JHA, xxx (1999)

REVIEW ARTICLE

THE MATERIAL CULTURE OF GREEK ASTRONOMY

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The application of the mechanical arts to astronomy was so well recognized a branch of mechanics that the Greeks had a special name for it. It was called "sphere-making" (*sphairopoiïa*). Sphere-making included the construction of celestial globes, to be sure, but it also included the making of other images of the heavens, such as models of the planetary system and mechanical calculating devices intended to replicate the motions of the Sun, Moon and planets.[1]

A discussion of the relation of sphere-making to the rest of mathematical knowledge is provided by Geminus, a Greek scientific writer of the first century A.D. Geminus wrote an elementary astronomy textbook (*Introduction to the phenomena*) that has come down to us more or less intact.[2] He also wrote a large book on mathematics, which contained a good deal of philosophy of mathematics, as well as mathematical exposition. This book has not survived, but much of its content is summarized by Proclus in his *Commentary on the First Book of Euclid's Elements*.[3] In his mathematical treatise, Geminus discussed the organization of mathematical knowledge and the relation of its branches to one another. Geminus's outline of the mathematical sciences is summarized in Figure 1.

FIG. 1. Organization of the mathematical sciences according to Geminus.

- Pure Mathematics (concerned with mental objects only)
  - Arithmetic (study of odds, evens, primes, squares, etc.)
  - Geometry
    - Plane geometry
    - Solid geometry
- Applied Mathematics (concerned with perceptible things)
  - Practical calculation (analogous to arithmetic)
  - Geodesy (analogous to geometry)
  - Theory of musical harmony (an offspring of arithmetic)
  - Optics (an offspring of geometry)
    - Optics proper (straight rays, shadows, etc.)
    - Catoptrics (mirrors, etc.)
    - Scenography (perspective)
  - Mechanics
    - Military engineering
    - Wonder-working (pneumatics applied to automata)
    - Equilibrium and centres of gravity
    - Sphere-making (mechanical images of the heavens)
  - Astronomy
    - Gnomonics (sundials)
    - Meteoroscopy (specialized instruments of observation)
    - Dioptrics (observation with dioptras)

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Mathematical knowledge is divided first of all into the pure (which deals with mental objects only) and the applied (which deals with perceptible things). Astronomy is one of six branches of applied mathematics. Geminus's three subbranches of astronomy are all concerned with the construction and use of instruments. As Geminus says, *gnomonics* is concerned with the measurement of time by means of sundials, while *dioptrics* is concerned with measuring the positions of the Sun, Moon, and the other stars by means of sighting instruments called dioptras. *Meteoroscopy* is apparently another branch of observational astronomy, based on the use of another class of specialized instrument. As for sphere-making, Geminus makes it a part of mechanics, perhaps because it involves the use of geared mechanisms and water power to activate its images of the heavens.[4]

If we consider the entire material culture of Greek astronomy — taking into account all astronomical objects either described by Greek writers or actually preserved today — we can place most of them in four classes: (1) cosmological models; (2) display pieces (such as sundials) related to time-keeping; (3) astronomical calculating devices; and (4) instruments of observation. Classes 1 and 3 comprise what Geminus called sphere-making, but it will be convenient to consider them separately. Class 2 corresponds to gnomonics, while class 4 corresponds to dioptrics + meteoroscopy.

These classes are not cleanly separable, for a single object might be used in different ways. For example, a celestial globe is primarily a model of the cosmos and an aid to instruction. But if it is mounted on an axis, so that it may be rotated, and equipped with a fixed horizon stand, it may also be used to find quantitative solutions to trigonometric problems associated with the daily motion of the heavens. The celestial globe has thus become a mechanical calculating device. Or consider the dioptra, in its simplest form a mere sighting tube used in teaching. When it was equipped with protractors (i.e., measuring circles, divided into degrees), the dioptra became an instrument of observation with uses in surveying. Nevertheless, these four classes are helpful for organizing discussion. Moreover, any individual concrete instrument was almost certainly used in a way that would have clearly relegated it to one of the four.

A fifth class that we will also consider comprises objects that express astronomical connections but that have merely symbolic value. Good examples are provided by astronomical stelae and by Greek and Roman coins. Geminus would not have recognized such objects as the tools of any branch of mathematics. However, they certainly do form a part of the material culture of Greek astronomy.

1. COSMOLOGICAL MODELS

Celestial Globes

The most important astronomical teaching model, from classical times down to the Renaissance, was the celestial globe. Cicero, quoting Gaius Sulpicius Gallus, makes

Thales (sixth century B.C.) its inventor.[5] Among the Greeks and Romans, however, Thales's name was a catchword for wisdom and learning and many discoveries were attributed to him that were in fact made much later.

The oldest systematic description of the celestial sphere of which we know was written by the mathematician Eudoxus of Cnidus, of the generation intermediate between those of Plato and Aristotle. In fact, Eudoxus seems to have written two separate descriptions of the sphere, called the *Phenomena* and the *Mirror*, which apparently differed but little.[6] None of Eudoxus's works has come down to us. However, we have a good idea of the content of his astronomical treatises, for they inspired the poet Aratus of Soli (third century B.C.) to write a verse *Phenomena*, which does survive and which was very popular in Antiquity.[7] In the *Phenomena*, the doctrine of the sphere is clear and complete. Aratus lists the constellations and describes their positions with respect to one another on the sphere. Moreover, he describes the important circles of the sphere (zodiac, equator, tropics) and even says which constellations lie along each of these circles. Thus we have good evidence for a complete understanding of the celestial sphere by the time of Eudoxus. Celestial globes, figured with the constellations and the principal celestial circles, almost certainly existed by the early fourth century B.C., if not a little earlier.

The earliest celestial globes, probably made of clay or wood, were fragile things and none has survived. The oldest extant globe is a marble sphere, supported by a statue of Atlas, now in the Museo Nazionale at Naples. This statue, transferred to its present location from the Farnese Palace in Rome, is commonly called the Farnese Atlas (see Figure 2; this eighteenth-century engraving of the Farnese globe is printed here, rather than a twentieth-century photograph, because it shows detail more clearly). The globe is a Roman copy (first or second century A.D.) of a Hellenistic original made perhaps several centuries earlier.[8] In the placement and representation of the constellations, the globe is consistent with the descriptions of the sky in the *Phenomena* of Aratus.

Atlas is supporting the celestial sphere. (The Earth, not shown, would be a tiny sphere located inside the celestial sphere.) The zodiac is represented by the triplet of rings arching across the upper part of the globe. The Greeks thought of the zodiac as a band about 12° in width — wide enough to contain the latitudinal wanderings of most of the planets. The ecliptic, or annual path of the Sun, is the middle of the three rings in the zodiac band: the Greeks called it "the circle through the middles of the signs". On the zodiac are several familiar constellations: (1) Taurus, (2) Gemini, (3) Cancer, and (4) Leo. A number of non-zodiacal constellations may also be seen: (6) Canis Major, (7) Argo, (8) Hydra, (9) Crater, (10) Corvus, and (15) Auriga. Partially hidden by the hand of Atlas are (12) Orion and (17) Lepus. Principal circles of the sphere include the celestial equator *CD*, the tropic of Capricorn *EF*, the tropic of Cancer *OK*, the solstitial colure *AB*, and the circle *AM* demarcating the always-visible stars. (The latter circle is what the Greeks called "arctic".)

The Farnese globe is a display piece. But globes could also be used in scientific research. Hipparchus (second century B.C.) made a celestial globe and probably



FIG. 2. A close-up of the Farnese globe, showing several constellations and the principal circles of the celestial sphere. The actual globe is 65cm in diameter. From G. B. Passeri, *Atlas Farnesianus*, in Antonio Francesco Gori, *Thesarus gemmarum antiquarum astriferarum*, iii (Florence, 1750). (Houghton Library, Harvard University.)

published a detailed description of the constellations to be drawn on it. Nearly three centuries later, Ptolemy still had access to Hipparchus's description or, less likely, to the globe itself. Hipparchus's descriptions were detailed enough to permit Ptolemy to confirm that the constellations maintained their positions relative to one another.[9]

Ptolemy also gives detailed directions for making a celestial globe.[10] The globe should be of a dark colour, to resemble the night sky. Most stars are to be painted in

yellow, but a few stars (such as Antares) that appear red should be painted so. Ptolemy's model was especially sophisticated, in that it was constructed to allow for precession: the axis of rotation could be moved to reproduce the slow shift in the position of the celestial poles from one century to the next.

There is evidence that both Hipparchus and Ptolemy made use of celestial globes to perform trigonometric 'calculations' when great numbers of calculations had to be made and high precision was not required. Consider, for instance, Ptolemy's *Phaseis*, a book devoted to phases (that is, heliacal risings and settings) of the fixed stars.[11] Fixed star phases were widely used in Greek culture as signs of the seasons. The morning rising of the Pleiades marked the beginning of summer, for example, while the morning rising of Arcturus marked the beginning of autumn.

Now, in his *Phaseis*, Ptolemy gave the dates of the morning and evening risings and settings of some thirty stars for five different latitudes on the Earth. To do this, he observed the dates of these star phases in Alexandria, then calculated the dates on which they would occur in the other latitudes. From the scatter in Ptolemy's calculated results, it has been inferred that he actually performed the 'calculations' with a celestial globe.[12] Phenomena involving star phases cannot be rendered very precise, because of uncertainties due to atmospheric conditions and variations in the observers' visual acuity. Thus, an elaborate trigonometric calculation would not lead to any real increase in accuracy over the globe. Given the fact that Ptolemy's list contains 580 star phases, his use of a globe appears perfectly sensible.

The Armillary Sphere

Similar to the celestial globe, but easier to construct, is the armillary sphere. Figure 3 reproduces a sixteenth-century illustration of an armillary sphere. The principal circles of the celestial sphere (equator, ecliptic, tropics, etc.) are represented by rings, which are fastened together to form a sort of skeleton sphere.

In the *Timaeus*, Plato describes the creation of the universe by the craftsman-god.[13] The craftsman-god rolled out world soul (like pie dough) and cut it into two strips. Each strip was bent around and fastened to itself to make a ring. Then the two rings were joined to one another at an angle, making a χ where they came together. These two rings were called by Plato the "circle of the same" and the "circle of the different". They represent the celestial equator and the zodiac. Plato's metaphor for the creation of the universe by the craftsman-god is the manufacture of an armillary sphere. Thus, by the fourth century B.C. the armillary sphere already served as an image of the cosmos.

Armillary spheres are handy for teaching astronomy. They can be used, for example, to demonstrate the variation in the length of daylight with the season, and with latitude on the Earth. No example of an armillary sphere has survived from Antiquity, but they are mentioned as teaching tools by Geminus in his *Introduction to the phenomena*. Geminus calls them "ringed spheres" ("*krikotai sphairai*") to distinguish them from the "solid spheres" ("*stereai sphairai*"), that is, from the

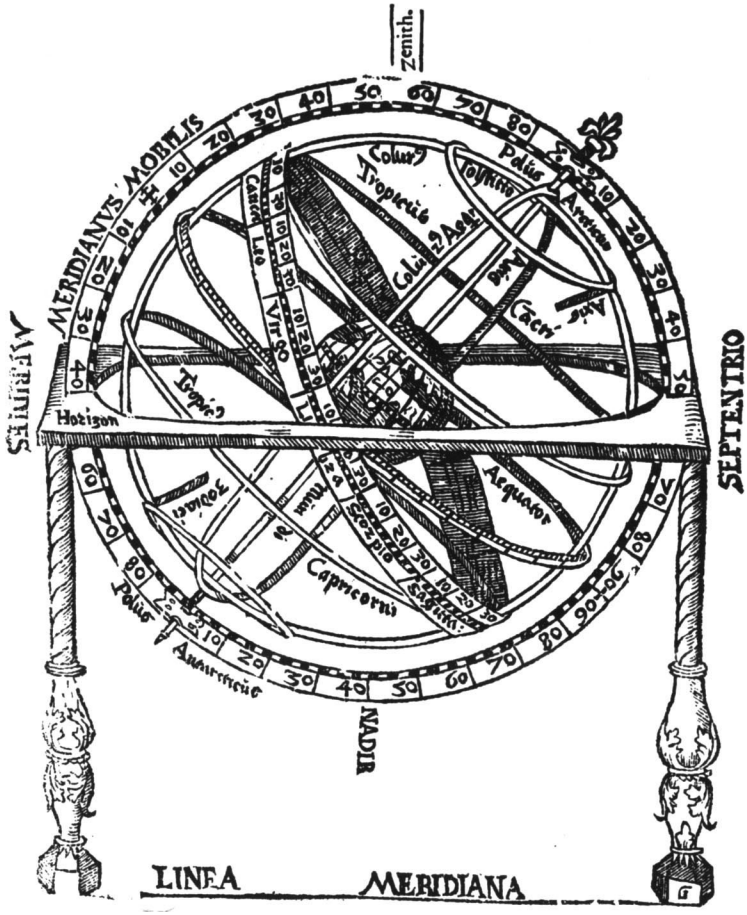


FIG. 3. An armillary sphere, which provides a fine example of *sphairopoïïa*. From the *Cosmography* of Petrus Apianus as reworked by Gemma Frisius: *Cosmographia ... Petri Apiani & Gemmae Frisii* (Antwerp, 1584). (Special Collections, University of Washington Libraries.)

celestial globes. And we do have a mural painting of an armillary sphere found at Stabiae, near Pompeii.[14] (The modern term 'armillary' is taken from a Latin word for an armband or bracelet.) By Ptolemy's time, sights had been added to the rings and the armillary sphere had become an instrument of observation (see below).

Models of the Planetary System

Greek planetary theory was, from its very beginning, geometrical in spirit. The planets were considered to ride on circles, or spheres. The compound motion resulting from several circular motions could be difficult to visualize. Geometrical diagrams

and physical models were natural aids to visualization.

In Book X of the *Republic*, Plato describes the universe metaphorically as a set of nested spindle-whorls.[15] Each planet rides on a spherical shell, and the shells for the individual planets are nested one within another. This concentric-spheres cosmology, worked out in detail by Eudoxus and endorsed by Aristotle, dominated cosmological thought down to the Renaissance. Theon of Smyrna (second century A.D.) says that he actually made a physical model of Plato's nested spindle-whorls.[16] This was, of course, merely a model of the planetary system, and not a device capable of quantitative prediction, but it does demonstrate an interest in physical planetary models by Theon, who is the most important pre-Ptolemaic writer (of those whose works have survived) on the deferent-and-epicycle theory. Plato himself would no doubt have approved of Theon's model-making: witness his remark in the *Timaeus* that it is useless to talk about the figures of the dance of the planets without a concrete model before our eyes.[17]

Models of the planetary system were certainly built long before Theon's time. One of the masters of this craft was Archimedes (third century B.C.). Archimedes is known to have designed a mechanical device that reproduced the motions of the Sun, Moon and planets, as well as an ordinary celestial globe. Archimedes was killed in 212 B.C. during the sack of Syracuse by the Roman army under the command of Marcellus, and his two models were taken back to Rome, where they excited considerable interest. We do not know whether Archimedes's planetary mechanism was capable of quantitative prediction. Probably, it at least represented the mean motions, and thus embodied some quantitative features, for Cicero says that it duplicated eclipses at the right times. Most likely, it was a gear-work mechanism.[18]

An interesting aspect of Geminus's division of the mathematical sciences (Figure 1) is that his branches of mathematical knowledge correspond to actual genres of writing. Thus, we actually possess, or at least have ancient mentions of, mathematical works in all of these categories. It was Archimedes who helped to establish sphere-making as a genre, for Pappus tells us that Archimedes composed a work called *Peri sphairopoiïas* (*On sphere-making*).[19] It has not survived.

2. DISPLAY PIECES RELATED TO TIME-KEEPING

Sundials

The sundial is the chief physical evidence of the scientific activity of the Greeks and Romans. Some 250 have been discovered at sites all over the Mediterranean.[20] The ancient dial makers were very inventive and many different kinds of dial have come down to us.

To judge by numbers, one of the most popular kinds was the *spherical dial*. In its simplest form, this consists of a hemispherical cavity cut into a block of stone. A gnomon is set into the stone with its tip at the centre of the cavity. This cavity is an

inverted, miniature model of the celestial sphere. The concave surface of the cavity was engraved with circles representing the tropics and the equator, as well as with other curves that indicated the hours.

However, a truly hemispherical dial with central gnomon would have been impractical. It would have been laborious to cut a complete hemisphere out of stone, and the cavity would have filled with rain water. Fortunately, a complete hemisphere is not needed, for the shadow tip will not fall just anywhere on the spherical surface. In particular, the shadow tip can never fall outside the belt between the two tropic circles. Therefore, the entire hemisphere is not needed, and the southern face may be cut away, as in Figures 4 and 5.

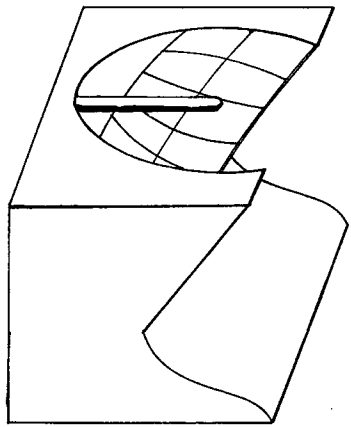


FIG. 4. Typical spherical dial with cut-away south face. Eleven hour lines mark the seasonal hours. Three day curves indicate winter solstice (highest), equinox, and summer solstice.

The hours indicated on the dial in Figure 5 are *seasonal* hours. The period from sunrise to sunset consists always of twelve hours, all equal to one another. Similarly, the night is divided into twelve equal hours. In the summer, the day hour is long and the night hour is short, while in the winter, the opposite is true. The hour we use today (one twenty-fourth of the whole diurnal period) is called the *equinoctial hour*. Although Greek astronomers did use equinoctial hours when they needed uniform units of time for precise calculation, the seasonal hour was the only one used in everyday life, and all surviving Greek and Roman sundials are marked in seasonal hours.

The popularity of the spherical dial was due to its simplicity. Because the dial is merely a reduced version of the celestial sphere, the theory governing the placement of the curves is very simple. The chief disadvantage associated with the spherical dial was the effort required to chip, bore and grind a cavity of acceptable shape.

Great numbers of *conical dials* are also preserved. Indeed, the known number of

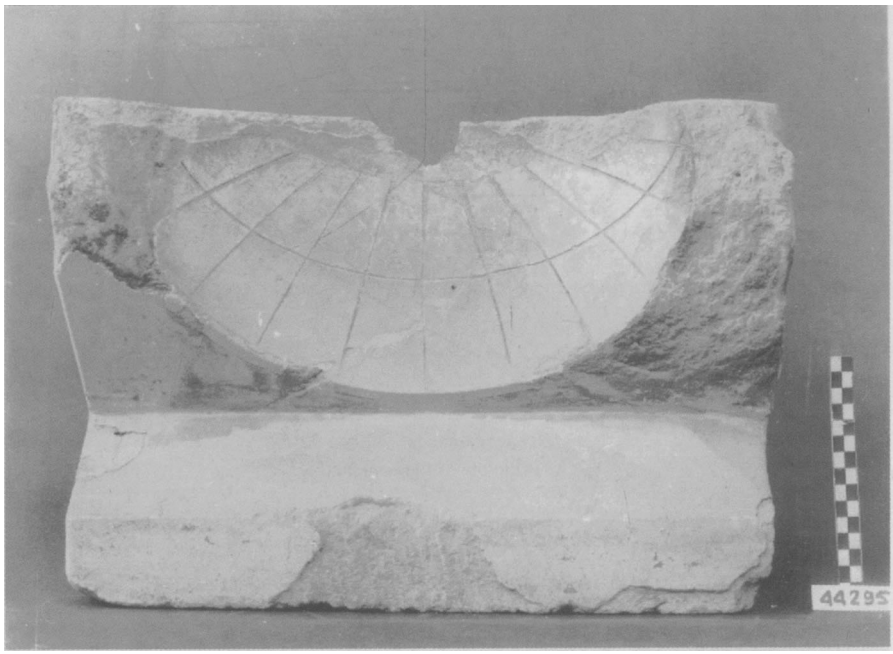


FIG. 5. Spherical dial from Pompeii. This dial is made of tufa covered with stucco. The eleven hour lines and the three day curves are coloured with deep red. 44cm wide. Gibbs no. 1026. (Soprintendenza Archeologica di Pompeii, Inv. 44295.)

this type exceeds even that of the spherical dials. In a conical dial, the shadow-receiving surface is a portion of the inner surface of a cone. Typically, the conical depression was cut into the edge of a roughly rectangular slab of stone, as in Figure 6. Figure 7 shows a conical Greek dial found near Alexandria. The stone-working involved in making a conical depression was easier than that required for a spherical cavity. But, by compensation, the theory was slightly more complicated: it was necessary to project the celestial sphere onto a conical surface.

About forty *plane dials* are also preserved. The theory underlying such dials is a good deal more complicated than the theory of spherical or conical dials, for the celestial sphere must be projected onto a plane surface. Figure 8 shows a horizontal plane sundial found in the Roman city of Aquileia. This dial is made of limestone and is about 1 metre wide. The shortest of the eleven hour lines (the noon line) lies on the line of symmetry and is the meridian. The gnomon hole is at the southern end of the dial. (The broken stub of an iron gnomon remains in the hole.) In use, the dial would lie on the ground, with its face horizontal, and its meridian aligned north–south. The bat-wing shape is characteristic of all Greek and Roman horizontal plane dials. The curve nearest the gnomon hole is the shadow track for the day of summer solstice, the straight line below this is the shadow track for the equinox,

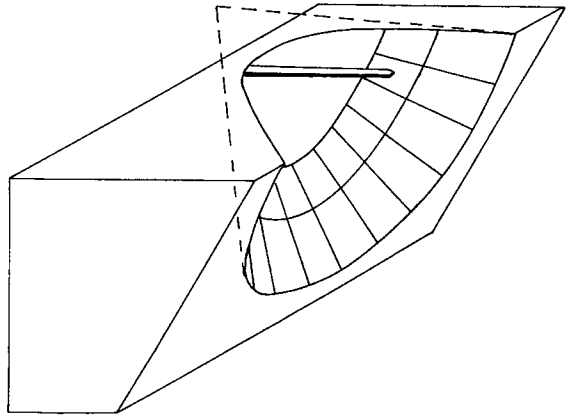


FIG. 6. Principle of the conical dial.

