sloping face for showing the time. Furthermore, there were two special types of portable sundials, except for the surviving Egyptian portable sundial. One is a diptych sundial, as shown in Fig. 2.8. This type of portable sundials had two leaves. For a simple

Fig. 2.7 Virtual imitation of Egyptian portable sundial [21]

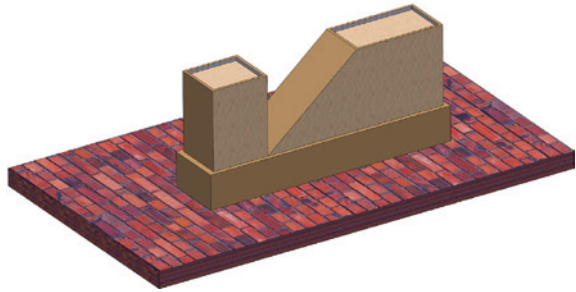


Fig. 2.8 A simple diptych (portable) sundials [40]

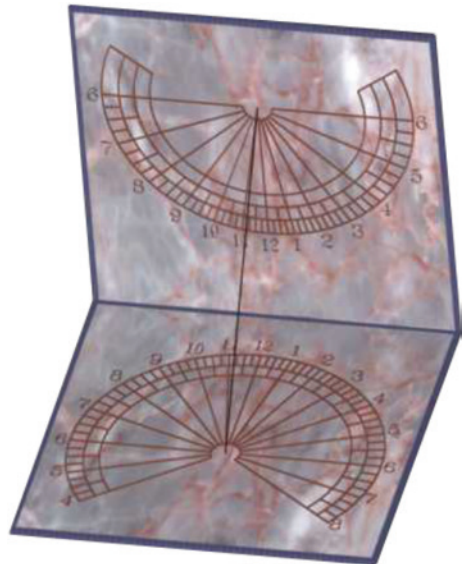
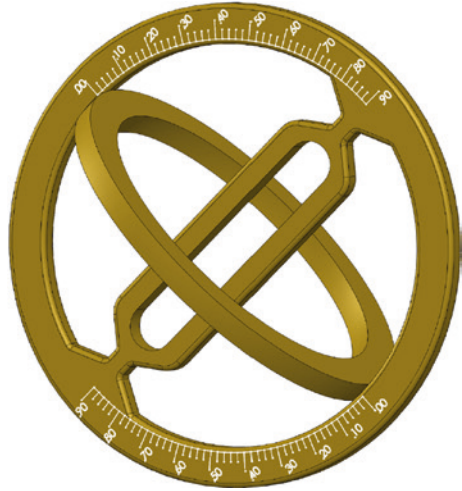


Fig. 2.9 Ring sundial [43]

diptych dial, the inter-face of one leaf was a vertical sundial and the inter-face of the other leaf was a horizontal sundial. Such a sundial can be adjusted according to users' latitude, by inclining it until its gnomon is parallel to the axis of the Earth. Actually, most portable sundials included a compass contained for orientation and are served completely in museums at present [19]. The other is the ring sundial, as shown in Fig. 2.9. Its main body was a ring held by a cord and had a hole through which lights could pass. Thus, the resulting light point could project on the ring with a timescale to indicate the hour of a day.

2.5 Calendrical Device

It is well known that one of the characteristics of gear mechanisms is to transmit motions with designated gear ratios. According to finding of archaeology, such a technique was used widely in the building of calendrical devices [22–28]. As mentioned above, all known ancient calendrical devices were associated with other astronomical mechanical devices to form multifunction astronomical mechanical devices until now. In what follows, some of these special mechanical devices are introduced.

2.5.1 *Astrolabe with Calendrical Gearing*

The astrolabe with calendrical gearing is the combination of the calendrical device and the astrolabe. It is an ancient astronomical mechanical device with compound functions. Except for the fundamental function to understand the night sky at some

observation position, this device can also operate the calculations of calendars through the application of mathematical gearing.

