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DICKS D. R., *The concepts of Greek astronomy*: BICS XI 1964 43-53. | Description de l'étape finale et pleinement évoluée de la pensée astronomique grecque telle qu'elle apparaît dans l'œuvre d'Hipparque et trouve son établissement définitif dans la *Μεγάλη Σύνταξις* de Ptolémée.

THE CONCEPTS OF GREEK ASTRONOMY*

by D. R. Dicks

The description I shall give is of the final, fully evolved stage of Greek astronomical thought, as it appears in the work of Hipparchus, c. 194-120 B.C. and finds its definitive statement in the great textbook of ancient astronomy, the *Μεγάλη Σύνταξις* (or *Almagest*) of Claudius Ptolemaeus, some 260 years later, a large part of which is based directly (as Ptolemy himself frequently states) on Hipparchus' work; as is well known, the Hipparchian-Ptolemaic theory of celestial movements held the field (with minor modifications by the Arabic astronomers) until the 16th century and even beyond.

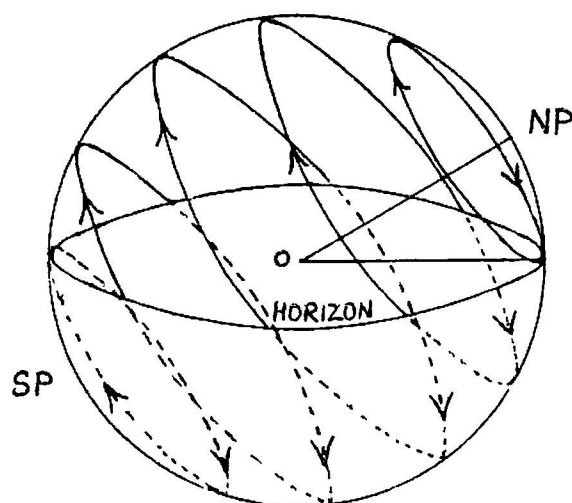
The earth is a solid spherical ball which remains motionless in the centre of the cosmos; the *οἰκουμένη* is a segment of this lying north of the equator and stretching from the Straits of Gibraltar in the west to the vaguely conceived land mass of India and China in the east; northwards, Britain is the limit of habitable land (a fitting comment on the British climate), and there is a faint possibility that the equatorial regions may also be inhabited. Round the earth is the celestial sphere, inside which all the heavenly bodies move in circular orbits (or combinations of circular orbits); outside the celestial sphere is - what? The unlimited void of the Pythagoreans? Aristotle's Unmoved Mover? Nobody knows. Fortunately, it doesn't matter from the point of view of mathematical astronomy; the important thing here is the celestial sphere and the earth in the middle of it. The boundary of the celestial sphere, conceived of as being so vast that the whole earth can be regarded as a mathematical point at its centre, is formed by the fixed stars (*τὰ ἀπλανῆ ἄστρα*); proceeding inwards one comes to the successive orbits of the planets in the order, Saturn, Jupiter, Mars, Sun, Venus, Mercury, Moon and finally to the central earth; this is, in fact, the order of the sidereal periods of the planets and, if we interchange sun and earth, the order of their distances in the heliocentric system.

Now, to a nocturnal observer in Mediterranean latitudes it is obvious that, apart from the moon, the fixed stars are the most striking phenomena that the night sky offers, by their very number and the regularity of their courses; it is the rising and setting of prominent fixed stars that provide the basis for the agricultural calendar, whereby the farmer regulated his operations throughout the year, and the earliest astronomical references in Greek literature and indeed the commonest in all ancient literature (with the possible exception of the sun) relate to the risings and settings of the fixed stars. So it is with these that I should like to deal first of all. From a very early period in all parts of the world man has observed the

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groupings and movements of the fixed stars; Nilsson in his standard work *Primitive Time-Reckoning* (Lund, 1920) has shown by hundreds of examples how the appearance or disappearance of a star cluster like, for example, the Pleiades, has served (and continues to serve for primitive tribes) as a means of marking the passing of time. In the Near East, it was the Babylonians who first invented names for the various constellations at least by 1000 B.C., and these were very largely taken over by the Greek astronomers and are, of course, still used to-day. Some were different - the Babylonians called Sirius, the Arrow Star, and the stars of Canis Major were divided by them between the Arrow and the Bow. Similarly the conception of the zodiac as a belt of constellations round the sky traversed by the sun in its annual path originated (between 500 and 400 B.C.) in Mesopotamia; when this was introduced into Greek astronomy is debatable - one traditional ascription to Cleostratus in the 6th century is certainly too early; another to Oenopides of Chios (late 5th century) is more probable though far from certain.