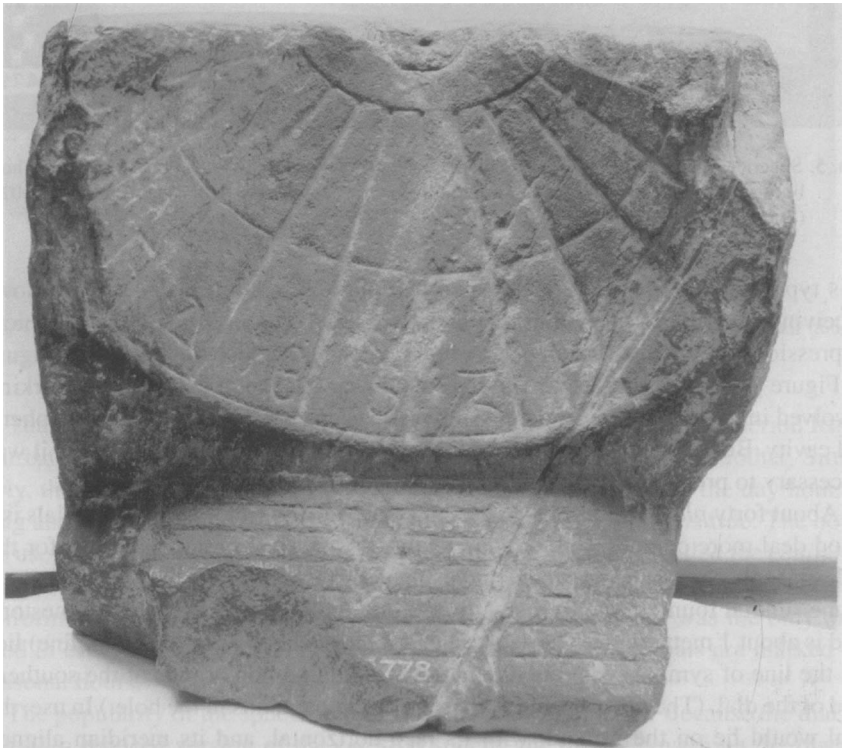


FIG. 7. Conical stone dial found near Alexandria at the base of Cleopatra's needle. The Greek numerals labelling the hour lines are a rare feature and are probably a Byzantine addition to this Ptolemaic dial. 40cm high × 43cm wide. Gibbs no. 3086. (British Museum, no. 1936 3-9 1.)

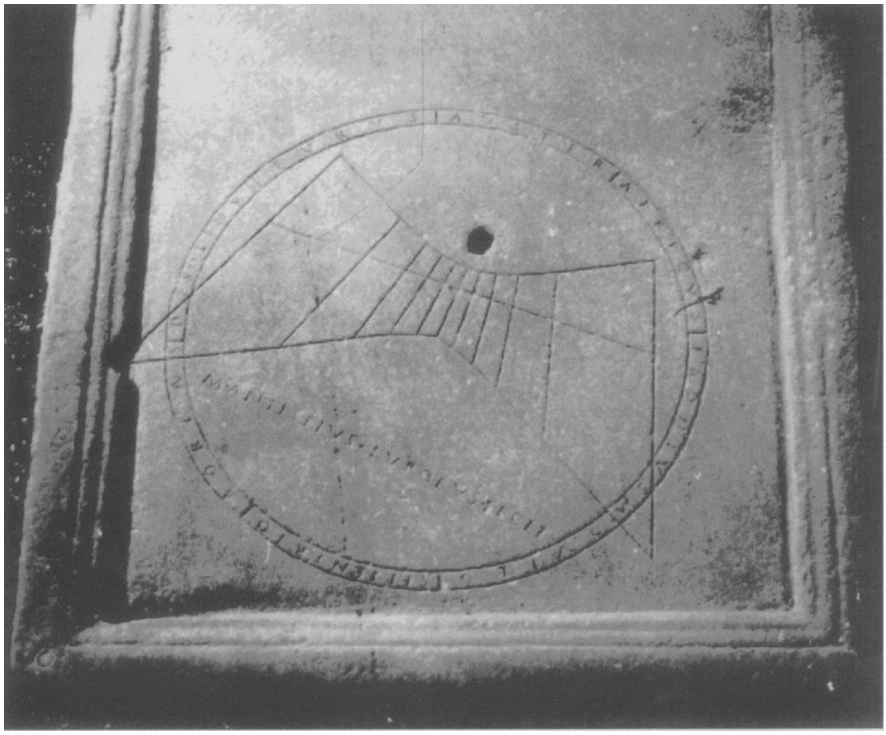


FIG. 8. A horizontal plane sundial. Gibbs no. 4002. (Museo Archeologico Nazionale di Aquileia.)

while the curve farthest from the gnomon hole is the shadow track for the winter solstice. This dial was engraved around its perimeter with the names of the winds in Latin, wind names being often used to indicate directions. Another inscription tell us the name of the maker of this dial: M. Antistius Euporus.

The most remarkable surviving example of ancient dialling is the Tower of the Winds in the Agora in Athens. This eight-sided marble building was constructed by a Macedonian astronomer, Andronikos of Kyrrhos, around 50 B.C. Figure 9 shows a general view of the tower, as sketched by James Stuart and Nicholas Revett, two British historians of architecture who published a series of engravings of Greek and Roman antiquities in 1762.[21] Each face of the tower bears a relief sculpture of a wind god. Below each relief is a sundial. The eight sundials, which face in eight different directions, had, of course, to be individually designed. On top of the tower was a weather vane (which no longer exists), which turned to indicate which wind was blowing.

The division of mathematics devoted to the theory of sundials was called by the Greeks *gnomonics* (see Figure 1). Two works in this genre have come down to us. The most sophisticated is Ptolemy's book, *On the analemma*.[22] The analemma is a



FIG. 9. The Tower of the Winds in Athens. From James Stuart and Nicholas Revett, *The antiquities of Athens* (London, 1762). (Beinecke Library, Yale University.)

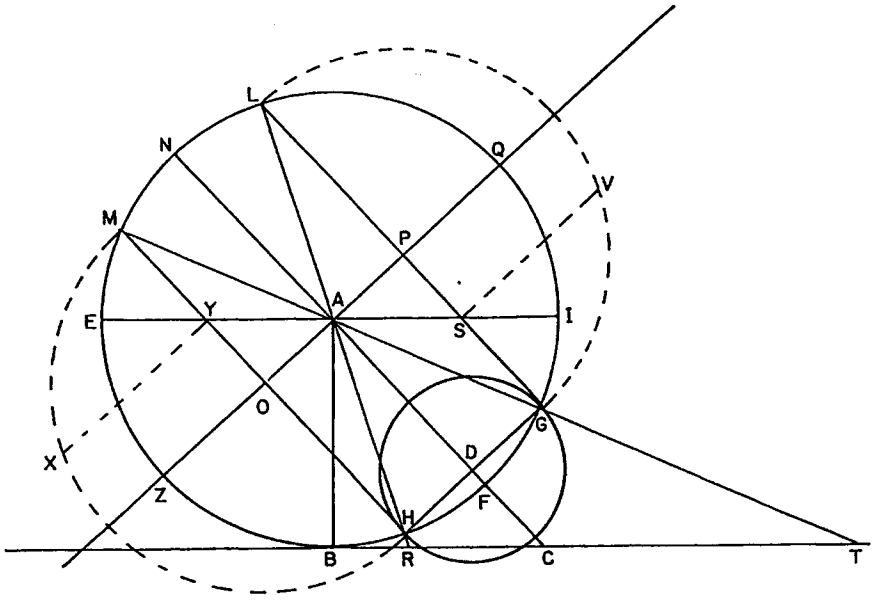


FIG. 10. The analemma described by Vitruvius.

two-dimensional projection, or folding, of the celestial sphere, which permits the easy determination of shadow directions and lengths. A somewhat earlier discussion of the analemma is provided by the Roman architectural writer, Vitruvius, in Book IX of his *Ten books on architecture*.[23]

In Figure 10 we see the analemma described by Vitruvius. Circle *NQB* is the celestial meridian. *AB* is the gnomon, and *BT* is the ground, onto which the shadows are projected. *AQ* is the axis of the universe, which makes an angle with the horizon *AI* that is equal to the latitude for which the sundial is to be designed. *NF* is the celestial equator. *LG* is the tropic of Cancer. The dashed semicircle *LVG* is the tropic of Cancer when it is folded down into the plane of the diagram. Note that *the analemma of Vitruvius is essentially a side view of an armillary sphere* (compare Figure 10 with Figure 3). Vitruvius does not bother to tell us how the analemma was actually used to construct a sundial — lest, as he says, he should prove tiresome by writing too much. In any case, Vitruvius is not a very original thinker and we can be sure the analemma was not his own invention. Modern scholars have reconstructed the methods that were probably used to produce a sundial from the analemma.[24]

One begins by dividing arc *LV* of the tropic of Cancer into six equal parts to represent the six seasonal hours between noon and sunset (for the resulting divisions, see Figure 11). Let us see how the analemma can be used to construct the shadow track for summer solstice on a plane, horizontal sundial. As an example,

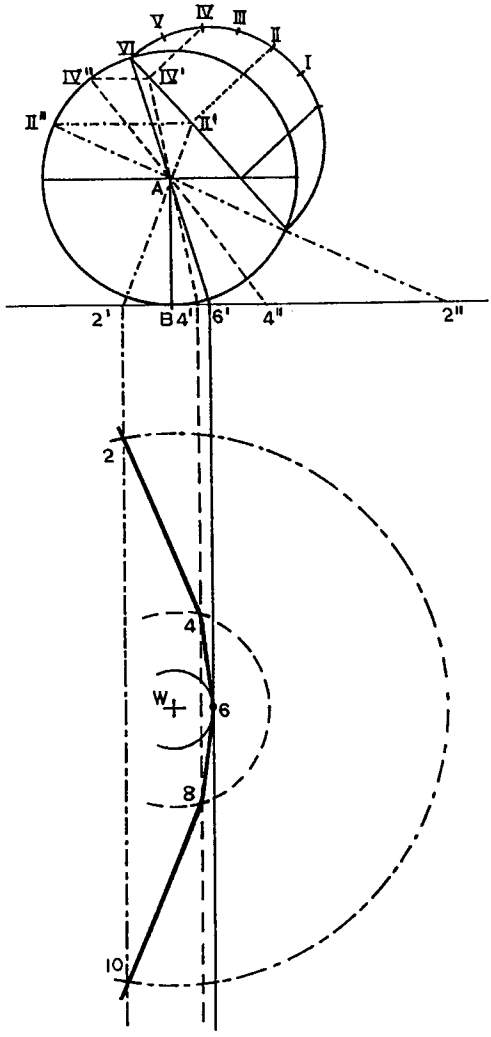


FIG. 11. Construction of the summer shadow track for a plane, horizontal sundial using the analemma of Vitruvius. This is a good illustration of *gnomonics*.

we shall determine the shadow at the second hour. Two projections are required. The first will tell us how far the tip of the shadow extends to the north or south of the gnomon. The second will give us the overall length of the shadow.

In Figure 11, point *II* is the position of the Sun at the second hour, on the folded-down tropic of Cancer. *II'* shows us where the Sun would be seen if we looked at the celestial sphere from outside. Thus, the shadow falls to the south of the gnomon by distance *B2'*. Place point *W* somewhere on the extension of line *AB*. *W* will be the

location of the gnomon in the completed sundial. Extend a line from $2'$ parallel to line *ABW*. The tip of the shadow falls somewhere on this line at the second hour of the day.

To find out how long the shadow is we proceed as follows. From H', project a line parallel to the horizon *EAI*. This line hits the meridian at H''. In making this projection, we have, in effect, rotated the Sun around to the meridian, keeping it always at the same height above the ground, which guarantees that we have not changed the length of the shadow. Now project a line from H'' through the tip *A* of the gnomon. This hits the ground at $2''$. Thus, at the second hour, the overall length of the shadow is $B2''$. Draw a circle of radius $B2''$ about *W*. One intersection of this circle with the vertical line through $2'$ gives point 2, the location of the shadow tip at the second hour. As a bonus, we also get point 10, the location of the shadow tip at the tenth hour. The completed shadow track for summer solstice is drawn in heavy line in Figure 11. This curve may be compared to the summer shadow track in Figure 8.

In using the analemma, an ancient dialler could either work graphically, as in Figure 11, or trigonometrically. The surviving dials are of widely varying quality. While many were designed and executed with great skill, some were made so sloppily that we can be sure the designer worked graphically, and with no great care.

The Anaphoric Clock and the Early Astrolabe

The slow filling or emptying of a container of water can provide the basis of a clock. The engineers of Hellenistic Alexandria devoted a good deal of attention to all kinds of water-activated devices.[25] However, direct human sensation of the passing of time comes from the celestial phenomena, especially the diurnal motion of the Sun. Thus all mechanical devices for telling time are, in a sense, imitations of the motion of the heavens. It is not surprising, therefore, that the Greeks contrived a kind of water clock that imitated the diurnal motion of the celestial sphere. This is called an *anaphoric* clock, because it imitated the "risings" of the constellations.

Vitruvius gives a short description of such a clock.[26] The moving part of the clock was a drum, around which was wrapped a chain. A float was attached to one end of the chain and a counterweight to the other end. As water slowly filled a container, the float rose and the counterweight descended, causing the drum to turn at the rate of one rotation a day. Vitruvius tells us that the flat face of the drum was inscribed with an image of the heavens, including the zodiac circle. In front of the drum was a grid of wires that represented the horizon and the hours of the day. Thus, as the drum turned, the constellations could be seen crossing successively over the horizon wire.

Fragments of two anaphoric clocks have been found.[27] Figures 12(a) and (b) show a fragment of a bronze constellation disk now in the Museum Carolino Augusteum in Salzburg. This disk was quite large — over a metre in diameter when it was intact. The preserved fragment is engraved with figures of the constellations

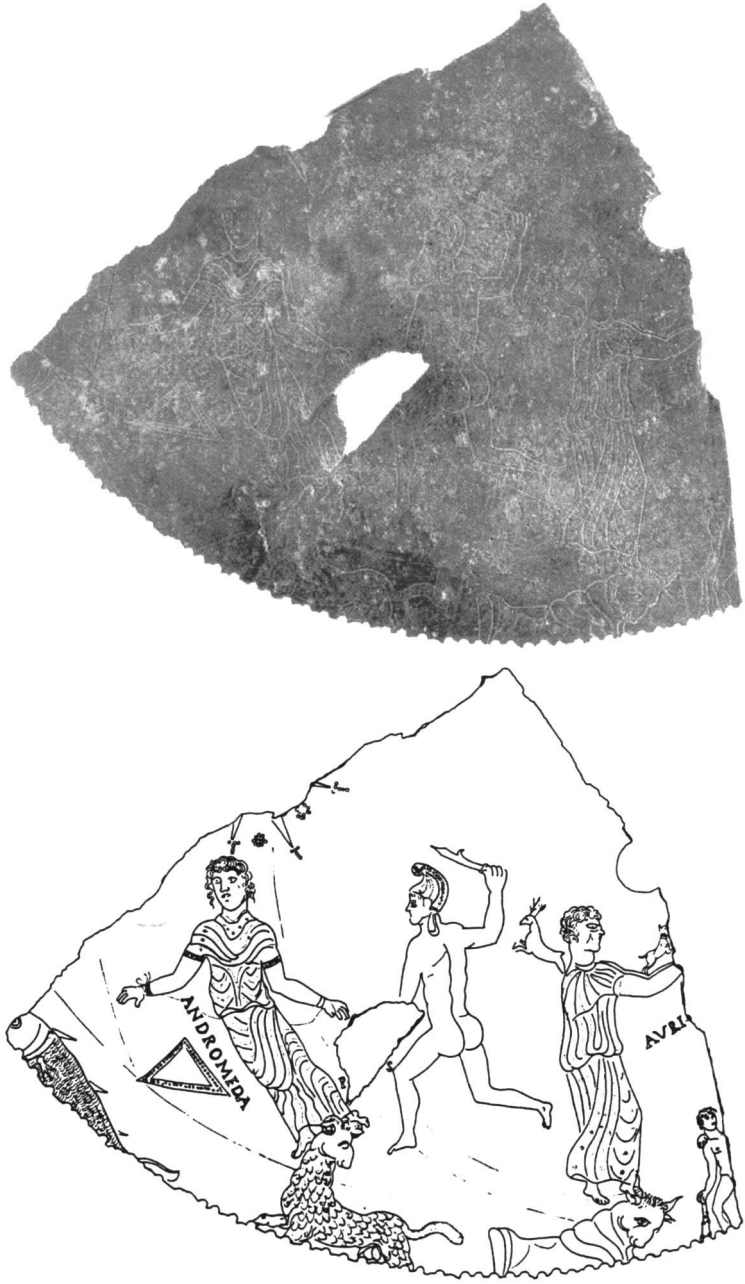


FIG. 12. (a, *above*) Fragment of the bronze constellation disk of an anaphoric clock, second century A.D.; (b, *below*) a sketch showing the details of the engraving. (Museum Carolino Augusteum, Salzburg.)

Triangulum, Andromeda, Perseus, and Auriga. The names Andromeda and Auriga are engraved next to the appropriate figures. The zodiac was represented by a circle with a series of holes drilled into it at regular intervals. The disk has broken off along this circle, giving rise to the serrated lower edge. On the preserved fragment, we can see the northern portions of the zodiacal constellations Pisces, Aries and Taurus. A peg, representing the Sun, was placed in the hole appropriate for the given day. As the disk turned, the Sun was carried past a series of wires marking the hours of the day and night.

The constellations were placed on the disk of the anaphoric clock by means of *stereographic projection*. This projection was discussed by Ptolemy in a book called the *On the planisphere*,[28] but the idea was a good deal older, and may go back to the time of Hipparchus. Stereographic projection is one way (among many) of mapping a sphere on to a plane. Stereographic projection has two especially valuable properties: it preserves circles and it preserves angles. Preservation of circles means that all the circles on the celestial sphere — such as the ecliptic and the tropics — are represented on the map as circles (or perhaps straight lines, which are circles of infinite radius). Preservation of angles means that if two circles cross on the sky at a certain angle, their projections will cross at the same angle on the map.

Figure 13 illustrates the basic principle of stereographic projection. The centre from which all projections are made is the south celestial pole (*SCP*). The plane of projection is that of the celestial equator. Thus, point H on the tropic of Capricorn is projected onto the plane of the equator as H'. The diameter HI of the tropic of Capricorn becomes diameter $H'I'$ in the projection. Thus, circles parallel to the equator become concentric circles in the projection. The farther south the circles lie on the celestial sphere, the larger they become in the projection. Oblique circles, such as the horizon, remain circles in the projection, but they end up off-centre. Vitruvius mentions that in the case of the anaphoric clock, the zodiac signs (each 30° long) become unequal in size. This is a normal property of stereographic projection, since the zodiac is an oblique circle. Moreover, analysis of the two extant fragments of clock disks show that the zodiac signs were, indeed, placed in accordance with stereographic projection.

The anaphoric clock is a sophisticated device and it is hard to know how common they were. There are channels carved into the paved floor of the Tower of the Winds that have been interpreted as channels for the water of an anaphoric clock.[29] The fact that the extant clock disks were found in such out-of-the-way parts of the Roman Empire as Austria and northern France suggests that these clocks may have been fairly common.

Stereographic projection is also the basic principle of the astrolabe.[30] Figure 14 is a photograph of a twelfth-century Arabic astrolabe. The top, lace-work metal disk (called the *rete*) represents the celestial sphere. The off-centred circle is the zodiac and the triangular pointers represent particular stars. Underneath the rete can be seen a metal plate engraved with curves representing the horizon and a family of circles (called *almucantars*) marking off altitudes above the horizon at 3°

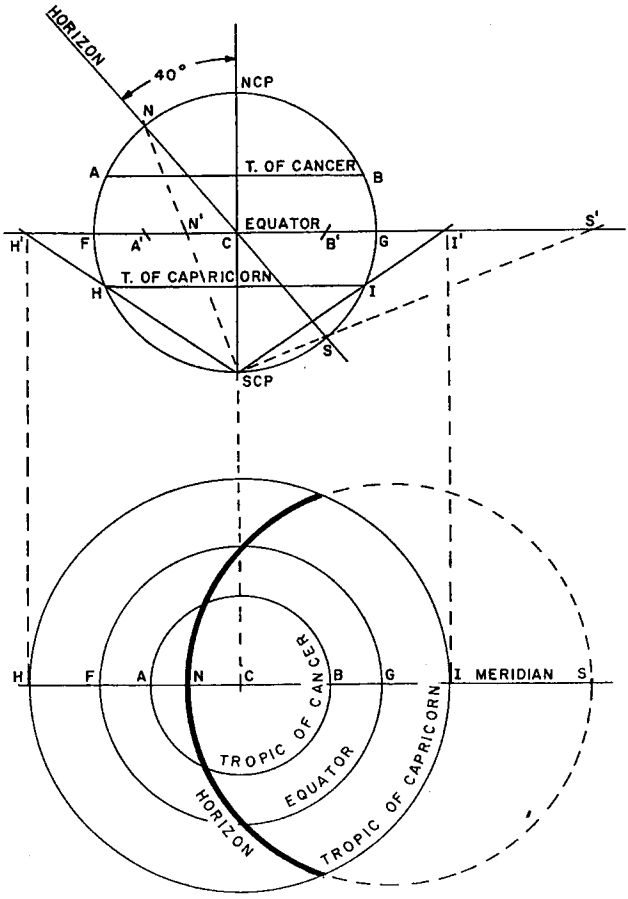


FIG. 13. Stereographic projection.

intervals. Also engraved on the plate is a system of curves representing the seasonal hours, and an additional set of curves (in dashed line) representing equinoctial hours reckoned from sunset. This plate is probably of later manufacture than the body and rete of the astrolabe.

The astrolabe was the most popular and common astronomical instrument of the Middle Ages. It could be used, for example, to tell time. If one observed a certain star at a particular altitude, one could place the pointer representing the star on the appropriate almucantar. One then looked to see where the Sun (the appropriate zodiac point for the day of the year) lay among the system of hour curves. The astrolabe is a sort of image-reversal of the anaphoric clock. In the case of the anaphoric clock, a solid disk representing the sky turns behind an open grid representing the seasonal hours. In the case of the astrolabe, an open grid (the rete)



FIG. 14. An astrolabe from Iran, engraved in Arabic with the date A.H. 525 (A.D. 1130/31) and signed by its maker, Badr ibn ʿAbdallah. 18.8 × 13.4 × 0.8 cm. (Adler Planetarium, no. A-84.)

representing the sky turns on top of a solid disk engraved with the hour curves.

Because the oldest surviving astrolabes come from medieval Islam, it was once thought that the astrolabe was a medieval invention. It is likely, however, that astrolabes with all their essential features existed by Ptolemy's time; and they certainly existed by the fourth century A.D. Theon of Alexandria wrote a treatise in Greek on the astrolabe. This does not survive, but a table of its contents has been preserved

and we do have two later treatises on the astrolabe, one in Greek and one in Syriac.[31] Their great similarity points back to Theon as the common source. Thus the astrolabe, the most representative instrument of medieval astronomy, was actually an invention of Greek Antiquity.