A complete historical record of mathematical gearing, as shown in Fig. 2.10a, illustrated the calendrical device by Al-Bīrūnī (973–1047), who is regarded as one of the greatest scholars of the medieval Islamic era and was versed in physics, mathematics, astronomy, and natural sciences [22–26]. Since relevant historical records did not definitely describe what mechanical devices contained such a calendrical gearing, the definition of the calendrical gearing is uncertain. It is mainly believed that the gearing could be associated with an Islamic astrolabe based on the investigation of other similar mechanical devices. But, it is believed that the gearing was a separate mechanical device and was a rare ancient astronomical device. This gearing is described completely in the manuscript of the Islamic treatise in 1000. And it functions to model the cyclic variation of moon phases and the calendars. Figure 2.10b illustrates Al-Bīrūnī’s relevant astronomical work for explaining various moon phases. Furthermore, Fig. 2.10c is the mechanical scheme of this mathematical gearing in the manuscript. It was clearly indicated that the mechanism was an ordinary gear train consisting of 8 gears and 5 separate arbors. Through the analysis of gear ratios, the gearing is known as using axis *B* as the input, that rotates once every 7 days; axis *A* rotates once every 28 days to display the position of the Moon; axis *C* rotates once every 59 days to reveal the age of the Moon; and axis *E* rotates once every 366.42 days.

Another example is the Persian astrolabe with calendrical gearing that dated back to AD 1221–22 and has been preserved in the Museum of the History of Science of Oxford [23, 24, 29], as shown in Fig. 2.11a. The front plate is for astrolabe, and two lugs on the rete serve as sights. The back plate is for the calendar without the use of a normal alidade. This device was operated by turning the central pivot, probably by hands or by using the astrolabe rete as a handle. The corresponding calendar and the lunar phase are moved accordingly. This compound mechanical device is found to consist of the gearing with the same purpose as that in Islamic treatise but with different gear ratios. Figure 2.11b shows the mechanical scheme of the calendrical gearing of this device. This gear train consists of 7 gears and 5 separate arbors. According to the analysis of gear ratios, the functions of this calendrical gearing are known as using axis *B* as the input, that rotates once every 7.375 days; axis *A* rotates once every 27.23 days to display the position of the Moon; axis *C* rotates once every 59 days to reveal the age of the Moon; and axis *E* rotates once every 354 days.

2.5.2 *Sundial with Calendrical Gearing*

This type of mechanical devices is the combination of the sundial and the calendrical device. A known example is the Byzantine sundial with calendrical gearing dated from late-fifth century of the Christian era or the first half of the