If you observe the stars night after night over a period of years you will discover three things about them; the first is that they all share in a continuous and uniform wheeling motion over the sky in the general direction of east to west - and the orbit of each star is curved; the second is that, whereas some of the stars have large orbits, pass directly overhead and are visible throughout most of the night before setting below the western horizon, while others have smaller orbits and can only be seen for a short time, there is yet another group of stars which never rise or set and which seem to circle a particular point in the sky; and the third discovery you will make is



O = OBSERVER

FIG. 1

that different stars are prominent at night at different seasons of the year, but that the same stars appear regularly at the same places in the same seasons in successive years. Fig.1 shows schematically the state of affairs. Here NP is the north pole and SP the south pole of the heavens; the complete, continuous line circle represents the (circumpolar) stars that never dip below the horizon, while the complete, dotted-line circle represents the stars that are never seen above the horizon at this particular latitude.

The reason why the stars of a summer night are different from those of a winter night is, of course, that the sidereal day (i.e. the time taken for one complete revolution) is 4 minutes shorter than the solar day of 24 hours, owing to the fact that the

sun itself is moving steadily relative to the stars, as I shall explain later. This means that a star that rises, say, 1 hour after sunset on a given night, will rise 4 minutes earlier on successive nights until eventually its rising will not be visible because the sun will not yet have set sufficiently below the horizon to enable the star to be seen in the still bright sky - when it *does* get

dark enough the star will already be well up in the night sky. Similarly, of course, at the other end of the night; if a star is seen rising just before the dawn (and is only just visible before the sun's rays outshine it), on successive nights it will rise earlier and earlier, its period of visibility reaching a maximum and then decreasing, until its rising is swallowed up by the sun's previous setting, when the star becomes invisible again.

Now it was observation of these differences in the rising and setting of stars that enabled the ancients, laymen and astronomers alike, to use the appearance of the heavens as a gigantic clock wherewith to measure the alternation of the seasons. Eight different risings and settings (in relation to the sun) were defined in, for example, the earliest Greek astronomical text that has come down to us, Autolycus' *Περὶ κινουμένης σφαίρας* and *Περὶ ἐπιτολῶν καὶ δύσεων*, c. 325 B.C. These were the visible morning rising (which takes place in the morning before sunrise), the visible evening rising (just after sunset), the visible morning setting (the first time the star can be seen setting on the western horizon before sunrise) and the visible evening setting (the last time it can be seen to set after sunset). Corresponding to these were four other risings and settings, when the star in question rose or set *exactly* with the sun; these true risings and settings as they were called were, of course, unobservable and play no part in practical astronomy. A glance at Figs. 2 and 3 (adapted from O. Schmidt's paper on Autolycus in *Den 11. skandinaviske matematikerkongress*, 1949, pp. 204-5) will perhaps clarify the matter. Fig. 2 shows the simplest