Parapegmata

Star calendars were an important part of the popular and practical astronomy of the Greeks. A star calendar (*parapegma*) listed the phases (heliacal risings and settings) of important stars and constellations in order of their occurrence in the year. Parapegmata served as vital complements to the Greek civil calendars. Because the Greek calendars were of the lunisolar type, sometimes the calendar year contained twelve months, and sometimes thirteen. Moreover, each major city had its own calendar, with different month names and different starting points for the year. Worse yet, the civil authorities had substantial freedom to tamper with the calendar. For all of these reasons, it was impossible to specify a time in the natural year (the year of the Sun and the seasons) by stating a date in a Greek civil calendar.

But every Greek would understand what was meant by "the morning rising of Arcturus": this was a universally accepted sign of the beginning of autumn. The purpose of a parapegma was two-fold: to tell the time of year and to foretell seasonal changes and shifts in the weather. Thus, in many (though not all) Greek parapegmata, the notices of heliacal risings and settings are accompanied by weather predictions.

Parapegmata were a major concern of the Greek astronomers. The list of those who are known to have composed parapegmata includes many of the great names — Euctemon, Eudoxus, Callippus, Hipparchus, and Ptolemy, whose *Phaseis* was mentioned above.[32] While many parapegmata were written on papyrus or other portable media, parapegmata were also inscribed on stone and set up in public places in some cities. Thus the parapegma was a prominent part of the material culture of Greek astronomy.

Figure 15 shows a fragment of a papyrus parapegma found among the Hibeh papyri and dated to the third century B.C. Although we do have quotations from earlier parapegmata, this fragment appears to be the oldest extant physical specimen of this genre among the Greeks. The fragment shown in Figure 15 begins:

> <Choiak 1,> ... The night is 13 4/45 hours, the day 10 41/45.
> 16, Arcturus rises in the evening. The night is 12 34/45 hours, the day 11 11/45.
> 26, the Crown rises in the evening, and the north winds blow which bring the birds. The night is 12 8/15 hours and the day 11 7/15. Osiris cirumnavigates, and the golden boat is brought out.
> Tybi <5,> the Sun enters the Ram.
> 20, spring equinox. The night is 12 hours and the day 12 hours. Feast of Phitorois.[33]

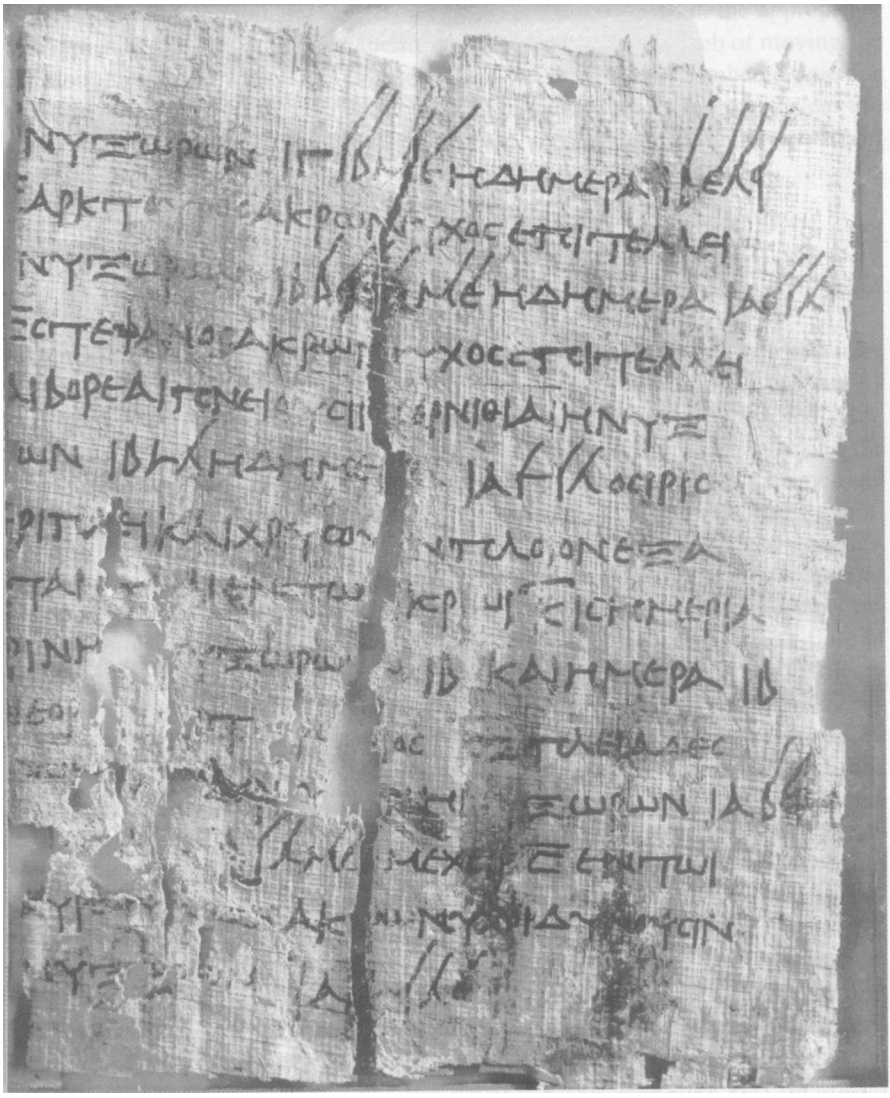


FIG. 15. Fragment of a papyrus parapegma from Greek Egypt, third century B.C. (P. Hibeh I 27, col. iv; Trinity College Library Dublin, Pap. F. 100.)

This parapegma is interesting for its blending of Egyptian elements with the traditional Greek subject matter. The days are indicated in terms of the Egyptian calendar. The star phases and weather predictions are accompanied by notices of festivals in the Egyptian religious cycle. Also of interest are the notices of the lengths of days and nights. According to the scheme used in this parapegma, the shortest day



Left Column

o The sun in the Archer.
o Orion sets in the morning and Procyon sets in the morning
o The Dog sets in the morning.
o The Archer begins rising in the morning and the whole of Perseus sets in the morning.
o o
o The stinger of the Scorpion rises in the morning.
o o
o The Arrow rises in the morning.
o The Southern Fish begins to set in the evening.
o The Eagle rises in the morning.
o The middle parts of the Twins are setting.

Middle Column

30

o The sun in the Water-Pourer
o [The Lion] begins setting in the morning and the Lyre sets.
o o
o The Bird begins setting in the evening.
o o o o o o o o o o
o Andromeda begins to rise in the morning.
o o
o The middle parts of the Water-Pourer rising.
o The Horse begins to rise in the morning.
o
o The whole Centaur sets in the morning.
o The whole Hydra sets in the morning.
o The Great Fish begins to set in the evening.
o The Arrow sets. A season of continual west winds.
o o o o
o The whole Bird sets in the evening.
o [Arcturus] rises in the evening.

FIG. 16. Fragment of a stone parapegma found at Miletus. (After the photograph in Diels and Rhem, *op. cit.* (ref. 34).)

is 10 equinoctial hours and the longest is 14. The length of the day changes uniformly by 1/45 hour from one day to the next. This crude scheme is mentioned in Egyptian sources going back to the twelfth century B.C. This parapegma is also interesting for the Eudoxan norm for the zodiac signs: the equinoctial and solstitial points are placed at the midpoints of their signs. Thus the equinox occurs 15 days after the Sun's entry into the sign of the Ram.

Figure 16 shows a fragment of a stone parapegma found at Miletus and dated to the second century B.C.[34] A hole for each day was bored into the stone and next to each hole were inscribed the star phases that occurred on that day. In some places, holes are bored between the lines of writing. These marked days for which there

were no celestial phenomena to be noted. A peg of wood stuck in the appropriate hole indicated the day of the year. Someone presumably had the job of moving the peg along by one hole each day (though it is also possible that numbered pegs for an entire month were inserted at one time). The stone parapegmata make clear the origin of the name for these star calendars: the verb *parapegnumi* means "to fix beside".

3. ASTRONOMICAL CALCULATING TOOLS

Planetary Tables before Ptolemy

Hellenistic planetary theory had roots in two different traditions with different priorities and goals. But before the time of Ptolemy these traditions were largely incompatible. For most readers, the more familiar tradition is undoubtedly the philosophical-geometrical one, based on Aristotle's philosophy of nature and the geometrical models introduced by Eudoxus and Apollonius of Perga. Geometrical planetary theory was in accord with accepted physical principles, the most important of which was the attribution of uniform circular motion to the celestial bodies. And it provided a qualitative account of the most obvious phenomena, such as prograde and retrograde motion. Geometrical planetary theory could therefore offer a plausible physical explanation of the basic facts, and it could offer a field of play for the geometer interested in proving theorems. But before the time of Ptolemy it was incapable of quantitative prediction.[35]

With the rise of interest in astrology, around the end of the second century B.C., there were pressing needs for calculating planetary positions from theory. Since philosophy and geometry failed to provide a means for doing this, the Greeks had recourse to arithmetic methods, which had long been cultivated in Babylonia. Sometime in the fourth century B.C. Babylonian scribes had developed planetary theories with quantitative, predictive capacity, which were based not on geometrical models, but on arithmetic rules. The arithmetic progression is one of the most characteristic features of the Babylonian approach.[36] The Greeks came into contact with Babylonian planetary theory during the Seleucid period (311–64 B.C.) and it must have been a shock: not only did the Babylonian approach yield numerical answers, but it did so without geometrical constructions and without any appeal to philosophy.

This put Greek astronomy into a difficult position. If you were a Greek steeped in Aristotelian physics and Euclidean geometry, you understood the heavens only if you thought in terms of deferents and epicycles. Thus, philosophically-oriented writers expounded geometrical systems based on combinations of uniform circular motion (even though these were incapable of numerical prediction). A good example of such a text is Theon of Smyrna's *Mathematical knowledge useful for reading Plato*, which dates from the early second century A.D. According to Theon, even though the Babylonian planetary theory succeeded in saving the phenomena, it was

unacceptable because it was not based on a proper understanding of nature.[37] On the other hand, if you were a Greek astrologer in Roman Egypt who needed to obtain planetary positions (even if great accuracy was not required), you had to fall back on arithmetic methods. The philosophically-based geometrical models and the arithmetically-based calculating schemes still existed side by side in the second century A.D.

Fragments of pre-Ptolemaic Greek planetary tables are preserved on papyrus and on wooden boards. Much of this material has only recently been subjected to close study. Babylonian planetary theory focused on direct computation of the times and places of important synodic events — first and last visibility, beginning and end of retrograde motion, and so on. The position of a planet in the zodiac on a given day can be obtained from Babylonian procedures, but not easily or directly. Rather, one must interpolate between the directly computed synodic events. For the practice of astrology among the Greeks of the Roman period, the most important things to calculate were the dates of entry of a planet into successive zodiac signs. This left Greek astronomers some room for ingenuity in the design of new kinds of arithmetic planetary tables. Many of the extant tables, both in Greek and in demotic, are concerned with the entry of planets into zodiac signs. The theories on which the tables were based cannot always be reconstructed with certainty, but it appears likely that many of them are based on Babylonian schemes.

One of the more exciting recent developments in the history of ancient astronomy has been the identification of Greek planetary tables that are direct borrowings from Babylonian planetary theory. Much of the new evidence has emerged from the work of Alexander Jones,[38] who is in the process of editing the astronomical material in the Oxyrhynchus papyri. These papyri were unearthed in the early decades of this century but the astronomical scraps were mostly neglected till now. According to Jones, the Oxyrhynchus material contains faithful Greek adaptations of most versions of the Babylonian planetary theory for every planet but Venus.

The evidence for Greek use of Babylonian planetary theory is important because it considerably changes the canonical history. Many earlier writers on the history of Greek astronomy have overstressed the continuity of its development, its allegiance to philosophical principles, and its cultural independence. One of the main reasons for this error is that the canonical story was largely constructed by philosophers. The problem goes all the way back to Proclus (fifth century A.D.), who in his *Hypotyposis* attempted to reconstruct the history of Greek astronomy out of his head, in keeping with the Platonic philosophy of nature to which he subscribed.[39] A second reason for the shortcomings of the traditional history of Greek planetary theory is that late Greek writers, including Proclus and even Ptolemy to some extent, did not appreciate how much their predecessors had borrowed from the Babylonians.

Thus the remains of the material culture, including the papyrus planetary tables, provide an essential complement to the literary evidence. Figure 17 shows a fragment of a papyrus planetary table from Greek Egypt. It is written in Greek numerals. But it

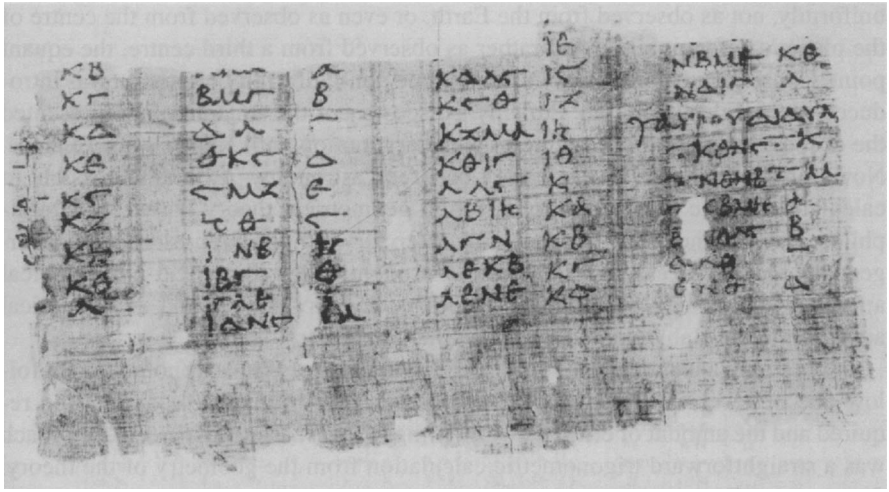


FIG. 17. A Greek papyrus planetary table, P. Mich. 151. This is an auxiliary table associated with an adaptation of the Babylonian theory of Mars in its simplest version (System A). (Department of Rare Books and Special Collections, University of Michigan Library.)

is an auxiliary table for use with a version of System A of the Babylonian theory of Mars.[40] Before Ptolemy's time, we should picture the astrologers of Greek Egypt doing their practical calculation of the planets with the aid of tables like this one.

Planetary Tables after Ptolemy

While arithmetic tables dominated practical computation of planet positions among the Greeks of the Hellenistic and early Roman periods, it is probable that tables based on geometrical models also existed before Ptolemy's time. The geometrical tables were, however, hopelessly inaccurate, because the Greeks had not yet found a satisfactory geometrical scheme for representing the non-uniformity of planetary motion. Ptolemy perhaps refers to these unsatisfactory geometrical tables when he speaks disparagingly of the "aeon tables" of his predecessors (we might call them perpetual tables).[41] In any case, we know very little about quantitative applications of geometrical planetary theory before Ptolemy's time. The definitive version of the geometrical planetary theory is Ptolemy's, as presented in his *Almagest*.

In Ptolemy's planetary theory, the motion of a planet is the combination of two circular motions about separate centres. The planet moves on a circular epicycle, while the centre of the epicycle itself moves on the deferent circle, the centre of which is slightly displaced from the Earth. (This description holds for Venus, Mars, Jupiter and Saturn; the theory of Mercury is more complicated.) While Ptolemy certainly drew upon the work of his predecessors, his own contribution to planetary theory was a large one. For he introduced into the theory of the planets the fundamental new idea of the equant point: the centre of a planet's epicycle moved

uniformly, not as observed from the Earth, or even as observed from the centre of the planet's deferent circle, but rather as observed from a third centre, the equant point. Consequently, in Ptolemy's theory, true non-uniformity of motion was introduced in the celestial region. Ptolemy's discovery of the equant point represented the deepest insight into the nature of planetary motion until Kepler's law of areas. Now, for the first time in the history of Greek astronomy, it became possible to calculate accurate planet positions from a geometrical theory based on natural-philosophical principles. This was a huge step forward, for it represented a convergence of the two great lines of planetary astronomy: the geometrical-philosophical approach associated with Aristotle, Eudoxus, and Apollonius, and the numerical approach of the Babylonian scribes and the Greek astrologers.

In obtaining a planet's position from Ptolemy's theory, an astronomer could follow one of several different procedures, depending on the level of precision required and the amount of effort he was willing to invest. The most precise approach was a straightforward trigonometric calculation from the geometry of the theory. Since such calculations would have been extremely tedious, Ptolemy included in the *Almagest* astronomical tables that greatly facilitated calculation, at the expense of a slight reduction in precision.[42] The advantage offered by such tables is that the *trigonometry has already been done* by the compiler of the tables. The user need only take appropriate numbers from the tables and perform a series of additions and subtractions. Everywhere, from late Antiquity to the Renaissance, planetary tables based on the planetary theories of Ptolemy were an essential tool of the practising astronomer. Where there were tables, real astronomy was practised. Where tables were lacking, there were only dilettantes and dabblers. Tables (and the texts that explained them) were therefore a prominent part of the material culture of astronomy. Figure 18 is a photograph of a portion of the tables for Mars in a ninth-century Greek copy of the *Almagest*.

Planetary Equatoria

While tables do greatly simplify the calculation of planetary positions from theory, they still require careful attention on the part of the user. If one is content with errors of "calculation" on the order of a degree or two, one may simplify things still further by making a scale drawing (on paper, wood or brass) of the geometrical diagram that represents the theory. Such a physical device, which may require movable parts, is called an *equatorium*. With the aid of an equatorium, the user can find the position of the planet for any desired date in a matter of minutes.

Of all the celestial bodies that move along the zodiac, the Sun has the simplest motion. In the solar theory of Hipparchus and Ptolemy, which remained standard until the time of Kepler, the Sun travels at uniform speed on a circle that is slightly eccentric to the Earth. Figure 19 shows how the solar theory is realized in physical form in an astronomical manuscript dated A.D. 1407. This is a folio from a copy of the *Theorica planetarum* of Campanus of Novara. Campanus's work, composed in

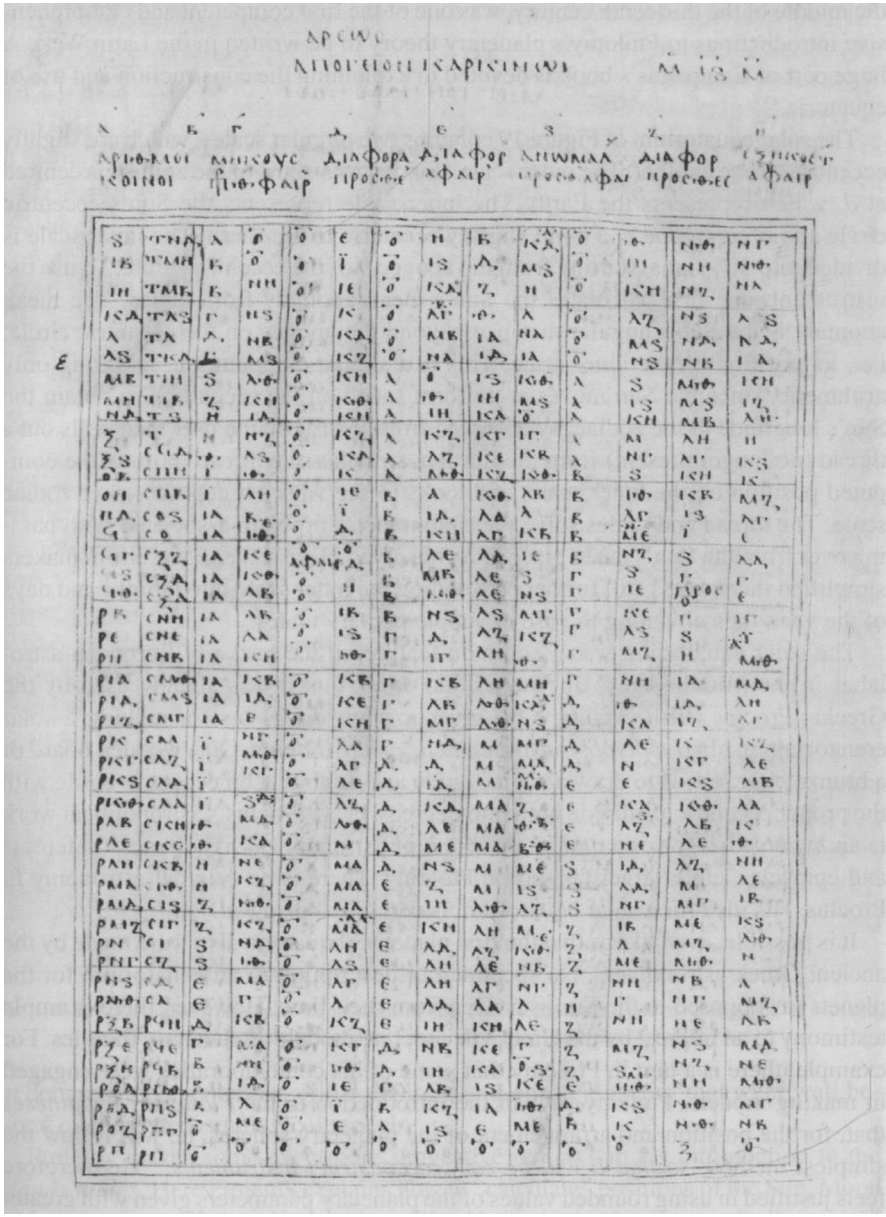


FIG. 18. The table of equations for Mars in a ninth-century parchment *Almagest*, one of the oldest surviving copies of Ptolemy's great work. The equations are the adjustments that must be applied to the planet's uniformly moving mean position to obtain its actual position. From Ptolemy's time until the Renaissance nearly all tables of equations were laid out in the same way. (Bibliothèque Nationale de France, Ms. grec 2389, fol. 310v.)

the middle of the thirteenth century, was one of the first competent and comprehensive introductions to Ptolemy's planetary theory to be written in the Latin West. A large part of Campanus's book is devoted to explaining the construction and use of equatoria.[43]

The solar equatorium of Figure 19 contains two circular scales, which are slightly eccentric to one another. The outer scale, divided into signs of the zodiac, is centred at *d*, which represents the Earth. The inner scale represents the Sun's eccentric circle and is centred at *c*, a point slightly eccentric to the Earth. The inner scale is divided into 30°-signs, starting from the apogee *b* of the eccentric circle. To use the instrument, one first calculates the Sun's mean anomaly from tables. The mean anomaly is the Sun's angular distance beyond the apogee on the eccentric circle; i.e., its position on the inner scale. This is a simple computation, requiring only arithmetic, since the Sun moves at uniform speed on the eccentric. To obtain the Sun's longitude in the zodiac, as observed from the Earth, the user then pulls out a thread (no longer present) from the Earth *d*, stretches the thread through the computed position on the inner scale, and looks to see where it cuts the outer zodiac scale. The thread and scales solve the trigonometry problem associated with passing over from the Sun's mean place to its observed place. Later equatorium makers simplified the process still further by dividing the inner scale into months and days of the year, thus obviating the use of supplementary tables.