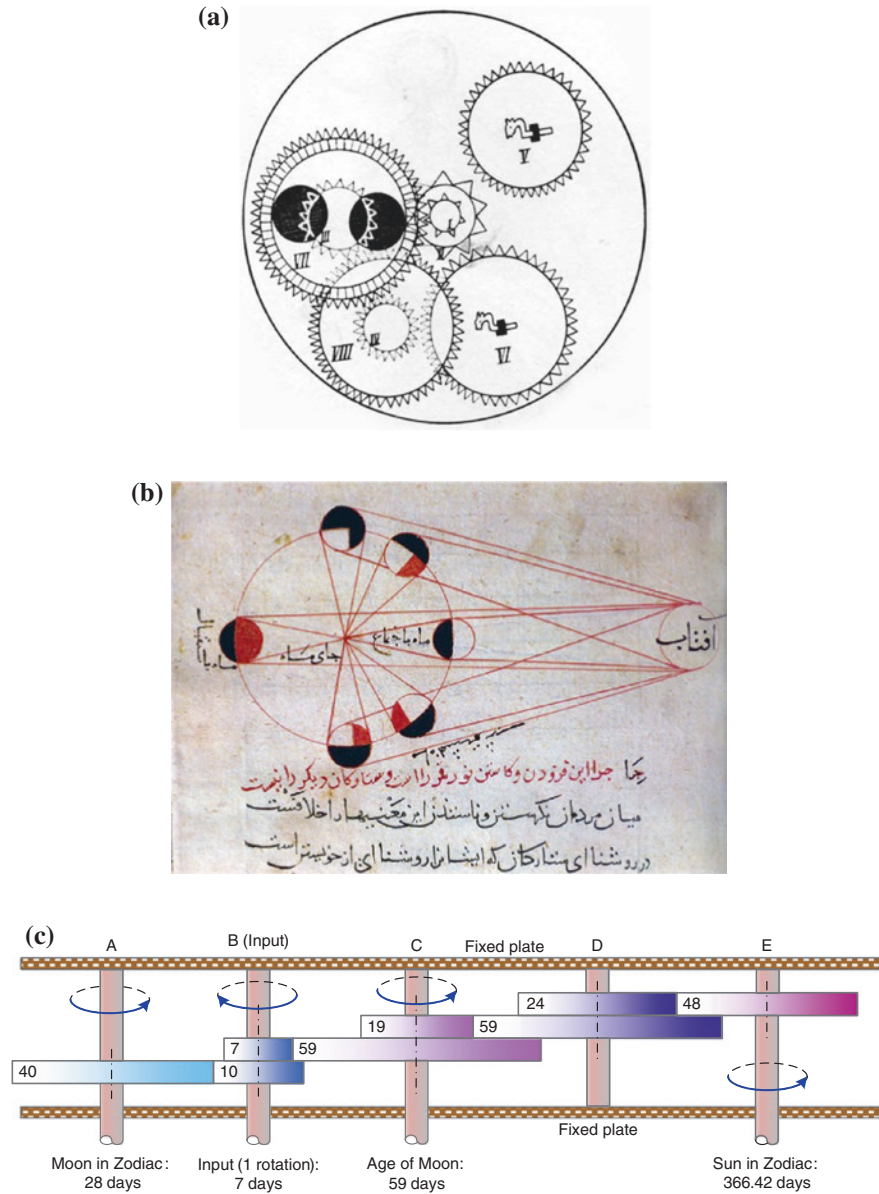


Fig. 2.10 Calendrical device by Al-Biruni. **a** Historical picture, reprinted from Ref. [24]. **b** Illustration of moon phase, reprinted from Ref. [43]. **c** Mechanical drawing [23]