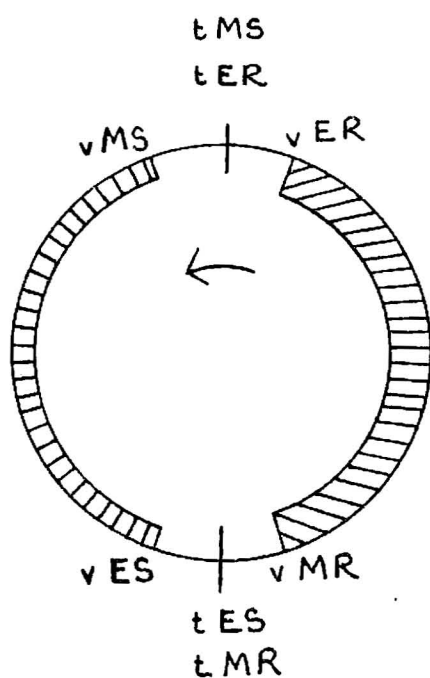


FIG. 2

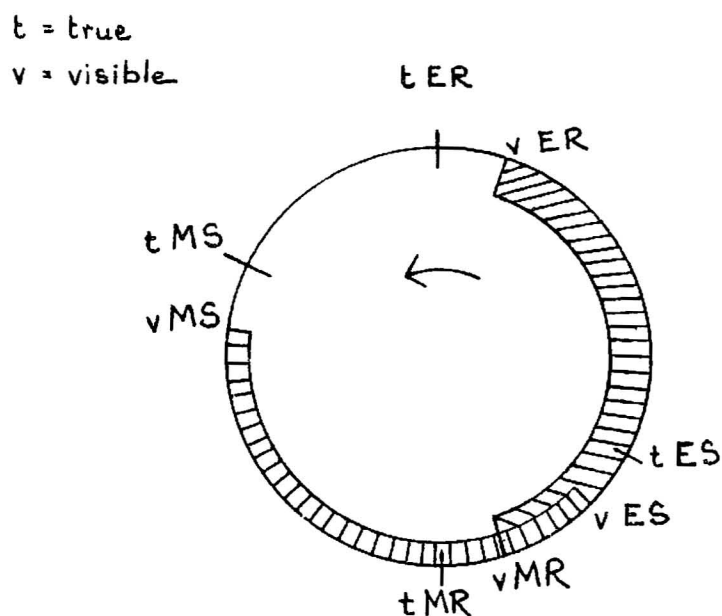


FIG. 3

case, of a star actually on the ecliptic - the ecliptic is the mathematical line on the celestial sphere that marks the annual path of the sun round the earth (not the daily path - I shall try to explain this later) and the direction of its movement is given by the arrow. The whole circle is, of course, 1 year; the shaded portions show the visibility of the star at setting and rising and the parts in between are when the star is invisible. Fig. 3 shows the position for stars north of the ecliptic. Here you will notice that the shaded portions overlap; this means that

when the sun is located on the arc vis. MR to vis. ES a star *can* (but this does not *always* happen - it depends on the position of the star) actually be seen *twice* in the same night - at the beginning of the night it sets, remains invisible for some hours, and then can be seen rising again at the end of the night. A similar figure could be drawn for stars south of the ecliptic. The visibility or invisibility of a star depends on its position relative to the ecliptic, on the sun's position along the ecliptic, which is, of course, altering every day, on the brightness of the star, and, naturally, on atmospheric conditions and the keenness of the observer's vision; it becomes quite complicated to work out in detail, but the general theory is (I hope) clear from these simplified diagrams.

Of the stellar risings and settings the two most important are the morning rising (sometimes called the heliacal rising) and the morning setting (sometimes called the cosmical setting); in general, it is these two $\varphi\acute{\alpha}\sigma\epsilon\iota\varsigma$, 'appearances', that are meant when the rising or setting of a star is mentioned in literary texts. References to them are common in the poets, particularly in didactic poetry, from the time of Hesiod onwards; Mair, in a very useful addendum to his translation of Hesiod (1908), entitled "The Farmer's Year in Hesiod", explains the matter clearly, and I don't think I need to spend more time on it. The $\varphi\acute{\alpha}\sigma\epsilon\iota\varsigma$ were gradually collected together into a mass of material, originally observational but soon becoming traditional in character, copied from one generation to another and, what is worse, transmitted without regard to the locality of the observer (because, of course, the risings and settings properly depend on the latitude of the observer), which formed the basis of the 'parapegma' texts discussed pre-eminently by Rehm in *Abhandl. der Bayerischen Akad. der Wissensch., phil.-hist. Abteilung*, neue Folge, Heft 19 (1941), and in his later article in *RE*. These calendar texts apparently go back to the time of Meton and Euctemon c. 432 B.C.; extracts are found in the Hippocratic corpus (*Περὶ ἀέρων, ὑδάτων, τρώων* and *Περὶ διαίτης*), the Eudoxian parapegma (c. 370 - which included observations for Egypt) was very influential, and both Hipparchus and Ptolemy wrote works of this kind, the latter's $\varphi\acute{\alpha}\sigma\epsilon\iota\varsigma$ being still extant.

There is one further phenomenon that must be mentioned before we leave the fixed stars, and that is the phenomenon known as the precession of the equinoxes. This is actually caused by the fact that the earth's axis does not point always in the same direction, but describes a small circle round the pole of the ecliptic with a period of 26000 years. Because of this, the points where the ecliptic intersects the equator, i.e. the equinoxes, show a very gradual displacement westwards round the ecliptic; the amount is about 50'' of arc a year. Hipparchus discovered this shift (but underestimated it) by comparing his own observations with some by Timocharis, an Alexandrian astronomer of the first decade of the 3rd century B.C.; to explain it he postulated a very slow uniform revolution of the sphere of the fixed stars round the poles of the ecliptic. Ptolemy in an uncharacteristically muddled account of Hipparchus' investigations (usually his reports are models of clarity) claimed to have verified his results, from which he obtained a value for precession of 1° in 100 years - a suspiciously convenient figure (the modern value amounts to 1° in 72 years). The resultant difference between the lengths of the solar or tropical year (solstice-solstice, or equinox-equinox) and the sidereal year (return of the sun to the same star again) was first established by Hipparchus, whose values are only about 6½ minutes and 5 minutes too large respectively.