The solar equatorium was a common feature on the backs of European astrolabes in the Middle Ages. But there is no doubt that it was already used by the Greeks. Proclus (fifth century A.D.) gives explicit directions for making a solar equatorium in his *Hypotyposis astronomicarum positionum*. On a wooden board or a bronze plate, one is to draw a zodiac circle and, within it, an eccentric circle with the proper eccentricity, divide both into degrees, etc.[44] Proclus's astronomical work is an *hypotyposis*, i.e., an *outline* or *sketch* of astronomical hypotheses (deferents and epicycles, etc.), largely based on Ptolemy. There is no original astronomy in Proclus. His idea for a solar equatorium is certainly borrowed.

It is possible, even likely, that the first planetary equatoria also were made by the ancient Greek astronomers. No specimen or description of an equatorium for the planets (as opposed to the Sun) survives from their time. However, there is ample testimony to an interest by the Greeks in concrete models of planetary theories. For example, there is a hint in Ptolemy that some of his contemporaries were engaged in making models. Ptolemy says in the introduction to his *Planetary hypotheses* that, for the position and arrangement of the planetary spheres, he will follow the simplest method, *so that it will be easy to construct instruments*.[45] He therefore feels justified in using rounded values of the planetary parameters given with greater precision in the *Almagest*. It is not clear whether the physical models he was thinking of were capable of quantitative results. Ptolemy's descriptions of his planetary theories in the *Planetary hypotheses* are certainly complete enough to guide quantitative work. In any case, Ptolemy's remark does tell us that someone was interested

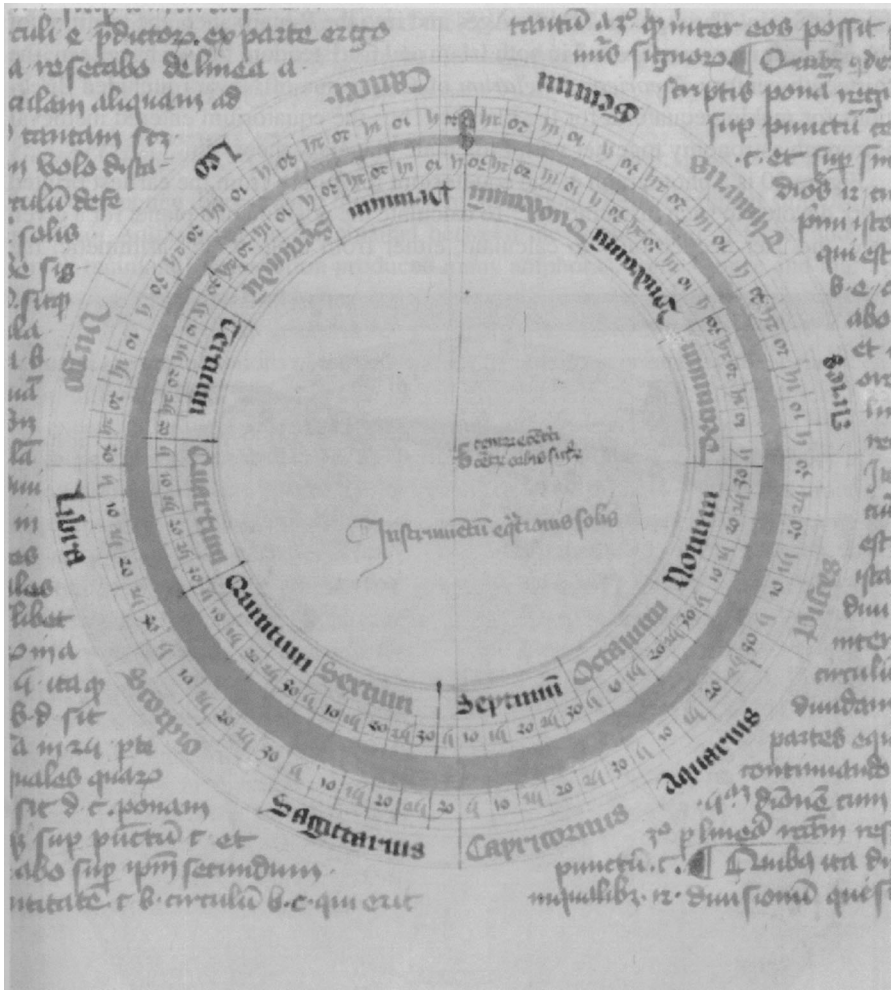


FIG. 19. A solar equatorium in a manuscript of the *Theorica planetarum* of Campanus of Novara. (Pepys Library, Magdalene College, Cambridge, Ms. Pepys 2329, fol. 56v.)

in concrete representations of the deferent-and-epicycle theory that went well beyond qualitative cosmological models.

Ptolemy makes some even more suggestive remarks in his introduction to the *Handy tables*. Here Ptolemy explains how to "calculate" positions of the Sun, Moon and planets according to the theories of the *Almagest, by drawing scale diagrams.*[46] It is only a short step further to make the diagrams reusable by adding moving parts.

The two earliest known treatises on planetary equatoria, both based on Ptolemaic planetary theory, were written by Ibn al-Samh and al-Zarqali in eleventh-century

Islamic Spain. Through the Middle Ages and into the Renaissance, the tradition of the equatorium was cultivated in both Islam and Christendom. As we have seen, the thirteenth-century *Theorica planetarum* of Companus of Novara included directions for making equatoria for the planets. Thus the equatorium entered medieval European astronomy together with Ptolemaic planetary theory.[47]

Figure 20 is a photograph of the equatorium for Saturn from the earliest printed work devoted to such instruments.[48] To calculate the position of a planet for a given date, the user needed only to calculate, either from tables or by arithmetic, the

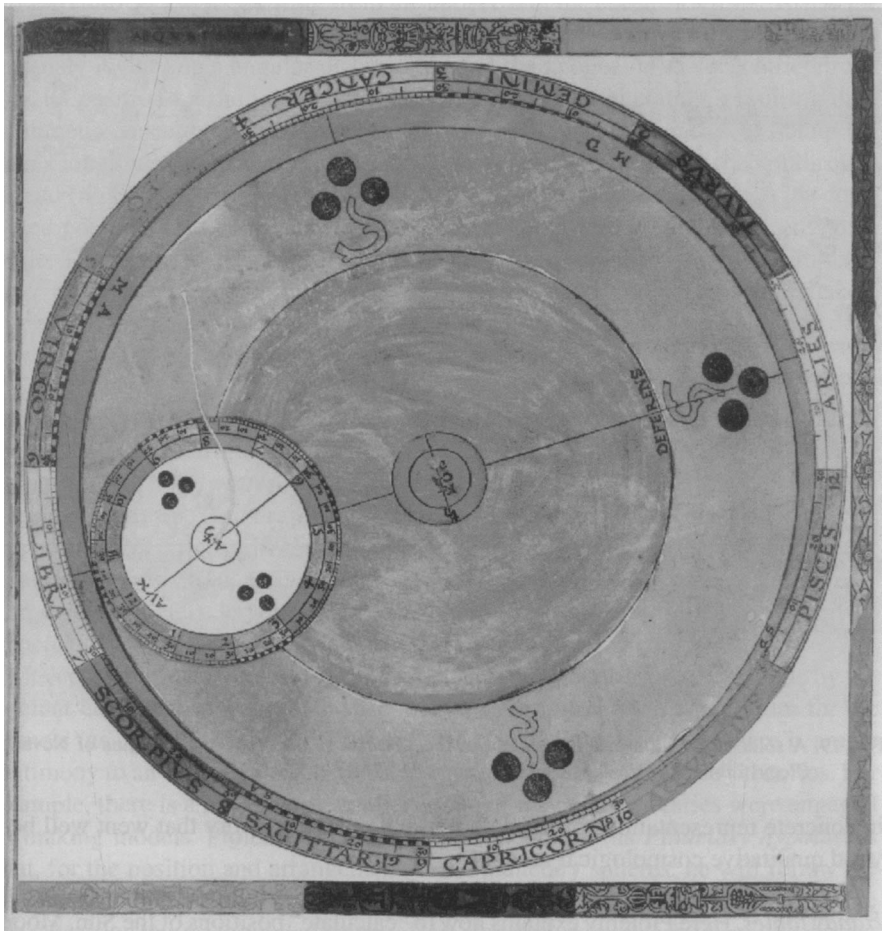


FIG. 20. The equatorium for Saturn in the oldest printed work devoted to such instruments. The equatorium consists of paper circles, called *volvelles*, that can be turned. Although the oldest known planetary equatoria are medieval, it is likely that similar instruments were made by the Greeks. From Johann Schöner, *Aequatorium astronomicum* (Bamberg, 1534), an unmodified reprinting of the edition of 1521. (British Library, Maps c.2.d.10, fol. A6.)

correct positions for the deferent and the epicycle disks, set the disks in the right places, then pull out a string from the Earth through the planet, and read off the planet's position against the zodiac scale.

Geared Calculating Mechanisms

In 1900, sponge divers found the wreck of an ancient Greek merchant ship off the island of Antikythera (in the channel between the western end of Crete and the Greek mainland). Excavation produced many amphoras, some bronze and marble statues, as well as the badly corroded remains of a geared calculating device, which contained at least thirty gear wheels. Its function seems to have been the representation of the mean motions of the Sun and the Moon, in accordance with the nineteen-year lunisolar cycle. The sophistication of the device, dated to the first century B.C., far exceeds that of any Greek text on the theory of geared mechanisms. In the case of gearwork mechanisms, then, the textual evidence alone would give a very mistaken notion of the level of technical sophistication actually reached in practice. After the discovery and interpretation of the Antikythera mechanism, it became far easier to credit Cicero's amazed (though vague) descriptions of Archimedes's astronomical mechanism. It seems likely that Archimedes's device was of this genre.

Figure 21 is a reconstruction of the gearing in the Antikythera mechanism.[49] The

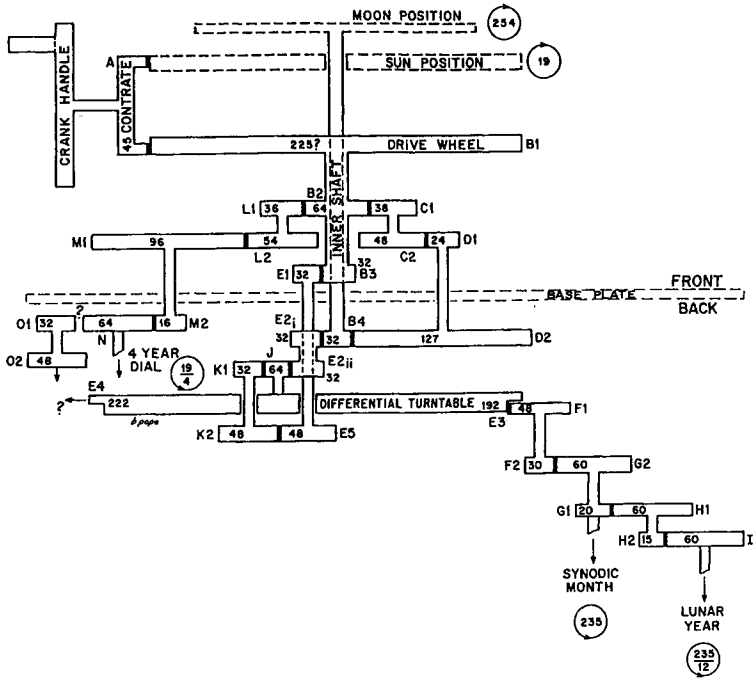


FIG. 21. Reconstruction of the gear train of the Antikythera mechanism. (From Price, *op. cit.* (ref. 49).)

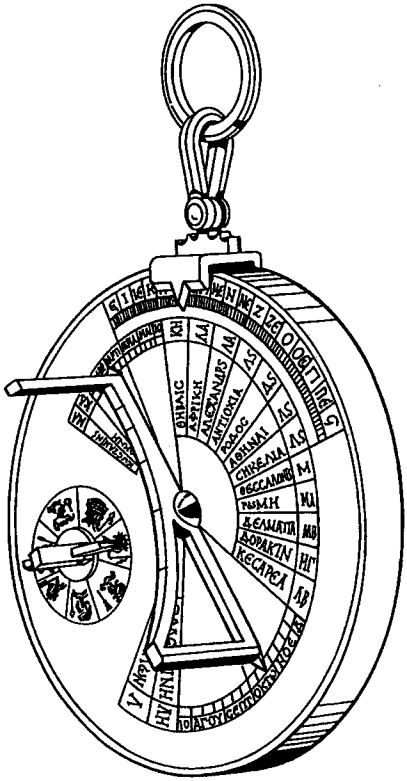


FIG. 22. Reconstruction of the front of a portable sundial and gear-work calculator from about A.D. 500. (From Field and Wright, *op. cit.* (ref. 50), by permission of Taylor & Francis.)

user turned the crank handle at the upper left of the diagram. A moving pointer (upper right) indicated the Sun's position in the zodiac, as well as the day of the Egyptian calendar. Similarly, a moving pointer indicated the Moon's position in the zodiac. Another display (lower right) indicated the phase of the Moon. Interestingly, the metal case of the mechanism was inscribed with a parapegma. The Antikythera mechanism was not an equatorium, in the strictest sense, because it was based only on mean motions, but it was clearly a very sophisticated device and it offered its user all the astronomical information likely to be needed in everyday life — all done by the turn of a dial.

Figures 22 and 23 show a reconstruction of a portable combination sundial and astronomical calculating device, which has been dated to about A.D. 500.[50] In Figure 24 we see extant portions of its gear train. In using the sundial, the user first adjusted the position of the suspension ring (at the top of Figure 22) for the latitude of his location. As a convenience, the device is inscribed with the names and latitudes of sixteen places, including Alexandria, Rome, Athens and Rhodes. Next, the

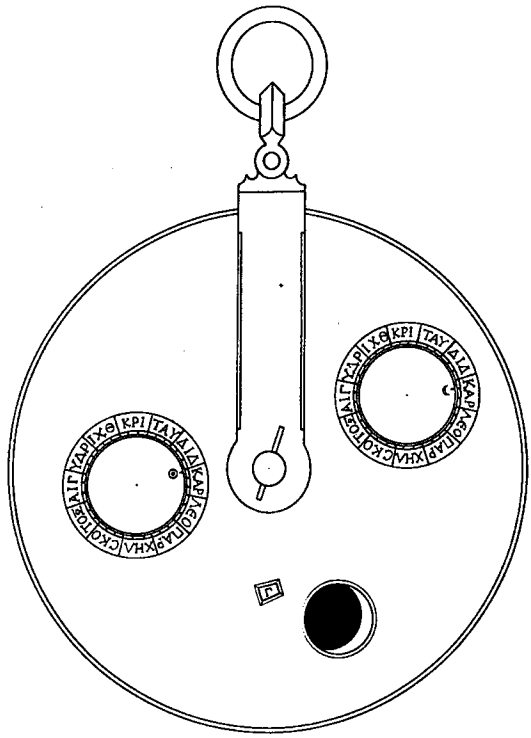


FIG. 23. Conjectural reconstruction of the back of the portable sundial-calculator. (From Field and Wright, *op. cit.* (ref. 50), by permission of Taylor & Francis.)

user turned the rotatable vane until it pointed to the correct month of the year. The vane includes a gnomon (the horizontal bar at the upper left) as well as a scale of hours (engraved on the curved part of the vane). To read the time, the user held the dial by the suspension ring and turned it until the shadow of the gnomon fell on the scale of hours.

The gearwork mechanism of this device was much simpler than that of the Antikythera mechanism. Nevertheless, it probably displayed the positions of the Sun and Moon in the zodiac, as well as the phase of the Moon. The Greek numerals 1–29 engraved around the perimeter of the extant gear showed through a window in the case to indicate the day of the month. This device is also remarkable for including the oldest known ratchet, visible in Figure 24. The user turned a dial (lower left of Figure 22) through one 'click' a day, and the ratchet prevented the user from turning the dial backwards. Surrounding the dial is a ring with seven divisions, engraved with the heads of the seven planetary gods; these, of course, represent the days of the week. This is one feature of the device that helps in dating it: the seven-day week became widely established about the beginning of the fourth century A.D.



FIG. 24. The portable sundial-calculator: the extant portion of the gear train. (Science & Society Picture Library, Science Museum, London.)

The display on the back of the device (conjecturally restored in Figure 23) indicated the positions of the Sun and Moon in the zodiac by means of pointers and the phase of the Moon by the fraction of a disk that was exposed to view.

4. INSTRUMENTS OF OBSERVATION

The Gnomon

In the early period (fifth century B.C.) the gnomon was the chief, and perhaps the only, instrument available for making observations of the Sun. The gnomon is simply a shadow-casting stick. Usually, it was set up vertically on level ground. The

determination of solstices was important for measuring the length of the year, as well as for connecting parapegmata to the civil calendars. Summer solstice occurred on the day of the shortest noon shadow; winter solstice, on the day of the longest noon shadow. At first, the astronomers were content to determine the solstices in just this way, to the nearest day only.

Of course, the solstices usually do not occur exactly at noon, but it is possible to interpolate between observations of noon shadows to obtain a more precise estimate of the moment of solstice. A summer solstice often cited by the ancients was observed at Athens by Meton and Euctemon in the archonship of Apseudes, on the 21st day of the Egyptian month of Phamenoth, *in the morning* (27 June 432 B.C.).[51] This time of day for the solstice, "in the morning", must have been the result of interpolation between noon observations made on several different days.

However, there are severe limitations on the precision of a solstice observed with a gnomon. Change in the Sun's declination is of course so slow around the solstices that the moment of greatest declination is very uncertain: for a week on either side of the solstice, the length of the noon shadow scarcely changes. In addition, the gnomon itself is subject to an uncertainty which renders it unsatisfactory as an instrument of precise observation: the edges of shadows are always indistinct, so a precise location of the shadow's tip is impossible. This fuzziness arises from the fact that the Sun is not a geometric point, but has an appreciable ($\frac{1}{2}°$) angular diameter.

Of all the instruments of observation used by the Greek astronomers, the gnomon was the simplest, and the only one that became widely diffused into the general culture. Long after the gnomon was abandoned as an instrument of observation by the Greek astronomers, it continued to play a role in two aspects of practical geography — in the definition of the geographical zones and in the specification of latitude.

The Greeks divided the surface of the Earth into zones, more or less as we do today. These zones were defined by the apparent behaviour of the Sun. For example, in the tropical zone (the belt on the Earth between the tropic of Cancer and the tropic of Capricorn), the Sun at noon can be either north or south of the zenith. Both Ptolemy and Strabo refer to this zone as *amphiskian* (*amphi*, both sides, + *skias*, shadow).[52] The zone between the tropic of Cancer and what we call the arctic circle is called *heteroskian*, because the noon shadow can only fall *one way*, to the north. Finally, in the frigid zone, north of our arctic circle, it is possible for the Sun to stay above the horizon for 24 hours at a time. On such days, the tip of the gnomon's shadow traces a closed curve (an ellipse) around the gnomon. The frigid zone is therefore called *periskian*, because the shadow goes all the way *around* the gnomon.

The gnomon was also used in everyday life to define the latitudes of places on the Earth. Today, we specify the latitude of a city by giving its angular distance from the equator, but the latitude is of course equal to the altitude of the celestial pole at that place. This latter method of specifying the latitude of a place was used by technical writers on astronomy and geography in Hellenistic times, although it

was uncommon in everyday life until about the second century A.D. The Byzantine sundial in Figure 22 makes use of this method.

Two other, equivalent, measures were frequently used. Perhaps the most popular was the length of the longest day. Thus, an ancient Greek would say that Rhodes is in the clime of $14\frac{1}{2}$ hours, because on summer solstice, the Sun there is above the horizon for $14\frac{1}{2}$ hours.

Yet another method was to give the length of the shadow cast by a vertical gnomon on the day of equinox. For example, in his *Natural history* Pliny informs us that in Egypt, on the day of equinox, the noon shadow is slightly more than half the length of the gnomon; at Rome, about 8/9 of the length of the gnomon; at Ancona 36/35 of the length of the gnomon; and so on.[53] The specification of latitude in terms of equinoctial shadows was of great help to the ancient geographers. Travellers' reports of shadow lengths helped them to sort out the details of the world map, for the measurement of shadows required no special training or instruments. One needed only to measure the noon shadow of any vertical object on the day that the Sun rose directly in the east. By contrast, the other two methods of measuring latitude required more specialized instruments — a water clock for the length of the solstitial day and a quadrant or dioptra for measuring the altitude of the pole.

A good example of the use of shadow lengths in a dispute among geographers is provided by Strabo in his analysis of the latitude of Britain. Strabo says that Hipparchus conjectured that the parallel through the mouth of the Borysthenes (Dnieper) is the same as the parallel through Britain, on the basis of the assumed fact that the parallel through Byzantium is the same as that through Massilia (Marseilles). "For Pytheas found the ratio of the gnomon to its shadow in Massilia and Hipparchus says he finds the same shadow, at the same time of year, in Byzantium."[54]

The Quadrant

Our best ancient source on instruments of observation is Ptolemy, who describes in the *Almagest* several instruments that he made or used himself. One of Ptolemy's simplest instruments was a quadrant (Figure 25), which he used to measure noon altitudes of the Sun. The quadrant, made from a block of wood or stone, is oriented with a smoothly dressed face in the plane of the meridian. Near one of the upper corners, a small cylindrical peg A is fixed at right angles to this face. The peg serves as the centre of the quarter circle CDE that is divided into degrees and, if possible, fractions of a degree. Below A is a second peg B, which serves as an aid in levelling the instrument. A plumb line is suspended from A, then splints are jammed under the block until the plumb line passes exactly over B. When, at noon, the Sun comes into the plane of the meridian, the shadow cast by peg A indicates the altitude of the Sun. Ptolemy does not say how large his quadrant was. Judging by the descriptions of other instruments by Pappus and Theon of Alexandria, Ptolemy's quadrant most likely had a radius of from one to two cubits (18 to 36 inches).[55]

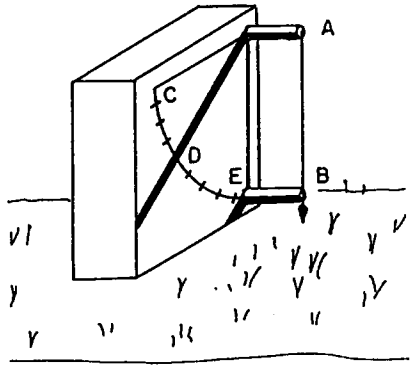


FIG. 25. Ptolemy's quadrant.

One advantage of the quadrant was that it reduced the uncertainty associated with the fuzziness of shadows. To be sure, the shadow of the cylindrical peg has a fuzzy edge. But in using the quadrant, the observer locates the *centre* of the shadow, rather than the edge. As the eye is able to spot the centre of a narrow line of shadow very accurately, the quadrant represented an important advance over the vertical gnomon.