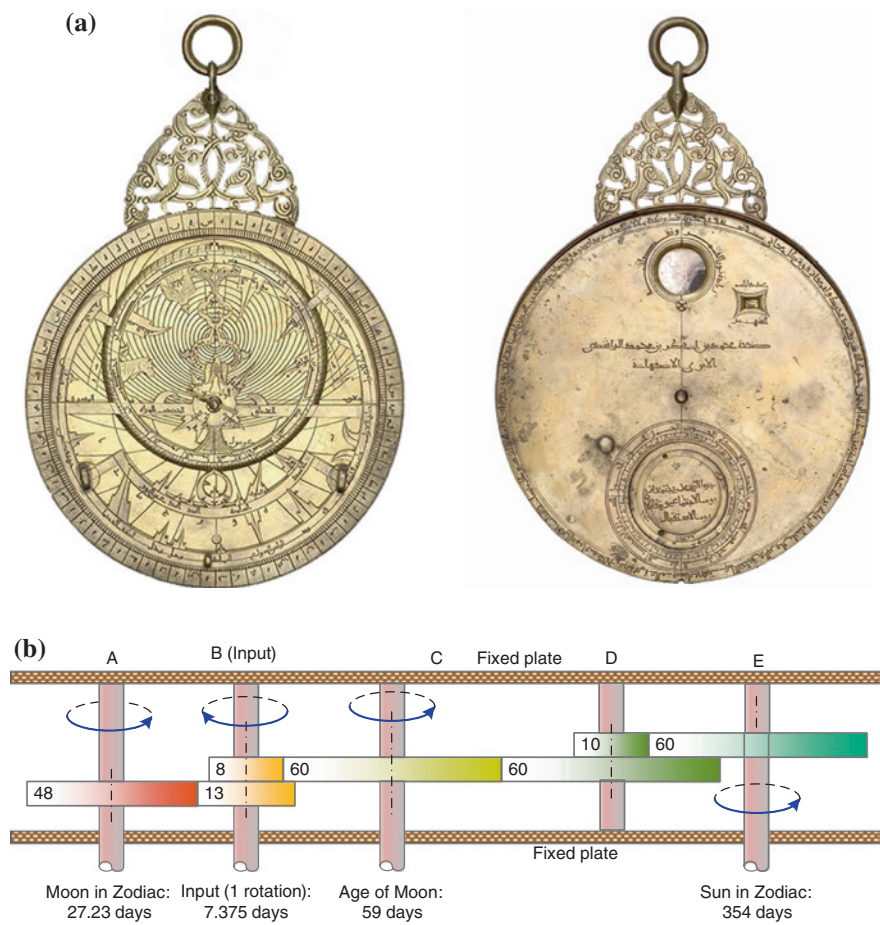


Fig. 2.11 Persian astrolabe with calendrical gearing. **a** Antiquity, reprinted from Refs. [14, 19, 24], copyright 2015, with permission from Museum of History Science. **b** Mechanical drawing [23]

sixth century [23–29]. It was much earlier than the Islamic calendrical device. The excavation of this mechanical device survives as fragments including 2 visible arbors [23, 30]. In 1984, a reconstructed model of the Byzantine sundial with calendrical gearing was presented by J.V. Field and M.T. Wright, as shown in Fig. 2.12[23, 30]. The calendrical gearing of the reconstructed model adopted similar design with the historical record of Islamic treatise and the Byzantine sundial with calendrical gearing to display the positions of the Sun and the Moon.



Fig. 2.12 Reconstruction model of the Byzantine sundial [23, 30]

2.6 Planetarium, Astrarium, and Astronomical Clock

Planetariums are diverse with ages. In early times, the planetarium was referred to as a mechanical device that could demonstrate the cyclic motions of heavenly bodies based on the universe model proposed at that time. This mechanical device was driven by gear mechanisms. However, in modern times, a planetarium usually refers to a theater built primarily for presenting educational and entertaining shows about astronomy and the night sky, or for training in celestial navigation.

An *astrarium* was also defined as a mechanical device for displaying the motions of the celestial bodies. It was generally for the *astronomical clock* [23]. According to historical literatures, this type of astronomical instruments is an outstanding achievement in the fourteenth century. The earliest astronomical clock was devised by Richard of Wallingford (1292–1336) between 1327 and 1330, but no historical descriptions or schemes about this earliest one exists [23]. Until now, the most famous example is the 7-sided brass astronomical clock, as shown in Fig. 2.13, designed and created by Giovanni de' Dondi, a professor in the University of Padua and a clock maker between 1348 and 1364 [18, 24, 29, 31–33]. Seven dials of the upper section of this astronomical clock, respectively, demonstrate the primum mobile, Venus, Mercury, Moon, Saturn, Jupiter, and Mars. Figure 2.14 shows all of the reconstructed dials of de' Dondi's astrarium. The mechanism contained in each dial of the astronomical clock was an epicyclic gear train with pin-in-slot joints [34, 35]. This special design was common in the ancient astronomical mechanical devices and was essential for the anomaly motion.

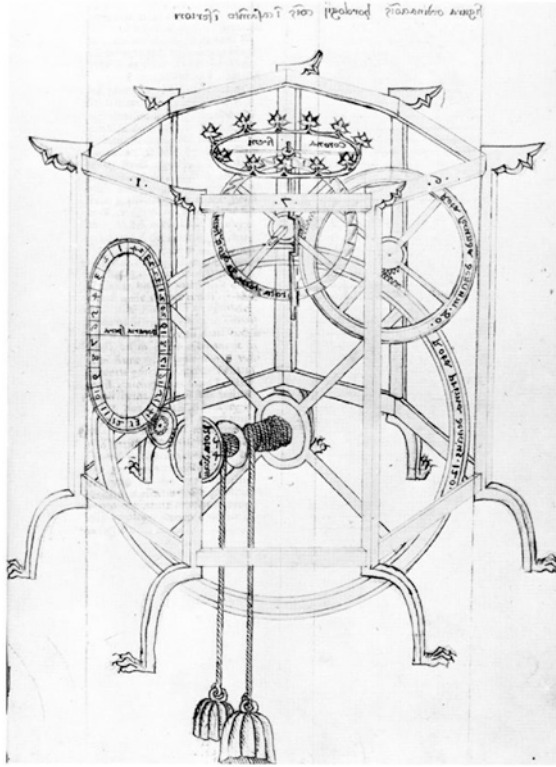


Fig. 2.13 Manuscript of astrarium by Giovanni de' Dondi [43]