The quadrant could be used to observe solstices and equinoxes. Solstices were, of course, the days on which the Sun's noon altitude was greatest (summer) or smallest (winter). At equinox, the noon altitude of the Sun was halfway between the noon altitudes of summer and winter solstice. (In observing either solstices or equinoxes, it might still be necessary to interpolate between noon observations made on successive days.) Carefully observed solstices and equinoxes were vital for determining several astronomical parameters: the length of the year, the obliquity of the ecliptic, and the lengths of the individual seasons.

The length of the year was determined most accurately by using solstices or equinoxes separated by many years. In Hipparchus's time there was still some suspicion that the length of the year might be variable. This suspicion resulted from the excessive faith placed by earlier astronomers in carelessly made observations. Hipparchus's careful analysis of many observations made by his predecessors and by himself showed that the supposed variation in the length of the year was no greater than the error of measurement in observing the moment of equinox or solstice. Hipparchus therefore took the length of the year to be constant and Ptolemy followed him in this.[56]

The difference between the Sun's noon altitudes at summer and at winter solstice fixes the angle between the tropic of Cancer and the tropic of Capricorn. Half this angle is equal to the obliquity of the ecliptic. As late as the second century A.D., some astronomers still believed that the Sun can wander a little north or south of the ecliptic. Theon of Smyrna, for example, says that the Sun can be as much as half a degree north or south of the ecliptic.[57] This mistaken notion probably originated

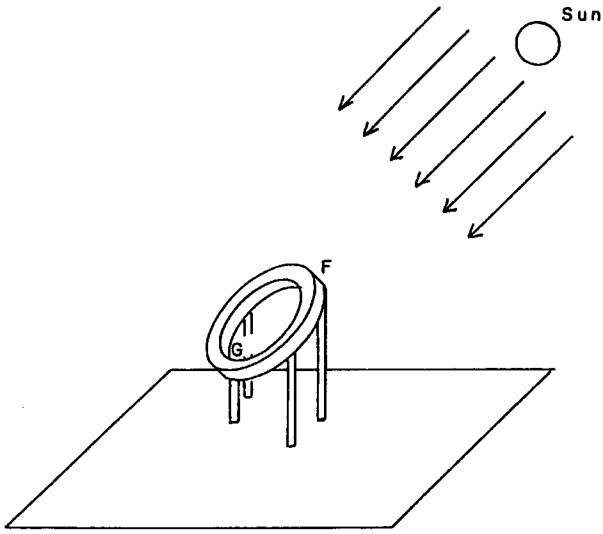


FIG. 26. An equatorial ring.

from the belief of earlier astronomers that they had observed the most northerly rising point of the Sun to vary a little from one year to the next, or from careless measurements of the Sun's noon altitudes on the solstices. The Greeks are often said to have ascribed too little importance to observation. But in the cases of the length of the year and the latitude of the Sun, we see that they often placed *too much* faith in poorly made observations. Ptolemy tells us that he measured the arc between the tropics a number of times.[58] No doubt he was not simply trying to establish an accurate value: he was also trying to convince himself that the older astronomers were wrong and that the arc between the tropics really is constant from one year to the next.

The lengths of the individual seasons were important for demonstrating the anomaly of the Sun's motion. The seasons are, of course, bounded by the equinoxes and solstices. The longest season (summer in our century, but spring in Antiquity) is about four days longer than the shortest (winter for us, autumn in Antiquity). Thus, the Sun appears to move a little more rapidly in some parts of the zodiac than in others. Hipparchus and Ptolemy used the lengths of the seasons to calculate the eccentricity of the Sun's orbital circle.[59]

The Equatorial Ring

A second, specialized instrument was available for the determination of the equinoxes: the *equatorial ring*. This consisted of a large metal ring (perhaps two cubits in diameter) placed in the plane of the equator (see Figure 26). The operation of this

instrument is illustrated in Figure 27. During the spring and summer, the Sun is north of the celestial equator. Its daily motion carries it in a circle parallel to the equator and to the equatorial ring. Consequently, the Sun shines all day on the top face of the ring and never on the bottom face. Contrariwise, in the autumn and winter, the Sun is below the equator, and shines all day on the bottom face of the ring. Only at the moment of equinox does the Sun come into the plane of the equator. At this moment, the shadow of the upper part of the ring (marked *F* in Figure 26) will fall upon the lower part (*G*) of the ring. Since the Sun has some angular size, the shadow of *F* will actually be a little thinner than the ring itself. Thus, at the moment of equinox, the shadow of the upper part of the ring will not quite cover the

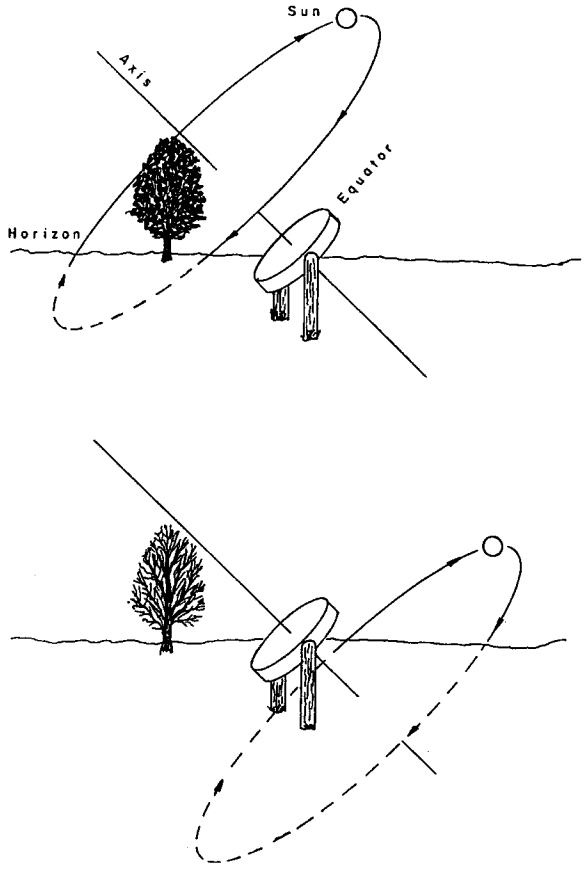


FIG. 27. Operation of an equatorial ring. On any day, the Sun's path through the sky is a circle parallel to the celestial equator. In spring or summer (top) the Sun's day circle is north of the equator. In autumn or winter (bottom), the Sun's day circle is south of the equator.

whole width of the lower part. The equinox is therefore indicated when the shadow falls centrally upon the lower part of the ring, leaving narrow illuminated strips of equal widths above and below the shadow. The accuracy attainable with the equatorial ring depends upon the precision with which it is placed in the plane of the celestial equator. As Ptolemy points out, if the ring is tilted out of the correct plane by only one-tenth of a degree, this can produce an error in the measured time of equinox of about a quarter of a day.[60]

Ptolemy does not say how the equatorial rings were adjusted, but the procedure may have been as follows. An approximately correct alignment could be obtained by facing the ring along an established meridian line. The tilt of the ring could be adjusted by use of a plumb line: the angle between the equatorial ring and the vertical should equal the latitude of the place of observation. Once the orientation of the ring was roughly correct, the need for fine adjustments could be determined by observations of the stars. For this purpose one would use bright stars lying near the equator, as for example the shoulders of Orion. Placing one's eye at the edge of the equatorial ring, one would sight a star and note its apparent distance above the opposite rim of the ring. Since the diurnal revolution carries all the stars in circles parallel to the equator, the stars will appear to remain at the same distances above an accurately aligned equatorial ring. If, in the course of the night, the star appeared to draw closer to, or move farther away from, the rim of the ring, this would indicate the necessary correction to the ring's orientation.

The advantage of the equatorial ring is that it can indicate the actual moment of equinox: one need not restrict oneself to observations taken at noon. A disadvantage of the equatorial ring is the difficulty of attaining and maintaining an accurate orientation. Indeed, Ptolemy notes that one of the large rings fixed to the pavement in the palestra of Alexandria had shifted imperceptibly, with the result that it suffered a shift in lighting *twice at the same equinox*. That is, according to the ring, the equinox occurred twice, at times few hours apart. Ptolemy seems for this reason to have mistrusted the equatorial ring and to have preferred the meridian quadrant, an instrument that is easier to align. But earlier astronomers, perhaps including Hipparchus, took at least some of their equinoxes by means of the equatorial ring.

It is possible that the double equinox indicated on the ring at Alexandria was produced just as Ptolemy surmised, by a misalignment of the ring. But there are two other causes that could have produced the same effect. First, the ring might have been warped. Second, false equinoxes can be produced by atmospheric refraction.[61] Refraction is of course appreciable only for objects quite near the horizon. When the Sun appears to be on the horizon, it is actually below the horizon by more than half a degree, but at an altitude of 15°, refraction amounts to only 3′. The meridian quadrant is again superior to the equatorial ring because the former permits observations only at noon, when the Sun is highest and refraction is least. When he wrote the *Almagest*, Ptolemy did not fully understand the effects of atmospheric refraction, but he could not help noticing that the meridian quadrant gave more satisfactory results than did the equatorial ring.[62]

The Armillary Sphere

The armillary sphere was the chief instrument used by Ptolemy for measuring the positions of celestial objects. Ptolemy calls this instrument an *astrolabon*, i.e., an instrument for "taking stars". Some modern writers call it the "spherical astrolabe", but it should not be confused with the (planispheric) astrolabe of medieval and Renaissance astronomy discussed above.

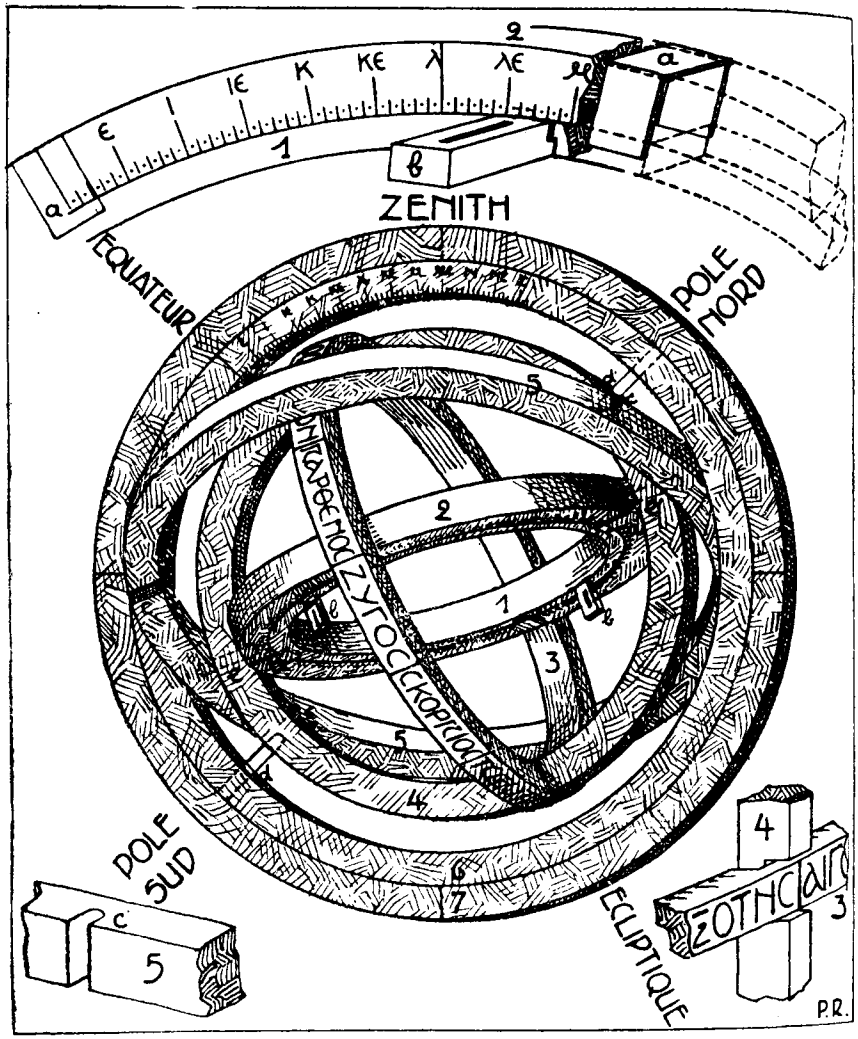


FIG. 28. Ptolemy's armillary sphere as reconstructed by P. Rome. The use of such instruments is perhaps the most sophisticated part of *meteoroscopy*. (From A. Rome, *op. cit.* (ref. 4), photograph courtesy of the University of Cincinatti Library.)

In *Almagest* V, 1, Ptolemy describes the armillary sphere that he constructed and used. Figure 28 is a modern reconstruction based on Ptolemy's description. The fixed Ring 7 is placed in the plane of the meridian. Ring 6 is turned within Ring 7 to adjust the instrument for the geographical latitude: axis *dd* must make an angle with the horizontal that is equal to the latitude. The inner nest of rings (1, 2, 3, 4, 5) may be turned as a unit about axis *dd*, thus simulating the diurnal revolution. Ring 1, equipped with sights, turns within Ring 2 and is used for measuring the latitudes of the stars. Rings 2 and 5 may be turned independently of one another about ecliptic axis *ee*, which pierces the solstitial colure (Ring 4). Ring 4 is rigidly attached to the ecliptic Ring 3. Rings 3, 2 and 5 are used in measuring the longitudes of the stars.

The great advantage of the armillary sphere was that it permitted direct measurements of celestial longitudes and latitudes (ecliptic coordinates). Suppose that the longitude of one reference object is known. This could be a star, whose longitude was previously measured. Or it could be the Sun, whose longitude can be calculated theoretically from tables. To take a specific example, let us suppose that the reference object is a star. Then it is possible to measure the ecliptic coordinates of any other star in the following way. After the armillary sphere is properly set up and adjusted for latitude, one must turn the inner nest of rings (1, 2, 3, 4, 5) about axis *dd* until the ecliptic ring of the instrument coincides with the real ecliptic. To achieve this alignment, one checks that the reference star is sighted at its proper longitude along ecliptic Ring 3. To do this, one turns Ring 5 on ecliptic axis *ee* until the ring is set at the known longitude of the reference star along ecliptic Ring 3. One then turns the whole inner nest (1, 2, 3, 4, 5) of spheres about the polar axis *dd* until the reference star appears to graze both the near and the far limb of Ring 5. The armillary sphere is then, in principle, aligned in the same way as the real celestial sphere.

To sight a secondary star, one turns Ring 2 on axis *ee* until the secondary star appears to graze that ring at both the near and the far limb. The longitude of the secondary star can then be read off on Ring 3. To measure the latitude of the secondary star, one sights it through the pinnules *bb* mounted on Ring 1, which is free to turn within the graduated Ring 2.

The armillary sphere was Ptolemy's preferred instrument for measuring the positions of stars and planets. Ptolemy's star catalogue, which gave the longitudes and latitudes of more than 1,000 stars, was compiled with the aid of the armillary sphere. This catalogue probably contained a mixture of Ptolemy's own measurements of star places and adaptations of star places measured by Hipparchus. The relative amounts of original and borrowed data have been the subject of lively controversy. As we have seen, Ptolemy describes his own armillary sphere; whether Hipparchus had also used an armillary sphere is uncertain but not implausible.[63] Although medieval astronomers sometimes made measurements of star places, no new star catalogue of a scope comparable to Ptolemy's was compiled until the fifteenth century, when the astronomers at Samarkand made a new one under the patronage of Ulugh Beg. Their principal instrument was also the armillary sphere.[64]

The first star catalogue of comparable scope to be compiled in the Latin West was that of Tycho Brahe (late sixteenth century). Ptolemy's armillary sphere is a complicated instrument, difficult to manufacture and align, and cumbersome to use. Tycho was noteworthy for the great care he took in the design and manufacture of his armillary instruments. He redesigned them for simplicity, by reducing the number of rings. He also thought carefully about the importance of symmetry and adequate support, to minimize distortions of the rings due to flexure under their own weight. Tycho's armillary instruments were larger than Ptolemy's and were perhaps the best instruments of this class ever made. Tycho also supplemented his armillary instruments with new ones unknown to Ptolemy. Nevertheless, he was clearly working in the same tradition. Ptolemy's instruments of observation defined the activities of the observational astronomer for more than a thousand years.[65]

The Dioptra

Originally the dioptra was a simple sighting tube (or a stick equipped with two sights) clamped to some sort of stand. The word simply means *something through which one looks*. The dioptra could be aimed at a star, as a way of pointing out a particular star to a student, and it could also be used to demonstrate the rotation of the celestial sphere.

Euclid (early third century B.C.), best known for his geometry, also wrote a short and elementary work on the celestial sphere, called *Phenomena*. In the first proposition, Euclid makes use of a dioptra to prove that the Earth is at the centre of the cosmos. He instructs us to aim a dioptra at Cancer when it is rising above the horizon. Then we are told that if we turn around and look through the other end of the dioptra, we will see Capricornus setting at the diametrically opposite part of the horizon. This proves that the Earth lies on a diameter of the celestial sphere drawn through Cancer and Capricornus. We can repeat the procedure with another pair of diametrically opposed signs; and since the Earth lies at the intersection of two diameters of the celestial sphere, it must be at the centre of the sphere.[66]

Of course, no one ever became convinced of the centrality of the Earth by carrying out such observations; Euclid's argument is a pedagogical demonstration rather than a true appeal to observational evidence. Such conventional demonstrations can have a long life: Copernicus, some 1,800 years later, used the same 'observations' to prove that the Earth is as a point in comparison with the celestial sphere.[67]

Geminus, in his *Introduction to the phenomena*, mentions the use of a dioptra to prove that the heavens revolve as a spherical unit. Geminus says that "all the stars observed through the dioptras are seen to be making a circular motion through the whole rotation of the dioptras".[68] This seems to imply an instrument more or less equivalent to that sketched in Figure 29. Sight *AB* can be aimed at the celestial pole and clamped. Sight *CD* is aimed at star *S* and clamped to *AB*. As the night goes by, *S* will move out of the sight *CD*, but the star can be recovered in the sights by rotating the instrument about axis *AB*.

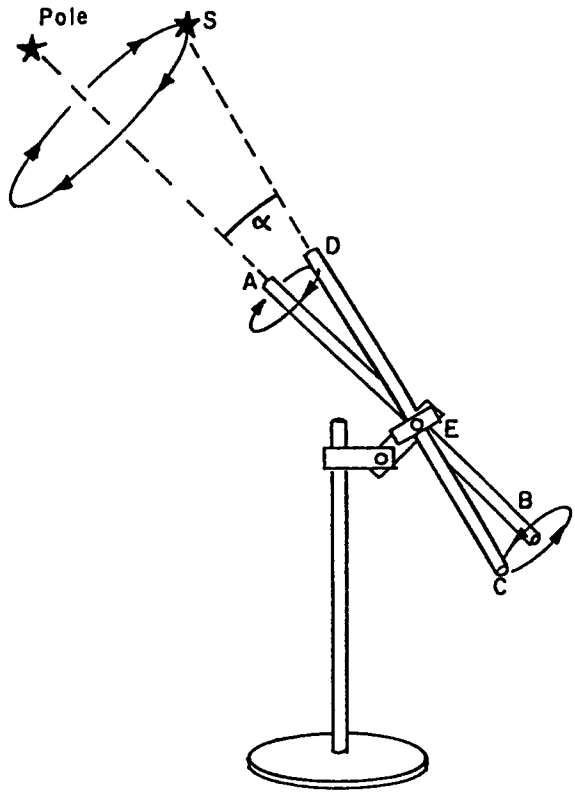


FIG. 29. Conjectural reconstruction of a dioptra mentioned by Geminus for demonstrating the circular motion of the stars.

The term *dioptra* was applied, not only to simple teaching tools, but also to a generalized surveying instrument, analogous to the modern theodolite. If the sights of the dioptra are fitted with protractors, the instrument becomes a device for measuring angles — for example, the angular heights of buildings or of mountains. We know that Dicaearchus of Messene (a student of Aristotle) wrote a work on the measurement of mountains,[69] and in all likelihood this involved the use of some sort of dioptra. Moreover, such an instrument is described in detail by Hero of Alexandria (first century A.D.) in his book, *Dioptra*.[70]

Yet another variety of dioptra was devised for measuring relatively small angles, notably the angular diameters of the Sun and Moon. Some of Ptolemy's predecessors had tried to determine these angular diameters by using water clocks to measure the times they required to cross the horizon when they were on the celestial equator. Ptolemy rightly rejected these methods as prone to error, and attempted to measure the angular diameters with a kind of dioptra. Ptolemy mentions this

instrument and says that Hipparchus used one before him.[71] But even before Hipparchus, Archimedes had described a similar instrument in his *Sand reckoner.*[72] A fuller description of the same sort of instrument is given by Pappus of Alexandria in his *Commentary* on Book V of the *Almagest.*[73] Figure 30 is based on Archimedes and Pappus. Rod *R* has a groove that runs its whole length (in Ptolemy's instrument, *R* was 4 cubits long). A cylinder or prism *C* is fixed to a small block that slides freely in the groove. Plate *P*, fixed to the end of the rod, has a small hole *H*. The observer aims the dioptra at the Sun or Moon and looks through the hole *H* with one eye. The position of *C* is adjusted until the Sun or Moon is exactly covered. From the diameter of *C* and the distance between *P* and *C* one may work out the angular diameter of the object sighted. Ptolemy mentions that, although he felt safe in *comparing* the sizes of the Sun and Moon this way, the absolute measurements seemed very doubtful, since there was a considerable uncertainty in the position of *C* required to produce perfect covering. Ptolemy therefore supplemented his dioptra measurements of the angular diameters by other, less direct, methods based on lunar eclipses.

Ptolemy's Instrument for Zenith Distances

Ptolemy describes an instrument he built expressly for measuring zenith distances (see Figure 31).[74] Ptolemy calls this a parallactic instrument, because he designed it for use in determining the parallax of the Moon. His plan was to measure the Moon's zenith distance when it was simultaneously near the summer solstitial point and either the northern or southern limit of its orbit. Since, in Alexandria, the summer solstitial point passes nearly vertically overhead, the parallax in these situations could be neglected. Thus Ptolemy found that the Moon's maximum latitude away from the ecliptic was 5°. Ptolemy then used the same instrument to measure the Moon's zenith distance when it was near the winter solstitial point, where the Moon is lower in the sky and the parallax is therefore great. In the Middle Ages, this

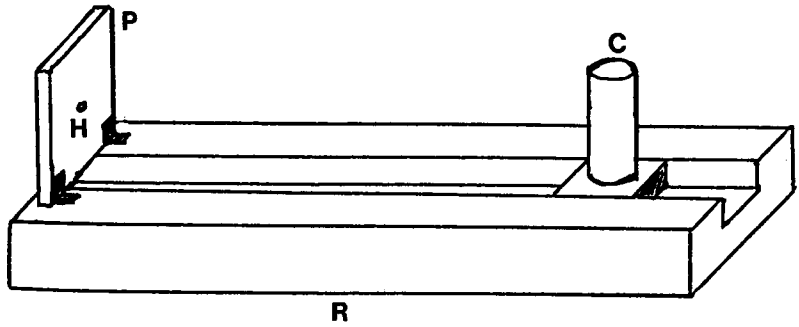


FIG. 30. A dioptra for measuring the angular size of the Sun or Moon. This instrument belongs to the art of *dioptrics*. The length-to-width ratio has been greatly reduced for convenience of illustration.

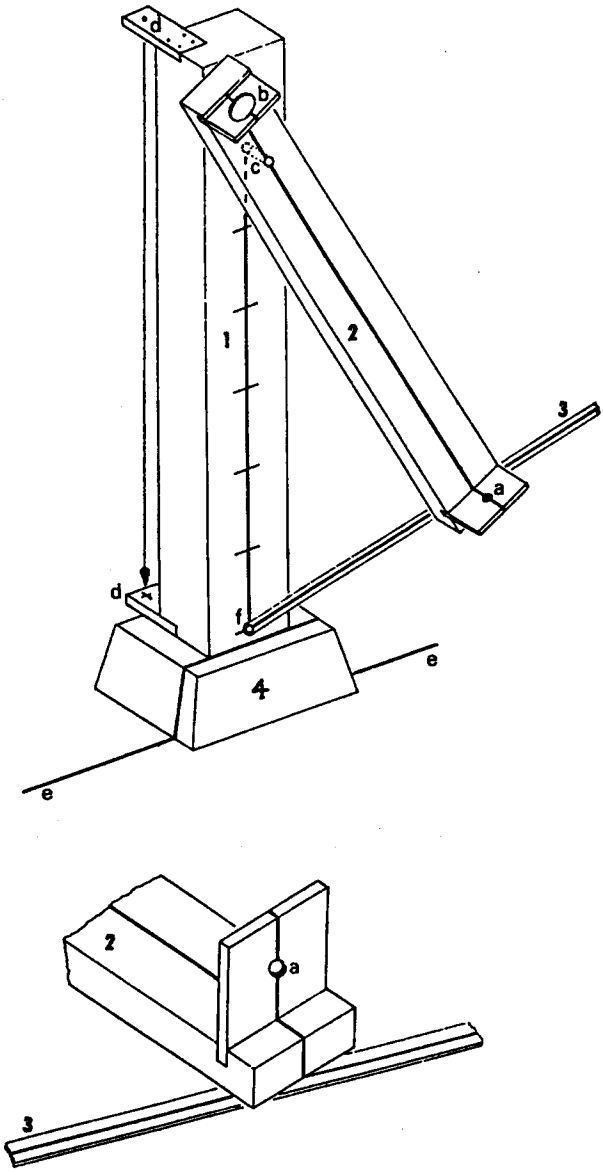


FIG. 31. Ptolemy's instrument for measuring zenith distances. (From Toomer, *op. cit.* (ref. 9).)

instrument was called the 'triquetrum', because of its form. Modern writers often use the terms 'parallactic rulers' or 'Ptolemy's rulers'.

In Figure 31, post 1 is set up vertically with its face along the meridian *ee*. The

instrument is levelled with the aid of plumb line *dd*. Plate 2 pivots about peg *c*, inserted into post 1. A thin rod 3 pivots about peg *f*. Rod 3 also passes behind sight *a* on plate 2. The celestial object is viewed through the sights at *a* and *b*, and the zenith distance of the object is the angle between 1 and 2.

How is the angle measured? Ptolemy says that line *cf* on the main post is divided into 60 parts, then subdivided into smaller parts. Further, distance *ca* on plate 2 is equal to *cf*. When the observer sights the Moon, he marks on rod 3 the position of sight *a*. Once this is done, he swings rod 3 up vertically so that it lies along scale *cf*. In this way he can measure distance *fa* in terms of the units marked on the vertical post. Finding angle *fca* (the Moon's zenith distance) then reduces to a simple trigonometrical problem, easily solved with the aid of Ptolemy's table of chords.

* * *

The astronomical objects that we have discussed were not all equally common. Sundials were many and parapegmata must also have been common. They were set up outdoors as display pieces, and must have been known to residents of even middling towns. Globes were used in teaching and were widely known beyond the educational setting through their occurrence on coins and in painting and sculpture. But among the instruments of observation, probably only the gnomon was widely known to the general public. The more specialized instruments of observation and the astronomical calculating machines must have been very rare.

In general, the Greek astronomers provide much less detail about their instruments and their methods of making observations than we might wish. This is, of course, almost universally the situation in the history of technique and technology. Even Ptolemy, who tells us the most, is sometimes disappointingly vague. It is also clear that many of his descriptions of observational practice represent idealizations, rather than literally accurate accounts of what he actually did. And the writers of late Antiquity who provide some extra details about Ptolemy's instruments (Pappus, Theon of Alexandria, and Proclus) may have had less experience in handling them than they would like us to believe. We cannot here undertake an analysis of the relation between theory and observation, or between instruments and practice, in Greek astronomy. These relationships were certainly complex, and evolved as Greek astronomy itself evolved. Early Greek astronomers were capable of simply assuming a value and using it as if it were the result of observation. A notable example is Aristarchus's use of 2° for the angular diameter of the Moon. Later Greek astronomers might adopt a parameter that was in circulation but also produce observations that confirmed it. A possible example of this is Hipparchus's use of 187 days for the length of spring + summer, a figure that was used in Callippus's parapegma, as well as his use of $94\frac{1}{2}$ days for the length of spring, a figure that is in fine agreement with the Babylonian solar theory of System A. But the clearest example of theory directing observation is to be seen in Ptolemy's equinoxes and solstice, which contain large errors but which are in excellent accord with

Hipparchus's values for the lengths of the year and of the seasons. This does not mean, of course, that observations of some kind were not actually made or that instruments were not used. But it should remind us that one reason for the invocation of instruments — then, as now — was to invest an astronomical discussion with authority. As we have seen, even elementary writers, such as Euclid in his *Phenomena* and Geminus in his *Introduction to the phenomena*, were aware of the credibility lent to a demonstration by the invocation of a dioptra.

5. SIGNS AND SYMBOLS

Astronomy had a far more important place in classical civilization than it has in our culture. Because astronomy was one of the canonical branches of higher learning, most Greeks who were privileged enough to have some education beyond the elementary level received an introduction to astronomy. Greek astronomy had practical applications in telling time — the time of year and of the month, as well as the time of day. Astronomy also had important links to philosophy and religion and served as the technical foundation for astrology, through which it acquired political significance. Finally, astronomy often provided inspiration and subject matter for the arts.

For all of these reasons, the material culture of Greek astronomy was rich and complex. So far, we have focused on objects that performed some astronomical function. Thus we have concentrated on the traditional categories of *sphairopoïïa*, dioptrics and gnomonics, as well as on the accoutrements of the calculating astronomer, such as planetary tables. Up till now, the survey has been reasonably comprehensive.

A similarly comprehensive account of astronomical motifs in their roles as signs and symbols would require a whole treatise. Leaving this field wholly out of account would, however, give the reader an incomplete impression of the material culture of Greek astronomy. In the final section of this review, then, we make no attempt to be exhaustive, but wish merely to indicate some of the more pervasive sources of astronomical images, as well as to point out a number of unusual items with which many readers may not be familiar.

Astronomical Stelae

Among the prefatory matter of several medieval copies of the *Almagest* is a short text that appears to be a copy of an inscription that Ptolemy had engraved on a stele and set up at Canobus. This text begins:

> As on the stele in Canobus: To the Saviour God, Claudius Ptolemaeus [dedicated] the elements and hypotheses of astronomy.... Erected in Canobus in the 10th year of Antoninus.[75]

The main content of the inscription is a list of parameters of the planetary theory — tropical and synodic periods, radii of epicycles, eccentricities, etc. Most writers have supposed that this inscription was based on the *Almagest*, and thus composed by Ptolemy after he had completed his masterwork, or else fabricated by some unknown writer of late Antiquity. Those who do not accept the authenticity of the Canobic inscription point to a few places where its parameters differ from those of the *Almagest*. However, Hamilton, Swerdlow and Toomer have argued that the Canobic inscription was an early work of Ptolemy's, composed, inscribed and dedicated before he had written the *Almagest*.[76] The departures of the parameters in the Canobic inscription from those in the *Almagest* are then explained by the fact that Ptolemy had not yet put his planetary theory into final form.

There is nothing extraordinary in a Greek astronomer inscribing a set of planetary parameters on stone and setting this up for public display. Indeed, one such inscription has actually been found. This is the so-called Keskinto inscription, found in 1893 at Keskinto, near Lindos, at the southern end of Rhodes. The inscription, dating from around 100 B.C., includes numerical values of planetary parameters and ends with an expression of thanksgiving to the gods. Another example of a public display of an astronomical system is an "astronomy of Eudoxus" which was written on whitened boards and contributed to the temple of Good Fortune at Delos. This no longer exists, but it is mentioned in the extant inventories (second century B.C.) of the temple. These public displays of the data of astronomical systems also have parallels in the history of philosophy. In the second century A.D., Diogenes of Oenoanda (in Lycia) erected a huge inscription of the tenets of Epicureanism.[77] Thus it is by no means implausible that the Canobic inscription is a genuine work of Ptolemy's.

What were Ptolemy's reasons for causing a stele to be engraved with astronomical parameters? The dedication to the Saviour God is consistent with the religious element that was sometimes present in Ptolemy's meditations on astronomy.[78] The stele may therefore have been intended as an expression of gratitude to the god who had helped him find the right way in astronomy. It may also have been intended to inspire due reverence in the passers-by who contemplated it. And, of course, it was Ptolemy's way of announcing his own success to a broader public. After all, if he had intended it merely as an act of private devotion, there would have been no need to include his own name in the inscription. Finally, the stele included an aesthetic aspect, for it represented a mathematical *tour-de-force*. Psychologically, Ptolemy's stele is related to the public display of sundials, globes and mechanical contrivances. The stele of planetary parameters, was, in part, a celebration of the achievements of the human mind.

Who was Ptolemy's Saviour God? There were, of course, many saviour gods in late Antiquity. But for Greek Egypt in Ptolemy's time, the most important was Sarapis. There was, moreover, a famous temple of Sarapis in Canobus.[79] Ptolemy's dedication of a stele to a Saviour god reveals a more ordinary, and less severely intellectual, strain in his religious feeling than one would infer from the references in the *Almagest* to the impersonal god of Aristotle.

Horoscopes

Material manifestations of astrology became increasingly common from the first century B.C. onward. While horoscopic astrology was certainly of Babylonian origin, as, indeed, many Greek and Roman writers claimed,[80] it was elaborated into a complex system by the Greeks in Egypt during the Hellenistic and Roman periods.[81] Greeks of the second century B.C. were probably practising horoscopic astrology with many of the features that came to characterize the art in its mature form. Interest in astrology grew rapidly in the first century B.C., as attested by many references to astrology in the Greek and Roman literature of this period. We have also nearly two hundred Greek and Roman horoscopes in the astrological writers, as well as in the papyri. The oldest extant Greek horoscopes are for the first century B.C. but the great bulk of them come from the first five centuries of our own era.

The oldest known Greek horoscope is a relief sculpture discovered in the Taurus range, on the summit of Nemrut Dag, 7,000 feet above sea level.[82] Here Antiochus I of Commagene built his tomb, and festooned it with enormous statues and Greek inscriptions about the cult of Antiochus himself, his parents and his favourite gods. The relief sculpture shown in Figure 32 depicts a crescent Moon in the constellation of the Lion, together with three planets, whose names are engraved in Greek:

ΠΥΡΟΕΙΣ ΗΡΑΚΛ[ΕΟΥΣ]
ΣΤΙΛΒΩΝ ΑΠΟΛΛΩΝΟΣ
ΦΑΕΘΩΝ ΔΙΟΣ.

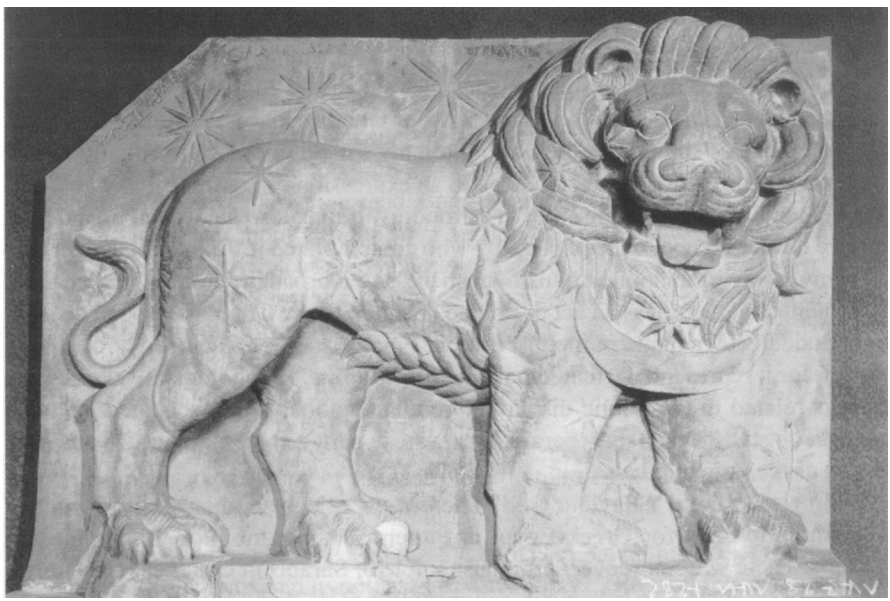


FIG. 32. The coronation horoscope of Antiochus I of Commagene at Nemrut Dag. (Photograph courtesy of Vorderasiatisches Museum, Berlin.)

Πυρόεις, Στίλβων and Φαέθων are the 'scientific' Greek names for the planets Mars, Mercury and Jupiter. Here they are associated with Heracles, Apollo and Zeus. The figure of the Lion shows nineteen stars more or less properly placed in the constellation. (This is the same as the number of stars attributed to Leo in the *Catasterisms* of Eratosthenes.) The conjunction of three planets and the Moon in Leo allowed Neugebauer and Van Hoesen to date this monument to 7 July 62 B.C. They surmised that it was intended to commemorate Roman recognition of Antiochus's reign over Commagene. This relief sculpture is spectacular evidence of Greek interest in Babylonian astrology by the first century B.C. However, it does not exhibit quite all the elements of the later Greek horoscopes. For example, there is no indication of the ascendant, or *horoscopos* (the rising point of the zodiac). In its simple statement of the locations of the Moon and planets, this horoscope resembles, in spirit, the Babylonian prototypes. Considering the provenance and early date of the monument, this is hardly surprising.

Most of the ancient Greek horoscopes that have come down to us are examples that are discussed in astrological treatises.[83] However, we do have a smaller number of Greek horoscopes preserved on papyrus. Usually, they are simply written out in words. But one of these, computed for a birth in the range A.D. 15–22, also bears an illustrative diagram (see Figure 33). This figure is not in the rectangular form that became canonical in the Middle Ages, but it has many of the essential attributes. The places of the planets in the zodiac are clearly indicated as are the horoscopic point, the midheaven (the point of the zodiac that was culminating), and the under-Earth (the point of the zodiac on the meridian below the ground).



FIG. 33. Modern sketch of a diagram in a papyrus horoscope for a birth some time during the period A.D. 15–22. Three of the four "centres" are labelled around the outside of the figure. Clockwise from the bottom are the under-Earth, the horoscope, and the midheaven. The twelve signs of the zodiac are written inside the circle, with Taurus just above the horoscopic point. The positions of the Moon, the Sun, Mars, Mercury and Saturn are also indicated. Sketch by Neugebauer and Van Hoesen, *op. cit.* (ref. 81), after the diagram in P. Oxy 235.

An Astrologer's Board

The literary horoscopes (i.e., those included in extended treatises) often provide detailed interpretation. By contrast, the horoscopes found on papyrus usually offer no interpretation but limit themselves to bare statement of the astronomical facts, namely, the positions of the Sun, Moon, planets, and horoscopic point. Many of the papyrus horoscopes may well be rough notes made by professional astrologers. If this is so, it is easy to understand why there is rarely any written interpretation: the astrologer interpreted the horoscope orally to his client. One papyrus provides some evidence that this was indeed the case, by mentioning a special board, apparently to be used by an astrologer in consultation with his clients. The astrologer lays out on the board special markers to represent the Sun, Moon and planets. The Sun is to be of gold, the Moon of silver, Saturn of obsidian, Mars of yellow-green onyx, Venus of lapis-lazuli streaked with gold, Mercury of turquoise. Jupiter should be of a dark blue stone, but underneath of crystal.[84] This writer is clearly making a connection between the planets and the magic properties of stones. Probably, we should imagine the board as a circular diagram divided into zodiac signs (like Figure 33). After computing the positions of the planets from tables, the astrologer placed the planet markers on the board in the appropriate signs. Probably he also used a table of ascensions to calculate the positions of the "centres" — especially the horoscopic point and the midheaven. These might then also be indicated on the board by markers. No such astrologer's board is extant, but we do have a number of small gem stones engraved with astrological symbols and magical incantations.[85] There is therefore every reason to suppose that the writer of our papyrus is describing a real object.

Images of the Constellations and Zodiac Symbolism

This brings us naturally to images of the constellations and zodiac symbolism — a vast field of iconography. Here we will restrict ourselves to a few items that provide testimony about the cross-cultural transmission of astronomy and astrology, about the connections of astrology to medicine and to religion, and about the political uses of astrological symbolism.

The Greeks must have drawn figures of the constellations from the very beginning, for in the *Iliad*, Hephaistos makes a shield for Achilles and decorates it with images of the constellations.[86] The most ancient constellation and star names among the Greeks include the Bear, the Pleiades, Arcturus, Orion and Sirius, which are mentioned by Homer and Hesiod. But it is unlikely that the sphere was filled with a complete set of constellations before the fifth century B.C. A significant step in the process was the adoption of the Babylonian zodiac by the Greek makers of parapegmata. Eudoxus's *Phenomena* (fourth century) and its verse popularization by Aratus (third century) helped to fix the Greek sphere. Aratus's poem often served as a source of inspiration for other poets, as well as for painters and sculptors. The Farnese globe (Figure 2) is clearly a part of this tradition.

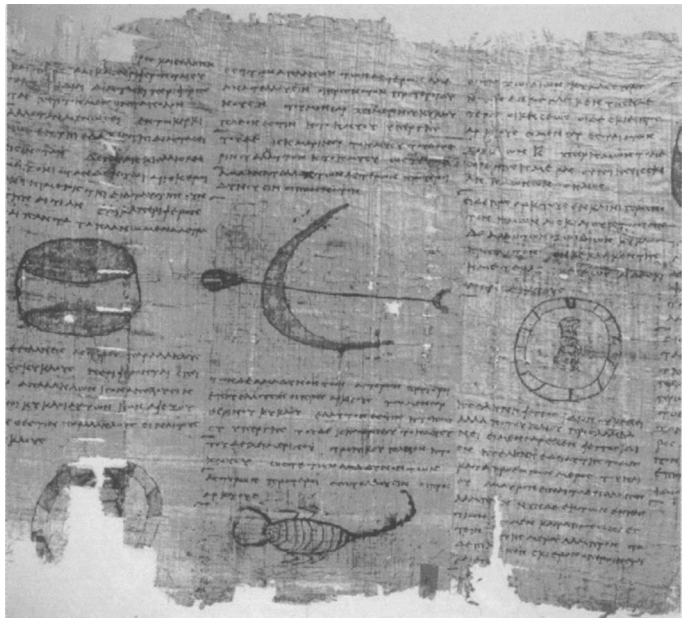


FIG. 34. A portion of the papyrus commonly known as "The Art of Eudoxus". (© Maurice et Pierre Chuzeville/ Musée du Louvre, Département des Antiquités Egyptiennes, N. 2325.)

Not all Greek astronomical art was of such merit. The papyrus commonly called "The art of Eudoxus" is interesting for the large number of drawings that decorate it[87] (see Figure 34). This papyrus from Hellenistic Egypt purports to be an introduction to astronomy. The content of the manuscript is elementary. It includes a short parapegma, simple accounts of the progress of the Sun and the Moon around the zodiac, descriptions of the circles on the celestial sphere, and a discussion of eclipses. In its treatment of the length of daylight, this papyrus follows the same simple rule as we saw in the parapegma of Figure 15 (that the length of daylight changes by 1/ 45 hour per day). The season lengths attributed to various authorities are the feature of this papyrus most commonly cited by modern historians. The end of the papyrus indicates that it represents the teachings of a certain Leptinos. But the discussion is so elementary and repetitive, and the organization so haphazard, that it is difficult to take this document seriously as an astronomical treatise. It may well be no more than a student's class notes. Many of the diagrams bear no apparent relation to the text: some must be mere doodles. But in Figure 34 we see the writer's illustration of the constellation of the Scorpion.

The most spectacular extant zodiac from Antiquity is the round zodiac of Dendera, shown in Figure 35. This sandstone relief formed part of the ceiling of a chamber of a temple in Dendera, Egypt. It was made in the first century A.D. — that is, during the period when the ruling class of Egypt spoke Greek, but Egypt was ruled by Rome. The relief is remarkable for its incorporation of the classical zodiac with

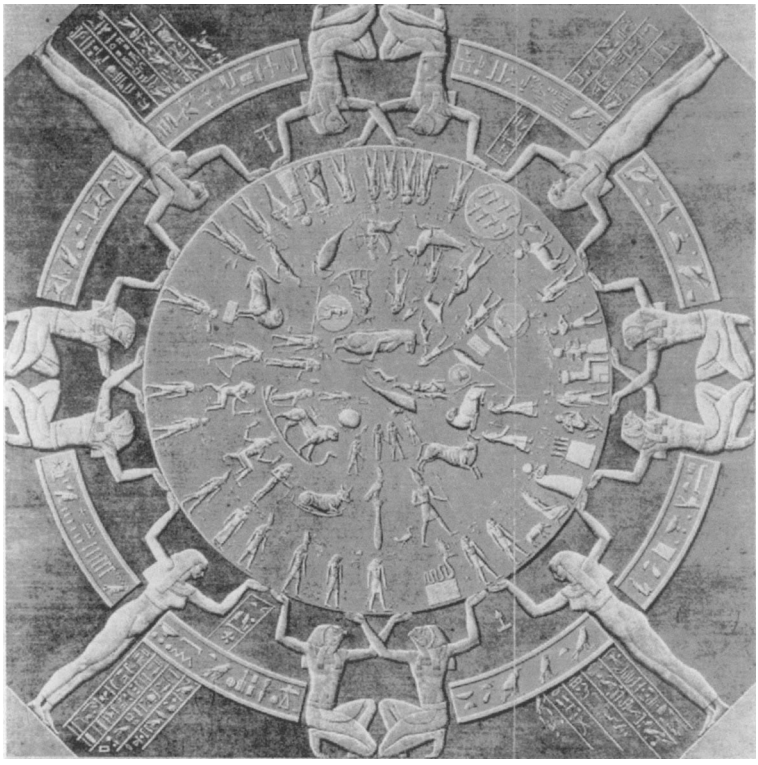


FIG. 35. The round zodiac of Dendera, first century A.D. (From *Description de l'Égypte* (ref. 88).)