In the fifteenth century, an unclear schematic drawing appeared in the manuscript of Leonardo da Vinci (1452–1519), as shown in Fig. 2.15a [29, 36]. The gear mechanism seemed to be a part of an astrarium and was supposed to serve the purpose of demonstrating the cyclic motion of Mars. Figure 2.15b shows the corresponding schematic drawing. There are 8 gears in this mechanism. Three of them (members 2, 6, and 9) are regarded as the carrier, and three of them (members 3, 7, and 10) are regarded as the input members for providing the input power. Therefore, this mechanism required three input sources to generate a controllable and constrained motion. By the viewpoint of modern mechanism, this mechanical device was a 9-bar mechanism with 14 joints and 2 degrees of freedom. The professional knowledge of mechanism is represented in Chap. 3. The chief concept of design should be satisfied with the Ptolemaic epicycle system. Certainly, it is obvious that the design of gear mechanism with pin-in-slot joints was applied again.

Besides, the demonstration function of planetarium was used for combining with other astronomical mechanical devices. For example, a French Gothic astrolabe, dated about 1300 and preserved in the Science Museum of London, has a similar purpose for displaying the relative positions of the Sun and the Moon in

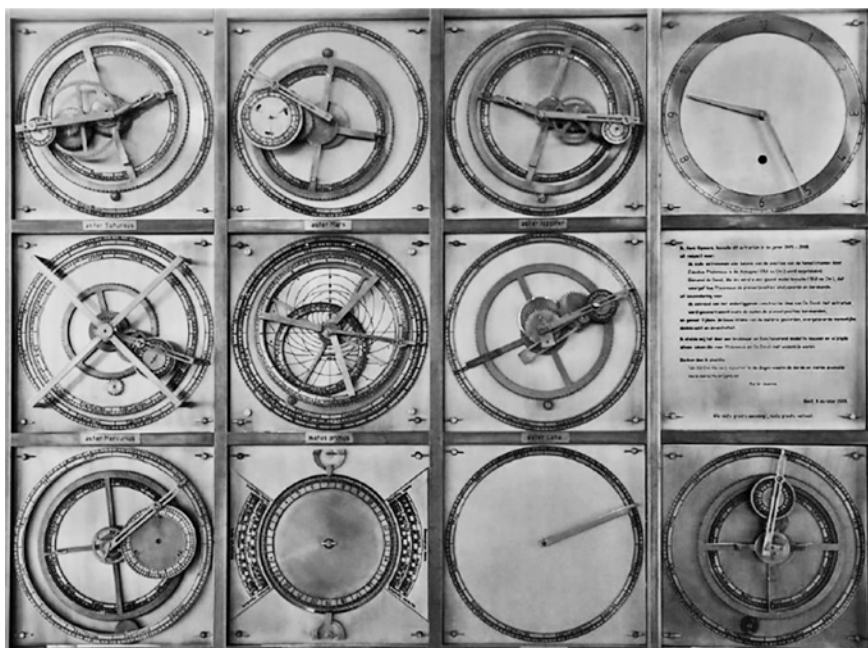


Fig. 2.14 Reconstructed dials of de' Dondi's astrarium [35]

the zodiac by the corresponding pointers driven by an arrangement of gears, as shown in Fig. 2.16 [24]. The gear mechanism was built over the front plate of the astrolabe. The existing situation of the Gothic astrolabe is quite complete, but lacking the Moon pointer. Therefore, its operation and functions are understood clearly.

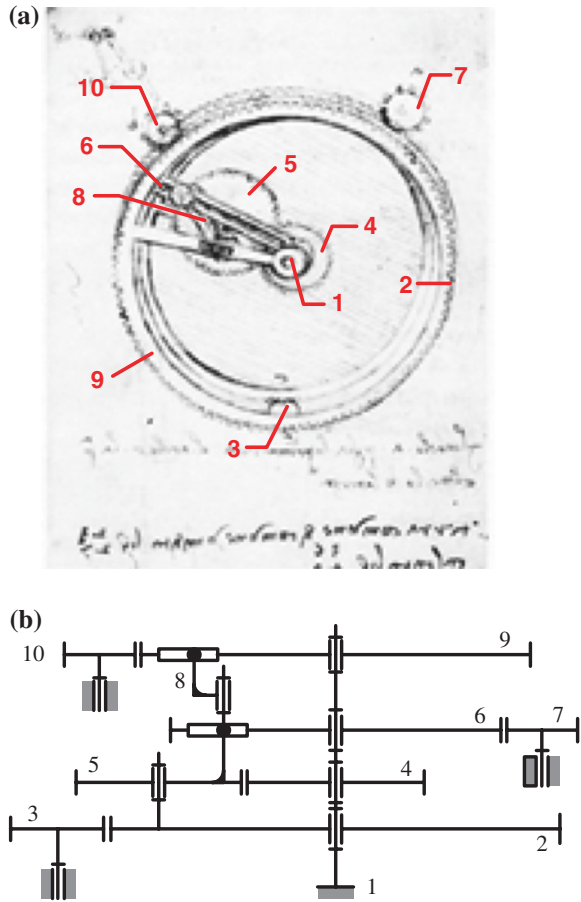
In fact, the names “planetarium” and “astrarium” are frequently used to call the same device. In the manuscripts and treatises by de' Dondi, these two names appeared successively several times to mean his own astronomical clock. Therefore, in the study of astronomical mechanical devices in early times, the roles of planetarium and astrarium shall be regarded as the same.

2.7 Orrery

An orrery is a modern astronomical mechanical device that is designed based on heliocentric model. It displays the relative positions and motions of the planets and the Moon in the solar system [37–39]. The design and function of the orrery is very similar to the ones of planetarium or astrarium. Nevertheless, the orrery only refers to a display device whose motions of celestial bodies are around the Sun, i.e., the center of device is the Sun. The orrery was invented by clock makers

Fig. 2.15 The planetarium by Leonardo da Vinci.

a Schematic drawing of historical manuscript [29, 36]. **b** Modern schematic drawing



George Graham (1673–1751) and Thomas Tompion (1639–1731) before 1719 and then gradually developed to be one of the achievements in the eighteenth century [37]. Such a device is typically driven by a gear mechanism, like a clock, and has a globe representing the Sun at the center as well as a planet at the end of each arm. The solar system is clearly represented in three-dimensional pointer system. The most important is that the revolution and the rotation of each planet can be understood easily.

2.8 Comparisons of Astronomical Instruments

A mechanical device is defined based on its functions and purposes. From the viewpoint of mechanical design, it is reasonable to believe that a common design for the specific purpose can be applied to various mechanical devices. A thorough

Fig. 2.16 French Gothic astrolabe, reprinted from Ref. [24], copyright 2015, with permission from Science Museum of London



investigation of the ancient astronomical mechanical apparatus is indispensable for understanding the historical development of mechanism designs for some specific output functions, such as computing, demonstration, and measuring.

According to available ancient astronomical mechanical devices (the Islamic calendrical device, the Byzantine sundial with calendrical gearing, and the Persian astrolabe with calendrical gearing), ancient mechanical design for the application of computing was ordinary gear trains. The excavation of some devices reveals that the design of gear mechanisms was workable and precise, even though the shapes of the teeth could be slightly different. In order to satisfy the calculations of different calendars, these astronomical apparatus with calendrical calculation had different teeth and numbers of gears to construct their gear trains.