Egyptian astronomical and religious symbolism. This is an example of the astronomical-astrological syncretism of late Antiquity, which paralleled the religious syncretism of the same period. The figures of the zodiac constellations form a rough ring, with a diameter about half that of the main circular panel. Around the perimeter of the main circle are thirty-six figures representing the Egyptian decans. Interspersed among the signs of the zodiac are five small figures bearing staffs, representing the five planets. It might be thought that the panel therefore represents a horoscope. But, in fact, each planet is shown adjacent to the sign in which it has its exaltation according to standard Greek astrological theory: Mercury just above Virgo (who holds the tail of the Lion), Venus next to Pisces, Mars atop Capricornus, Jupiter just beneath Cancer, and Saturn just to the right of Libra. Many of the other figures are not identifiable with complete certainty. The zodiac of Dendera was taken to France following Napoleon's Egyptian expedition and it is now in the Louvre. Figure 35 is an engraving made by Napoleon's Egyptologists for the publication that illustrated their discoveries.[88]

While some of the classical constellations were of Greek origin, others were

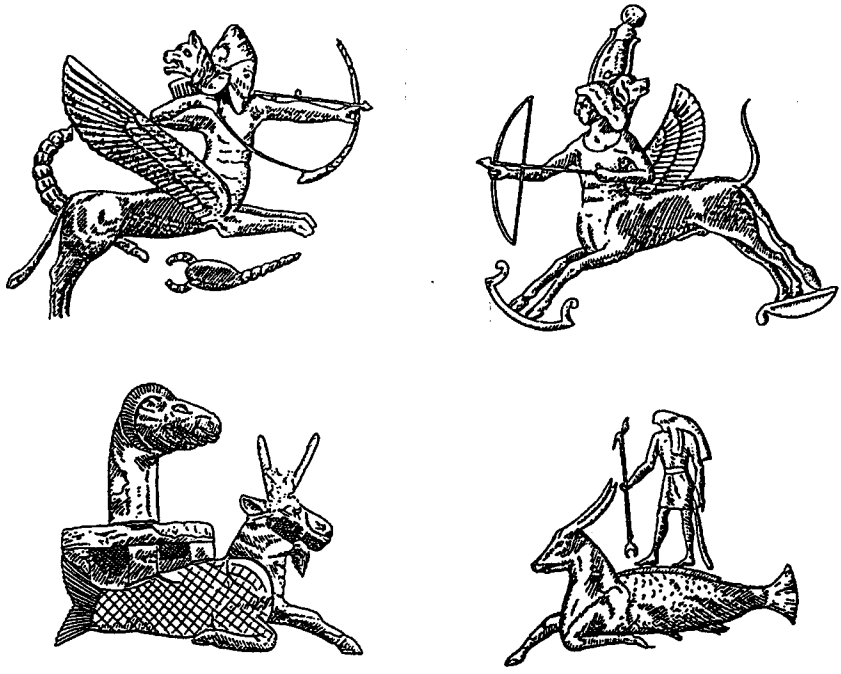


FIG. 36. Zodiac figures in Babylonian (left) and Greco-Egyptian (right) styles. The Babylonian figures are from boundary stones of the Kassite period (*c.* 1200 B.C.). The Greco-Egyptian figures are from the round zodiac of Dendera, *c.* A.D. 25. The constellations represented are Sagittarius (*above*) and Capricornus (*below*). (From William J. Hinke, *A new boundary stone of Nebuchadrezzar I from Nippur*, H. V. Hilprecht (ed.), *The Babylonian Expedition of The University of Pennsylvania*, Series D, vol. iv (Philadelphia, 1907).)

Hellenizations of older Babylonian constellations. This is demonstrably so in the case of most of the zodiac constellations. Figure 36 presents striking visual evidence for the Babylonian origins of the Greek zodiac. On the left are figures of two zodiacal constellations as represented on Babylonian boundary stones of the Kassite period, *c.* 1200 B.C. (Boundary stones were used for marking parcels of land.) On the right are the same two constellations as figured on the round zodiac of Dendera. The resemblance between the Greco-Egyptian figures and the Babylonian prototypes is remarkable, extending even to such details as the positions of the forelegs of the goat-fish creature, Capricornus.[89]

With the rise of astrology, zodiac diagrams intended to illustrate particular astrological doctrines became common. (The round zodiac of Dendera, showing the planets in their exaltations, is an especially spectacular example.) Figure 37 is a typical "man of the signs" drawing. Although this drawing is from a fifteenth-century manuscript, the theory it illustrates is as old as Greek astrology. Each part of the human body is governed by a sign of the zodiac. The correspondences are simple:

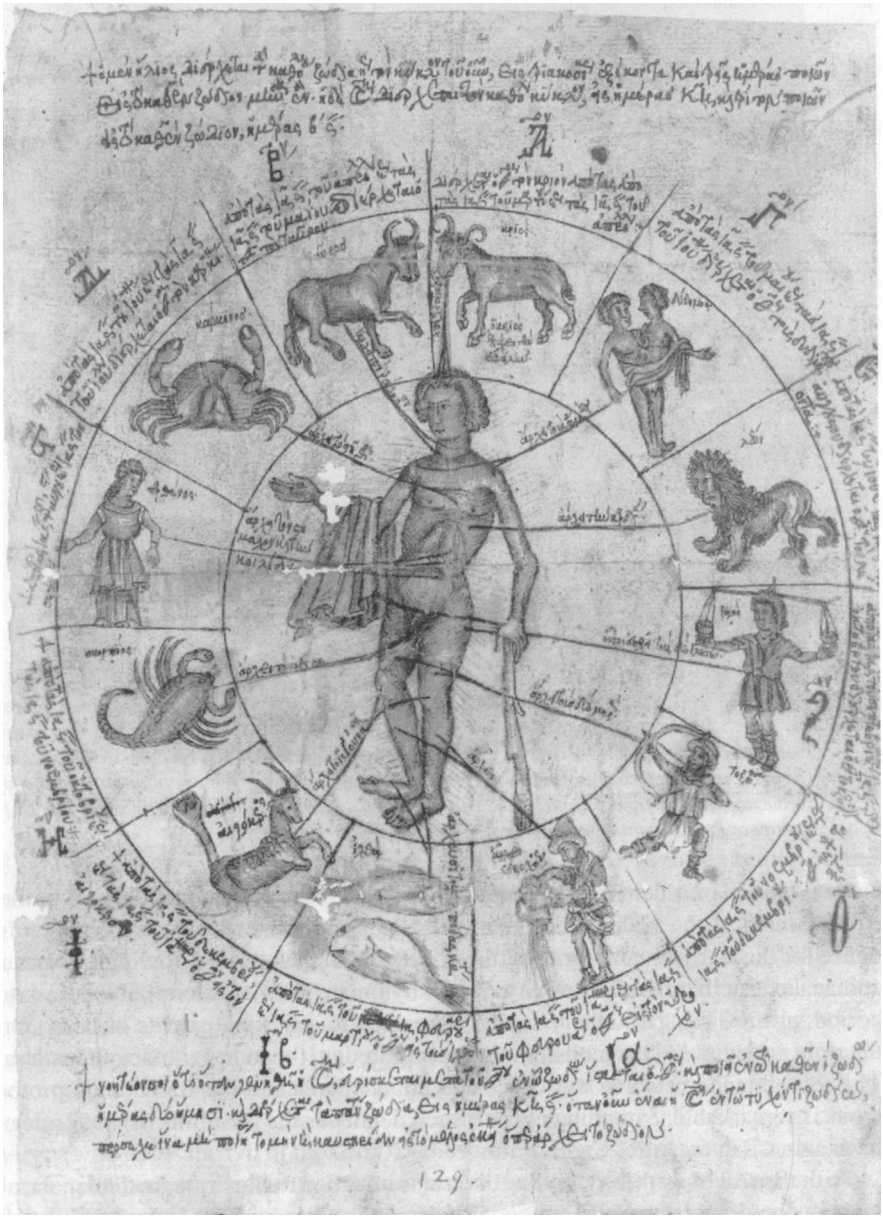


FIG. 37. A typical "man of the signs" drawing. (Bibliothèque Nationale de France, Ms. Grec 2419, fol. 1.)



FIG. 38. Relief from the first Mithraic sanctuary of Heddernheim, Germany. The relief is of yellow sandstone, 1.83 × 1.76 m. (Museum Wiesbaden.)

we start at the head with Aries and simply work our way down the body and around the zodiac, fetching up with Pisces to govern the feet. This doctrine is attested already by Manilius and by Sextus Empiricus;[90] its most important application was in medical astrology.

The vast corpus of inscriptions and sculptures associated with the cult of Mithras provides the best known and most plentiful examples of religious uses of astronomical imagery.[91] This cult, with Iranian roots, spread through the Roman world in the second century A.D. Although Mithraic monuments have been found from Susa to Spain, and from North Africa to Northern England, they are heavily concentrated along the Danube and the Rhine, that is, along the most heavily defended frontier of the empire, which testifies to the popularity of Mithraism among the Roman army. A large concentration of Mithraic artifacts has also been found in Rome itself. The public rites of Mithraism, open to men only, were practised in

specially-built small rooms, usually called "caves" by the ancients, but now often called Mithraea. The men associated with a single Mithraeum formed a close-knit cell of initiates, constrained by a rule of secrecy from divulging their practices to others.

The imagery in Mithraic monuments shows some variation, but it is surprisingly uniform across the empire. The central image of the cult is Mithras slaying a bull with his knife. Typically this image is found carved in relief in a prominent place at a Mithraeum, often underneath an arched sculpture of the twelve signs of the zodiac. In Figure 38 we see one of the best-known and best-preserved relics of Mithraism, a sandstone relief found in a Mithraeum near Heddernheim in 1826 and now in the Städtisches Museum at Wiesbaden. This relief is unusual in that it was carved on both sides and was fitted with a pivot so that it could be turned around. In Figure 38 we see Mithas slaying a bull in a grotto; the twelve signs of the zodiac form an arch immediately above him. Mithras may also (as here) be accompanied by other deities, in the forms of a dog, snake, scorpion and raven, which are also susceptible of astronomical interpretation. The raven perches on the god's billowing cloak, the dog leaps up against the bull's chest, and the scorpion grasps its genitals. Underneath the bull is a two-handled amphora or *krater*, and wriggling on this is a snake. Two other deities, Cautes and Cautopates, carry torches; Cautes stands to the right with uplifted torch, Cautopates to the left with his torch inverted.[92]



FIG. 39. Relief from a Mithraeum in Sidon in Phoenicia. Parian marble, second to fourth century A.D. (© Pierre et Maurice Chuzeville/ Musée du Louvre, Département des Antiquités Orientales, AO 22255.)

Figure 39 is a remarkable relief found at Sidon and now in the Louvre; it has been variously dated to the second or fourth century A.D. Here the images of the zodiac constellations stand out more clearly and the reader may have fun picking them out. Mithras's companions, the snake, dog and two ravens, are also present. The familiar scorpion, grasping the bull's genitals as usual, here doubles as a part of the zodiac ring. The busts in the four corners represent the four seasons, while two additional busts in the top centre are of the Moon and Sun.

Scholars have made many valiant attempts at interpreting the iconography, but without reaching consensus.[93] The difficulty is that, for the most part, we have only the images themselves to go by, for Mithraism left no written liturgy. That some elements of astrology were important in the religion seems apparent from the monuments. Also, we know that the cult members were divided into seven ranks, each of which was under the protection of a planetary god: Raven (under Mercury), Nymphus (Venus), Soldier (Mars), Lion (Jupiter), Persian (Moon), Heliodromus (Sun) and Father (Saturn).

Political Uses of Astronomical Images

Coinage is a rich source of astronomical and astrological symbolism. Astronomical objects appeared on Greek coins as early as the fifth century B.C., although they were not very common. Astronomical motifs on early Greek coins include the lunar crescent, stars (usually shown with six, eight, or sixteen rays), and the Sun; a popular combination was a crescent accompanied by one or several stars. The obverse of the coin often bore the head of a god, such as Athena, Dionysos or Demeter, but might well substitute an image of a stag, a horse, a bull or an owl.[94]

The basic patterns persisted in the Greek kingdoms of the Hellenistic period, except that the head of the king or queen tended to displace the old divinities. Symbols of agricultural plenty also became more common. In the Ptolemaic kingdom of Egypt, commonly occurring images on coins included: apple branch, bee, caduceus, ear of wheat, cornucopia, and the royal eagle on a thunderbolt, which was very common indeed.[95] But we do also find astronomical images. The coin shown in Figure 40 is from Greek Egypt, from the time of Queen Berenice II. This



FIG. 40. A coin from Ptolemaic Egypt, about 230 B.C. On the obverse is a portrait of Queen Berenice II; on the reverse, a cornucopia and two six-rayed stars. (British Museum, BMC Berenice II, 1923 11-8-1.)



FIG. 41. A silver coin from the reign of Augustus. The obverse bears the portrait of the emperor. The reverse displays the comet that appeared during the funeral games of his adoptive father, Julius Caesar, together with the motto, "Deified Julius". (British Museum, BMC Augustus 323 AR.)

Berenice is best known for her hair, commemorated as a constellation (our Coma Berenices) by Conon, her court astronomer.[96] The Ptolemaic dynasty, which ruled Egypt from about 320 B.C. until Roman annexation in the first century B.C., made full use of the Egyptian custom of deification of the monarch. In the dynastic cult Berenice II and her husband Ptolemy III Euergetes were benefactor gods. Thus the cornucopia in Figure 40 is a reminder to the queen's subjects that she is the source of material welfare; and the six-rayed stars connect the queen with the celestial realm.

After the rise of astrology, the political use of astronomical symbols on coins became very common. Good examples are provided by many coins from the reign of Augustus. After the assassination of Julius Caesar, his adoptive son Octavian (later Augustus) became involved in a protracted struggle for power characterized at first by delicate political manoeuvring and later by open warfare. As a part of this struggle, Octavian held funeral games to commemorate Caesar. Moreover, Octavian began a campaign, which was ultimately successful, to have Caesar proclaimed a god. This effort of Octavian's was greatly aided by a gratuitous gift from heaven: in the course of Caesar's funeral games, a comet appeared in the night sky. It eventually became bright enough to be seen in the daylight. The coin shown in Figure 41 illustrates the political use that Octavian made of this celestial event after he had become emperor and taken the name Augustus. The obverse bears a portrait of Augustus himself. But the reverse carries an image of the comet and its tail, an eight-rayed star, and the motto DIVVS IVLIVS — *divine* (or *deified*) *Julius*.[97]

An especially blatant example of the political use of zodiac symbolism is provided by the aureus shown in Figure 42. On the obverse is the customary portrait of the emperor, Augustus. On the reverse, a Capricorn is shown with a rudder and a globe of the Earth between its forelegs. Capricorn was Augustus's zodiac sign. While this symbolism reminded Augustus's subjects of his imperial and personal power, the cornucopia served to soften the message.[98]

Images of Astronomers

While we have many busts and coin-portraits of political leaders and military men, likenesses of scientific writers are very rare. There are, to be sure, 'portraits' of



FIG. 42. Gold coin from the reign of Augustus, whose zodiac sign was Capricorn. The Capricorn steers the world: it holds a rudder and a globe between its forelegs. (British Museum, BMC Augustus 1964 12-3-80.)

Euclid and others, but these were nearly all produced centuries after the fact — they are merely symbolic figures. The bust of Theon of Smyrna, shown in Figure 43, is very unusual. Theon of Smyrna was the author of a book called *Mathematical knowledge useful for reading Plato*, which has been cited a number of times above. The book contains a number of references to Plato and is Platonic in its underlying philosophy of nature, but it is very far from being a commentary on Plato's writings. In fact, Theon's book is an introductory survey of mathematics. Traditionally, the Greeks divided mathematics into arithmetic, geometry, astronomy and music theory, and a section of Theon's book probably was devoted to each of these. The section dealing with geometry and a part of that devoted to music theory have not come down to us, but we have, more or less intact, the sections on arithmetic and astronomy. While Theon was not an important astronomer, his book is valuable, since his is the only extant detailed account of deferent-and-epicycle theory before Ptolemy.

The bust of Theon of Smyrna shown in Figure 43 was found at Smyrna and is now in the Musei Capitolini in Rome. The Greek inscription says that the bust of Theon, the Platonic Philosopher, was dedicated by his son, Theon the priest; the bust may therefore actually resemble Theon the philosopher. Moreover, the bust provides a means of dating him: art historians assign it to the reign of Hadrian (early second century A.D.). Furthermore, in the *Almagest*, Ptolemy refers to observations made at Alexandria by a certain Theon. Thus it is possible that Theon of Smyrna was an elder friend (perhaps a teacher) of Ptolemy himself; the dates are right, and Theon of Smyrna's astronomical knowledge is amply attested by his extant work. But the name was common, and so we cannot be certain that Ptolemy's Theon was the same man.

Figure 44 shows a small bronze coin from Roman Bithynia. The coin was struck during the reign of Severus Alexander, who was emperor of Rome A.D. 222–35. The obverse bears the customary image of the emperor himself. But the reverse, shown here, bears an image of the astronomer Hipparchus. The Greek legend around the edge reads "Hipparchus of Nicaea", Nicaea being Hipparchus's native town in Bithynia. In Hipparchus's day (second century B.C.) Bithynia was an independent nation. It became a Roman province in 74 B.C. On the coin we see Hipparchus, who



FIG. 43. Theon of Smyrna. (Musei Capitolini, Rome.)

is bearded and wears a *himation*, the familiar over-the-shoulder garb of ancient Greece. He sits at a table that supports a celestial globe. The coin was minted centuries after Hipparchus's death and certainly cannot be taken as a likeness; but it does demonstrate that Hipparchus's astronomical accomplishments were



FIG. 44. A bronze coin from Roman Bithynia, bearing an image of Hipparchus. (British Museum, BMC Nicaea 97 AE.)

remembered, if not understood, by his countrymen. It may well be the oldest piece of money that carries the portrait of an astronomer.

* * *

The picture sketched here of the material culture of Greek astronomy should not be considered a snapshot of a moment in time. Indeed, the objects that we have examined span seven hundred years from the earliest (globe, gnomon, parapegma) to the latest (the early astrolabe). Our knowledge of the historical development of most of these objects is severely limited. As we have seen, the invention of the globe was sometimes attributed to Thales, and globes certainly existed by the time of Plato, but we have precious little reliable information about them until much later. In the case of sundials, we have Vitruvius's unreliable list of inventors and dial types, going all the way back to Eudoxus, Aristarchus and Apollonius, but no treatise on gnomonics except for the very late one by Ptolemy and the brief discussion of the analemma by Vitruvius himself. It seems unlikely that there were many sundials before the third century B.C. In Hellenistic times there must have been a rapid proliferation, as new kinds of dial were invented and explained in treatises on gnomonics that are now lost. The gearwork calculating mechanisms probably originated in the third century, Archimedes being a noteworthy practitioner of this genre of mechanics. Among the instruments of observation, various kinds of dioptra probably were known in classical times, but this family of instruments underwent its most rapid development in the Hellenistic period. The more specialized instruments of observation, notably the armillary sphere, are probably of later origin. Indeed, we have no evidence for such an instrument until Ptolemy, though it is likely that it was invented somewhat before his time. As we have seen, the anaphoric clock, described by Vitruvius, probably originated late in the Hellenistic period; but its eventual offspring, the astrolabe, did not appear until the second century A.D. Planetary tables based on arithmetic methods emerged after the Greeks had absorbed some of the lessons of Babylonian astronomy, in the second century B.C. Experimentation with planetary tables based on geometrical methods originated in the period from

Hipparchus to Ptolemy, but we know almost nothing about these tables before Ptolemy finally showed how to make them work. For the planetary equatoria we have no hard evidence at all, although it seems possible that they existed by Ptolemy's time, or at least by the time of Theon of Alexandria.

The pattern that emerges, then, is this: while some of the material manifestations of Greek astronomy were products of the classical age, many others were developments of the Hellenistic period, and notably those that incorporated quantitative features that we associate with measurement or prediction. While many objects showed a continued evolution into the Roman period, the basic categories (*sphairopoïïa*, gnomonics, dioptrics) seem to have been rather stable from the Hellenistic period to the close of Antiquity. A completely different situation applies to the symbolic use of astronomical signs and objects. Although close connections were established between astronomy and the artistic imagination already in the classical period, there were fundamental shifts in the political, social and religious values of astronomical symbolism in late Hellenistic and Roman times. Here the crucial developments were the rise of personal astrology and the growth of the new mystery religions.

The relation between textual and physical evidence can go either way: the objects may teach us things that the texts are silent about, or the texts may describe objects that have not survived. And, of course, we do not always know whether a writer who tells us about an interesting object is describing an object he has actually seen, one he has heard about, or even one he has only imagined. The sophisticated instruments of observation are known only through the evidence of texts, for no such objects have been preserved. But in the case of geared calculating mechanisms, the sophistication of the Antikythera mechanism far exceeds anything we might have expected from the elementary nature of the extant Greek texts on gears. Working out a complete picture of the material culture of Greek astronomy clearly requires attention to all that has been left to us.

Acknowledgements

I would like to express my gratitude to the University of Puget Sound for grants that helped to make possible the development and publication of this project. I owe a great debt to Michael Hoskin, who has been a critical reader and editor, in the best sense of the term, and whose suggestions have greatly improved the article. My colleague, Ili Nagy, generously took time from her own work to help me locate materials in Italy. Finally, this paper is dedicated to the memory of Olaf Pedersen, who first suggested that I undertake this study.

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Association, lxiv (1954), 77–85. See also Derek J. Price, "Precision instruments: To 1500", in Charles Singer *et al.* (eds), *A history of technology*, iii (New York and London, 1957), 582–619. A good general introduction to the images of ancient and medieval science is John E. Murdoch, *Album of science*, i: *Antiquity and the Middle Ages* (New York, 1984).

2. Germain Aujac (ed. and transl.), *Géminos: Introduction aux phénomènes* (Paris, 1975). Carolus Manitius (ed. and transl.), *Gemini elementa astronomiae* (Leipzig, 1898).
3. Glenn R. Morrow (transl.), *Proclus: A commentary on the First Book of Euclid's Elements* (Princeton, 1970).
4. Geminus is vague in distinguishing between dioptrics and meteoroscopy. According to Geminus the parts of astronomy are "gnomonics, which is engaged with the measurement of the hours through the placement of gnomons; meteoroscopy, which discovers the different altitudes [of the pole?] and the distances of the stars and teaches many other complex matters from astronomical theory; and dioptrics, which examines the positions of the Sun, Moon and the other stars by means of just such instruments [i.e., dipotras]". (Aujac (ed.), *op. cit.*(ref. 2), 117. Morrow, *op. cit.* (ref. 3), 34–35.) We shall see below that there were many different kinds of dioptra. Ptolemy (*Geography* I, 3) uses *meteoroskopion* for an instrument for taking celestial observations and says that he has given its description. Proclus (*Hypotyposis* VI, 2) uses *meteoroskopeion* for a more complex version of the armillary astrolabe described in *Almagest* V, 1. So it is clear that both dioptrics and meteoroscopy dealt with taking astronomical observations with instruments, most probably with two different classes of instrument. Geminus's classification of the mathematial sciences is discussed by Paul Tannery, *La géométrie grecque* (Paris, 1887), 38–42, and by Thomas L. Heath, *A history of Greek mathematics* (Oxford, 1921), i, 10–18. See also A. Rome, "L'astrolabe et le météoroscope d'apres le commentaire de Pappus sur le 5e livre de l'*Almageste*", *Annales de la Société Scientifique de Bruxelles*, série A, xlvii (1927), 2e partie, 77–102. According to Pappus of Alexandria (fourth century A.D.), "one also calls mechanics those who are skilled in *sphairopoïa* and construct a representation of the heavens with the aid of the uniform circular motion of water" (F. Hultsch (ed.), *Pappi Alexandrini Collectionis quae supersunt* (Berlin, 1876–78), iii, 1026; Paul Ver Eecke (transl.), *Pappus d'Alexandrie: La collection mathématique* (Paris, 1933), ii, 813–14).
5. Cicero, *De re publica* I, 14.
6. The source for these titles of Eudoxus's works is Hipparchus's *Commentary on Aratus and Eudoxus*. Carolus Manitius (ed. and transl.), *Hipparchi in Arati et Eudoxi Phaenomena commentariorum libri tres* (Leipzig, 1894), i, 2.1–3.
7. A. W. Mair and G. R. Mair (eds and transl.), *Callimachus, Lycophron, Aratus* (London and Cambridge, Mass., 1921).
8. For photographs of the Farnese Atlas see J. B. Harley and David Woodward (eds), *The history of cartography*, i: *Cartography in prehistoric, ancient and medieval Europe and the Mediterranean* (Chicago, 1987), 142–3. For a study of medieval celestial globes see Emilie Savage-Smith, *Islamicate celestial globes: Their history, construction and use* (Smithsonian Studies in History and Technology, xlvi; Washington, D.C., 1985). See also Otto J. Brendel, *Symbolism of the sphere: A contribution to the history of earlier Greek philosophy* (Leiden, 1977).
9. Ptolemy, *Almagest* VII, 2. J. L. Heiberg *et al.* (eds), *Claudii Ptolemaei Opera quae exstant omnia* (Leipzig, 1898–1954), i: *Syntaxis mathematica* [= the *Almagest*]. For an English translation see G. J. Toomer, *Ptolemy's Almagest* (London, 1984).
10. Ptolemy, *Almagest* VIII, 3.
11. For Ptolemy's *Phaseis*, see *Opera* (ref. 9), ii: *Opera astronomica minora*, 1–67.
12. Otto Neugebauer, *A history of ancient mathematical astronomy* (New York, 1975), 928–31. It has also been suggested that Hipparchus used a globe as a calculating device in compiling the "phenomena" section of his *Commentary on Aratus and Eudoxus*. See R. Nadal and J.-P. Brunet, "Le 'Commentaire' d'Hipparque, I. La sphère mobile", *Archive for the history of exact sciences*, xxix (1984), 201–36, and "Le 'Commentaire' d'Hipparque, II. Position de 78 étoiles", *ibid.*, xl (1989), 305–54. See also Gerd Grasshoff, *The history of Ptolemy's star*

catalogue (New York, 1990), 190–1.

13. Plato, *Timaeus* 36B–D.
14. Geminus, *Introduction to the Phenomena* XVI, 10–12. For the mural of an armillary sphere, see Pascal Arnaud, "L'image du globe dans le monde romain: Science, iconographie, symbolique", *Mélanges de l'École Française de Rome*, xcvi (1984), 53–116, p. 73; as well as D. Camardo and A. Ferrara, *Stabiae: Le ville* (Castellamare di Stabia, 1989), 67–68.
15. Plato, *Republic* X, 616B–617D.
16. Theon of Smyrna, *Mathematical knowledge useful for reading Plato* III, 16. J. Dupuis (transl.), *Théon de Smyrne, Philosophe platonicien. Exposition des connaissances mathématiques utiles pour la lecture de Platon* (Paris, 1892; reprinted Brussels, 1966).
17. Plato, *Timaeus* 40B–D.
18. For mentions of Archimedes's models see Plutarch, *Marcellus* XVII, 3–5; Ovid, *Fasti* VI, 277–80; Cicero, *De re publica* I, 14; *Tusculan disputations* I, 25; *On the nature of the gods* II, 34–35. In the latter passage, Cicero also mentions a similar planetary mechanism constructed by Posidonius, who was his contemporary.
19. Ver Eecke (transl.), *op. cit.* (ref. 4), ii, 813–14.
20. The standard authority is Sharon L. Gibbs, *Greek and Roman sundials* (New Haven, 1976). See also: D. J. Price, "Portable sundials in Antiquity", *Centaurus*, xiv (1969), 242–66. Mario Arnaldi and Karlheinz Schaldach, "A Roman cylinder dial: Witness to a forgotten tradition", *Journal for the history of astronomy*, xxviii (1997), 107–17.
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23. For a translation with an especially useful commentary, see Jean Soubiran, *Vitruve: De l'architecture, Livre IX* (Paris, 1969).
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32. The most important source for the early history of this genre among the Greeks is the parapegma

appended to Geminus's *Introduction to the phenomena* (ref. 2). A useful survey of Greek and Roman parapegamata is available in the article "Parapegma" by Albert Rehm in *Paulys Real-Encyclopädie der classischen Altertumswissenschaft*, Neue Bearbeitung von G. Wissowa (Stuttgart, 1894–). See also Neugebauer, *History* (ref. 12), 587–9.

33. Translation adapted from Bernard P. Grenfell and Arthur S. Hunt, *The Hibeh papyri: Part 1* (London, 1906), 152.
34. H. Diels and A. Rehm, "Parapegmenfragmente aus Milet", *Sitzungsberichte der königlich Preussischen Akademie der Wissenschaften*, 1904, 92–111. Roman display calendars also used the hole-and-peg technology. The Roman examples were based on the Roman calendar year. Some Roman examples exhibited calendrical information only (day of the week and day of the month) and no astronomical information at all. Others included holes for indicating the current zodiac sign. An especially interesting example is the large bronze tablet known as the Calendar of Coligny, found north of Lyons and dated to the second century A.D. It is inscribed in Gallic and is the most extensive known sample of an early written Celtic language. The Calendar of Coligny covered a five-year lunisolar cycle. For discussion and an illustration see Stephen C. McCluskey, *Astronomies and cultures in early medieval Europe* (Cambridge, 1998), 54–60.
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50. J. V. Field and M. T. Wright, "Gears from the Byzantines: A portable sundial with calendrical gearing", *Annals of science*, xlii (1985), 87–138.
51. Sources for Meton's solstice include Ptolemy, *Almagest* III, 1 and Diodorus Siculus, *Histories* XII, 36.1–2. Of course, Meton did not express the date in terms of the Egyptian calendar; rather, this is the result of a conversion applied later by Hellenistic astronomers. The stated time of equinox is more than a day early.
52. Ptolemy, *Almagest* II, 6. Strabo, *Geography* II, 2.3–3.2.
53. Pliny, *Natural history* II, 182. See also Vitruvius, *On architecture* IX, 7.1.
54. Strabo, *Geography* I, 4.4, transl. by H. L. Jones. Pytheas of Massilia was a navigator, famous among the Greeks, who, around 285 B.C., explored the northwest coast of Europe. He recorded his exploits in a book, *On the ocean*, which has not survived.
55. Ptolemy, *Almagest* I, 12. This instrument is sometimes called the *plinth*. Ptolemy also describes a second form of meridian instrument, in which a complete graduated circle, engraved on a metal ring, replaces the quadrant. Proclus also gives a detailed discussion of the meridian ring in *Hypotyposis* III, 5–27. According to Proclus, this instrument should be not less than one half cubit in diameter. But a meridian ring of such small size would be so inadequate that we may well wonder how much experience Proclus had with real instruments. Both the quadrant and the meridian ring are discussed by Theon of Alexandria in his commentary on the *Almagest*. See A. Rome (ed.), *Commentaires de Pappus et de Théon d'Alexandrie sur l'Almageste*, ii: Théon d'Alexandrie, *Commentaire sur les livres 1 et 2 de l'Almageste* (Studi e Testi, lxxii; The Vatican, 1936), 513–26. For a still useful French translation see [Nicolas] Halma, *Commentaire de Théon d'Alexandrie sur le premier livre de la Composition Mathématique de Ptolémée* (Paris, 1821; reprinted Paris, 1993), 219–27. For valuable insights into the use of these instruments, see John P. Britton, *Models and precision: The quality of Ptolemy's observations and parameters* (New York, 1992).
56. Ptolemy, *Almagest* III, 1.
57. Theon of Smyrna, *Mathematical knowledge useful for reading Plato* III (ref. 16), 12.
58. Ptolemy, *Almagest* I, 12.
59. Ptolemy, *Almagest* III, 4.
60. Ptolemy, *Almagest* III, 1. Theon of Alexandria makes a few remarks about observing with such rings and implies that their diameters are generally "not less than two cubits" (A. Rome (ed.), *Commentaires de Pappus et de Théon d'Alexandrie sur l'Almageste*, iii: Théon d'Alexandrie, *Commentaire sur les livres 3 et 4 de l'Almageste* (Studi e testi, cvi; The Vatican, 1943), 817–18).

61. Frans Bruin and Margaret Bruin, "The equatorial ring, equinoxes and atmospheric refraction", *Centaurus*, xx (1976), 89–111. A. Rome, "Les observations d'équinoxes et de solstices dans le chapitre 1 du livre 3 du Commentaire sur l'Almageste par Théon d'Alexandrie", *Annales de la Société Scientifique de Bruxelles*, lvii (1937), 213–36 and lviii (1938), 6–26. See also Britton, *Models and precision* (ref. 55).
62. In the *Almagest*, Ptolemy makes a few vague references to atmospheric refraction. For example (*Almagest* I, 3) he mentions the familiar Moon illusion — the supposed fact that celestial bodies look bigger when they are near the horizon — and makes an analogy to the change in apparent size of objects immersed in water. But in his later *Optics* (V, 23–31) Ptolemy presents a very cogent discussion of atmospheric refraction. He notes that a celestial body when rising or setting appears to lie on a more northerly circle of declination and says that this is seen with the aid of an instrument for measuring stars. This could well refer to the use of an armillary sphere. Ptolemy also offers a psychological explanation of the Moon illusion (*Optics* III, 59–61). A. Mark Smith, "Ptolemy's theory of visual perception: An English translation of the *Optics* with introduction and commentary", *Transactions of the American Philosophical Society*, n.s., lxxxvi/2 (1996), 238–42 and 151–2. Cleomedes is the only other ancient writer who seems to be aware that refraction of the visual ray might have consequences for astronomy. Cleomedes mentions an eclipse of the Moon in which both the Sun and the Moon were seen above the horizon. Robert Todd (ed.), *Cleomedis Caelestia* (*METEΩPA*) (Leipzig, 1990), II, 6. For a French translation of Ziegler's 1891 edition of the Greek text see Richard Goulet, *Cléomède. Théorie élémentaire* (Paris, 1980), 171–4. The dates of Cleomedes are highly uncertain. Some writers have placed him in the first century A.D., others in the fourth.
63. On the use of the armillary sphere as instrument of observation see James Evans, "On the origin of the Ptolemaic star catalogue", *Journal for the history of astronomy*, xviii (1987), 155–72 and 233–78. A number of details of practice that had not been noticed by bookish historians were discovered and elucidated by J. Włodarczyk, who actually made and used one of these instruments. See his "Examining the armillary sphere", *Journal for the history of astronomy*, xviii (1987), 173–95. The debate over the origin of the star catalogue was reopened in the modern period by Robert R. Newton, *The crime of Claudius Ptolemy* (Baltimore, 1977). The most detailed study, with a history of the debate up to 1990, is Grasshoff, *The history of Ptolemy's star catalogue* (ref. 12). For a useful brief overview of the principal arguments, see Hugh Thurston, *Early astronomy* (New York, 1994), 150–5. For a recent development, favouring a Hipparchan date for the catalogue, see A. K. Dambis and Yu. N. Efremov, "Dating Ptolemy's star catalogue with the proper motions: Hipparchan epoch", *Journal for the history of astronomy*, forthcoming. According to Pappus, the diameter of the astrolabe is one cubit. The similar but more complex meteoroscope is half as large. A. Rome (ed.), *Commentaires de Pappus et de Théon d'Alexandrie sur l'Almageste*, i: Pappus d'Alexandrie, *Commentaire sur les livres 5 et 6 de l'Almageste* (Studi e Testi, liv; Rome, 1931), 6. See also Rome, *op. cit.* (ref. 4).
64. Evans, "On the origin of the Ptolemaic star catalogue" (ref. 63), 162–3.
65. H. Raeder, E. Stromgren and B. Stromgren, *Tycho Brahe's description of his instruments and scientific work as given in* Astronomiae instauratae mechanica (Copenhagen, 1946). See also Victor Thoren, *The Lord of Uraniborg: A biography of Tycho Brahe* (Cambridge, 1990).
66. J. L. Berggren and R. S. D. Thomas, *Euclid's* Phaenomena*: A translation and study of a Hellenistic treatise in spherical astronomy* (New York, 1996), Proposition 1, 52–53.
67. Copernicus, *On the revolutions of the heavely spheres* I, 6.
68. Geminus, *Introduction to the phenomena* XII, 1–4.
69. Dicaearchus is mentioned as an authority on the heights of mountains by Theon of Smyrna, *Mathematical knowledge useful for reading Plato* III (ref. 16), 3.
70. For the text of Hero's *Dioptra* see *Heronis Alexandrini Opera quae supersunt omnia*, iii, ed. by H. Schone (Leipzig, 1903). See also A. G. Drachman, "Hero's dioptra and levelling instrument", in Singer (ed.), *A history of technology* (ref. 1), iii, 609–12, and A. G. Drachman, "A detail of Hero's dioptra", *Centaurus*, xiii (1950), 241–7.

71. Ptolemy, *Almagest* V, 14. Ptolemy says that Hipparchus used a dioptra four cubits long.
72. For a discussion of Archimedes's *Sand reckoner* see E. J. Dijksterhuis, *Archimedes*, transl. by C. Dikshoorn (Princeton, 1987). For the dioptra, see pp. 364–5.
73. Pappus gives a short description of the dioptra in his commentary on Book V of the *Almagest*. See Rome, *Commentaires*, i (ref. 63), 90–92. The most detailed ancient description is in Proclus, *Hypotyposis* (ref. 39) IV, 87–99.
74. Ptolemy, *Almagest* V, 12. For a Renaissance illustration of an astronomer using this instrument see William Cuningham, *The cosmographicall glasse* (London, 1559), figure reproduced in Olaf Pedersen, *Early physics and astronomy* (2nd edn, Cambridge, 1993), 80.
75. For the text of the Canobic inscription, see Ptolemy, *Opera* (ref. 9), ii, 149–55. For a discussion of the contents see Neugebauer, *History* (ref. 12), 913–17.
76. N. T. Hamilton, N. M. Swerdlow and G. J. Toomer, "The Canobic Inscription: Ptolemy's earliest work", in J. L. Berggren and B. R. Goldstein (eds), *From ancient omens to statistical mechanics: Essays on the exact sciences presented to Asger Aaboe* (Copenhagen, 1987), 55–73.
77. For a discussion of the Keskinto inscription see Neugebauer, *History* (ref. 12), 698–705. For a squeeze of the inscription see Paul Tannery, *Mémoires scientifiques* (17 vols, Paris, 1912–50), xv, 119. For the text, see F. Hiller de Gaertringen, *Inscriptiones Graecae insularum Rhodi, Chalces, Carpathi cum Saro Cosi* (Inscriptiones Graecae, xii/1; Berlin, 1895), inscription no. 913. For the mention of the boards of the astronomy of Eudoxus at Delos, see R. Vallois, "Le temple Délien d'Arsinoé Philadelphe ou d'Agathé Tyché", *Comptes rendues de l'Académie des Inscriptions et Belles Lettres*, 1929, 32–40, p. 36; and F. Dürrbach and P. Roussel (eds), *Inscriptions de Délos*, iii (*Actes des fonctionnaires Athéniens préposés à l'administration des sanctuaires après 166 av. J.-C. (nos. 1400–1479)*; Paris, 1935), no. 1442B, lines 41–42. For the inscription of Diogenes of Oenoanda, see Martin Ferguson Smith, *The Epicurean Inscription* (Naples, 1993), and *idem*, *The philosophical inscription of Diogenes of Oinoanda* (Vienna, 1996).
78. Ptolemy, *Almagest* I, 1.
79. Strabo, *Geography* XVII, 1.17.
80. Geminus, *Introduction to the phenomena* II, 5. Strabo, *Geography* XVI, 1.6. Sextus Empiricus, *Against the professors* V, 2. Cicero, *On divination* II, 87–89. Vitruvius, *On architecture* IX, 6.2. The assertion of the Greek and Roman writers has been confirmed by the discovery of cuneiform horoscopes. For these, see A. Sachs, "Babylonian horoscopes", *Journal of cuneiform studies*, vi (1952), 49–75.
81. Several good treatments of Greek and Roman astrology are available. A classic and still indispensible work is A. Bouché-Leclercq, *L'astrologie grecque* (Paris, 1899; reprinted Brussels, 1966). A good brief account of the basic principles is provided in the introduction to G. P. Goold, *Manilius: Astronomica* (Cambridge, Mass., 1977). For an accessible treatment that is up to date in terms of historical evidence, see Tamsyn Barton, *Ancient astrology* (London, 1994). For the place of astrology in the public life of Rome see Frederick H. Cramer, *Astrology in Roman law and politics* (*Memoirs of the American Philosophical Society*, xxxvii (1954)). Of vital importance for reconstructing the actual practice of ancient Greek astrology are the extant Greek horoscopes collected in O. Neugebauer and H. B. van Hoesen, *Greek horoscopes* (*Memoirs of the American Philosophical Society*, xlvii (1959)). For entry to the enormous mass of late Greek astrological material, see *Catalogus codicum astrologorum Graecorum* (12 vols, Brussels, 1898–1953).
82. On the archaeology of Nemrut Dag see K. Akurgal, *Ancient civilisations and ruins of Turkey*, 4th edn (Istanbul, 1978), 346–51.
83. The most important of these is the *Anthology* of Vettius Valens (late second century A.D.). David Pingree (ed.), *Vettii Valentis Antiocheni Anthologiarum libri novem* (Leipzig, 1986). Also significant is the astrological poem of Dorotheus of Sidon, which however, survives only in an Arabic translation. David Pingree (ed. and transl.), *Dorothei Sidonii Carmen astrologicum* (Leipzig, 1976).

84. Hans Dieter Betz, *The Greek magical papyri in translation*, i (Chicago, 1986), 312; Betz's inventory number PGM (for Papyri Graecae Magicae) CX, lines 1–12.
85. For examples, see Barton, *Ancient astrology* (ref. 81), Plate 13.
86. Homer, *Iliad* XVIII, 478–89.
87. Earlier writers sometimes call this P. Parisinus 1. But it is now kept at the Musée du Louvre under the number N 2325. For the text see F. Blass, *Eudoxi ars astronomica* (Kiel, 1887). For a French translation see Paul Tannery, *Recherches sur l'histoire de l'astronomie ancienne* (Paris, 1893), 283–94.
88. *Description de l'Égypte, ou, Recueil de observations et des recherches qui ont été faites en Égypte pendant l'éxpédition de l'armée française, publié par les ordres de Sa Majesté l'empereur Napoléon le Grand* (Paris, 1809–28), iv, Plate 21. For another Greco-Egyptian zodiac (this one from Latopolis), see Plate 87 to vol. i in the same work. For a brief but interesting discussion of the Dendera zodiac, see Owen Gingerich, "Astronomical scrapbook: Ancient Egyptian sky magic", *Sky & telescope*, May 1983, 418–20. For a discussion and illustrations of the Egyptian consellations, see Otto Neugebauer and Richard A. Parker, *Egyptian astronomical texts* (London, 1969), iii.
89. The standard source for Babylonian constellations is Felix Gössmann, *Planetarium Babylonicum oder Die Sumerisch-Babylonischen Stern-Namen*, Anton Deimel (ed.), *Sumerisches Lexikon*, iv/2 (Rome, 1950). See also Hermann Hunger and David Pingree, *MUL.APIN: An astronomical compendium in cuneiform* (Horn, Austria, 1989). For a photograph of a boundary stone in the British Museum decorated with astronomical images see Michael Hoskin (ed.), *The Cambridge illustrated history of astronomy* (Cambridge, 1997), 22.
90. Manilius, *Astronomica* II, 453–65. Sextus Empiricus, *Against the professors* V, 21–22.
91. The fundamental survey of Mithraic material is Maarten Vermaseren, *Corpus inscriptionum et momumentorum religionis mithriacae* (2 vols, The Hague, 1956–60). See also Leroy C. Campbell, *Mithraic iconography and ideology* (Leiden, 1968).
92. For a description of the other features of this relief and references to the vast literature concerning it, see Vermaseren, *Corpus inscriptionum* (ref. 91), ii, 64–66.
93. For two recent attempts at an astronomical interpretation see David Ulansey, *The origins of the Mithraic mysteries: Cosmology and salvation in the ancient world* (Oxford, 1989), and J. D. North, "Astronomical symbolism in the Mithraic religion", *Centaurus*, xxxiii (1990), 115–48.
94. A useful tool is the table of astronomical motifs on Greek and Roman coins by L. Anson, *Numismata Graeca*, vi (1916), 1ff, reprinted in Cramer, *Astrology in Roman law* (ref. 81).
95. See *A catalogue of the Greek coins in the British Museum: The Ptolemies, Kings of Egypt* (London, 1883).
96. For the story see Callimachus, *Aetia* 110 and Catullus, poem 66.
97. For a detailed study see John T. Ramsey and A. Lewis Licht, *The comet of 44 BC and Caesar's funeral games* (Atlanta, 1997). The earliest Roman accounts of this object described it as a star (*sidus*) and the earliest coins to depict it showed it without a tail. The images on coins acquired a tail in 17 B.C. See Stefan Weinstock, *Divus Julius* (Oxford, 1971), 379.
98. For many other examples see Harold Mattingly, *Coins of the Roman Empire in the British Museum*, i: *Augustus to Vitellius* (London, 1923; revised 1976). Augustus was born under Libra and therefore presumably conceived under Capricorn (Bouché-Leclerq, *op. cit.* (ref. 81), 369). The Capricorn also symbolized the ascent of the Sun after the solstice and, hence, the birth of a new age.