The variation of moon phase is a cyclic astronomical phenomenon. It seemed to be regarded as one of the calendars. The function for displaying the variation of moon phase was usually attached to the calendrical device. The manners for showing the moon phase were particular and diverse. They depended on the relative motion of the Moon disk and the fixed plate for showing the moon phase. They could have a rotatable moon disk with full-black circles that were regarded as the moon shadow. Depending on the corresponding gearing, the moon disk was driven

to gradually show the shadow in a hole of fixed case. Or, a Moon disk that was white and had a hole rotated over a fixed full-black plate for moon shadow. The fixed case still had a hole. And, the new moon appeared when the hole of Moon disk coincided with the hole of the fixed case. Furthermore, a Moon disk could be replaced by a Moon ball. This manner was rare, but existed in ancient astronomical apparatus.

For the function to demonstrate the motions of celestial bodies, the study of ancient astronomical apparatus concludes two different designs. One design is the ordinary gear train used in the Islamic astrolabe with calendrical gearing, the Byzantine sundial with calendrical gearing, the Persian astrolabe with calendrical gearing, the French Gothic astrolabe, and the orrery. Such a mechanical design represents the mean motions of heavenly bodies. Since these motions are almost anomaly, there are errors between the prediction positions of these apparatus and the actual observation positions in the night sky.

Another design is a planetary gear train with pin-in-slot joints. This design was applied in all dials of the Dondi's astronomical clock and the scheme of the manuscript by Leonardo da Vinci to generate the variable rate of output so as to satisfy the anomaly motions of the celestial bodies. The difference between the application examples is the numbers of the pin-in-slot joints. For these designs, the number of applied pin-in-slot joints is determined by their demonstrated planets and the universe model that the planets applied. According to the historical development of astronomy, both Dondi's astronomical clocks and the planetarium by Leonardo da Vinci were invented after the publication of the Ptolemaic system. Thus, it is confirmed that the demonstrations of planetary motions of these apparatus should adopt the Ptolemaic system. The numbers of pin-in-slot joints used made the designs satisfy the geometrical models of the astronomical theory at that time. Such a design concept was believed to have spread into Western scientific culture.

Except for the investigations of functions and mechanisms, the manufacture technique is also a point. For the ancient astronomical mechanical apparatus, gears were regarded as the soul of mechanisms. The difficulty of manufacturing was related to teeth shape, size, and teeth number of gears. The teeth shape of most early gears approximated to equilateral triangles, and the gear of Olbia is a particular example. Their shape and the required shape cutter were obviously simpler than modern gears. These early gears could be manufactured much easily, but the triangular shape made impact and vibration stronger during the engagement process of gears. In general, the size of the gears used in astronomical apparatus was so fine that they could be installed in a constrained case. As to the choosing of teeth number, it was absolutely related to the precision of scale division of a circle. Thus, all teeth could averagely surround the gear without deforming the shape.

Furthermore, coaxial arbors of gears were much popular in the ancient astronomical mechanical apparatus and clockwork. This design must consist of a hollow outer arbor, and the inner arbor could pass through it. The outer arbor and the inner arbor rotated, respectively. The manner for mounting a gear and an arbor was not constrained. Sometimes, some of the gears had squared holes by which they were fitted to their arbors. The relevant traditional technique was persisted generation by generation. At least, the design is used widely in the later content of this book.

2.9 Remarks

The research of ancient astronomical mechanical apparatus contributes to the understanding of the historical developments of their applications, mechanical designs, and relevant manufacturing techniques. It is essential that such an investigation provides the fundamental bases for constructing an astronomical mechanical apparatus with some specific functions.

Ancient astronomical mechanical apparatus, based on their functions, were classified into applications for observation, measuring time, measuring distance, computing, and demonstration. Except for separate ancient astronomical apparatuses, some of them are compound apparatus with multifunctions. For calendrical calculation and demonstration of celestial bodies' motions, several design examples are introduced and the relevant types of mechanisms and manufacturing technologies are analyzed.

In summary, it is believed that the design concepts to operate the motions with variable rates and the calendrical calculation were spread out in the Western world. And, the manufacture technique for these clock mechanisms had been preserved as a tradition.

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