Now let us turn to the great luminary of day, the sun. It is unnecessary to stress its importance. If you observe the successive risings and settings of the sun over a period of many years,

you will find that it does not rise or set at exactly the same points of the horizon at the same time each day, but that (in northern latitudes) its rising and setting points oscillate between two limits north and south of due east, and north and south of due west; on only two days of the year, in spring and autumn, does the sun rise and set due east and due west at 6 a.m. and 6 p.m. And, of course, you will discover that after 365¼ days the rising and setting sun returns to the same points of the horizon and the same times. You will also find that the sun does not take the same number of days to traverse the four quarters of its course, from the northern limit to due east (to speak only of the risings), from there to its southern limit, back to due east, and finally back to the northern limit - in fact, the four astronomical seasons. There is only one possible way to reconcile all these phenomena, given the concept of the spherical earth fixed at the centre of the celestial sphere, and that is to postulate that the sun circles the earth in one complete year in an orbit that is inclined to the celestial equator; this orbit is constant, the sun never deviates from it, and it can be represented as a mathematical line drawn round the celestial sphere and passing through the constellations of the zodiac - it is called the ecliptic, because eclipses can only take place when sun and moon are on this line (the term is actually late - first apparently in Achilles Tatius, 3rd cent. A.D.: Hipparchus and Ptolemy always refer to it as ὁ λοξὸς κύκλος or ὁ διὰ μέσων τῶν ζῳδίων κύκλος). Moreover, the sun's annual movement along the ecliptic is in the opposite direction to that of its daily motion, i.e. it moves steadily

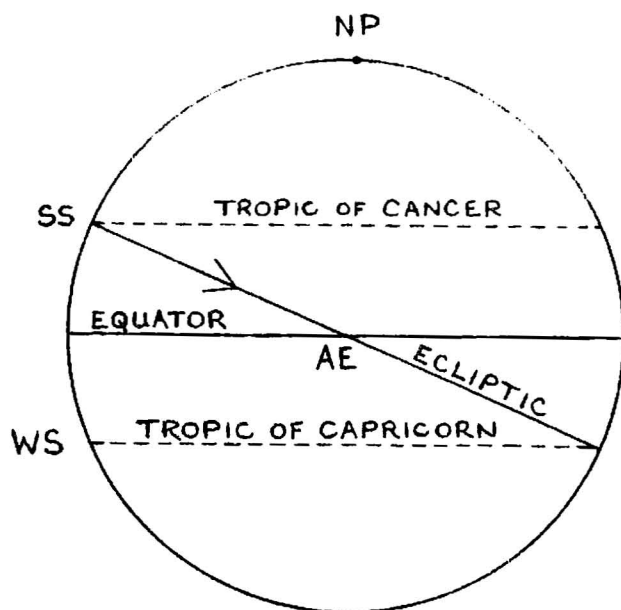


FIG. 4

eastwards among the stars as well as partaking in the daily westward rotation of the whole celestial sphere. Fig. 4 shows diagrammatically the state of affairs. Here SS (summer solstice) and WS (winter solstice) represent the northernmost and southernmost limits of the sun's annual path (αἱ τροπαὶ ἡλίου), reached in June (when the sun is in Cancer) and December (when the sun is in Capricorn) respectively; AE, the point at which the ecliptic intersects the equator, represents the autumnal equinox (September), and on the diametrically opposite part of the sphere (at the back of the diagram, as it were) would be VE, the vernal equinox (March) - these two points are αἱ ἱσημερίαι. The arrow indicates the direction of the sun's annual motion. The

angle between the equator and the ecliptic, i.e. the obliquity of the ecliptic was measured by Eratosthenes, Hipparchus and Ptolemy as $23^{\circ} 51'$ (actually $8'$ too large according to the modern calculated value for Hipparchus' time).

Now the ecliptic is marked by the 12 signs of the zodiac, each spanning 30° ; at any given moment 6 of these signs are above the horizon and 6 below. If at midnight a zodiacal sign culminates

(i.e. crosses the meridian, the north-south line through the observer's zenith), then we know that at midday the sun is in the sign diametrically opposite, i.e. 6 signs away - a fact which obviously one cannot observe directly. Furthermore, the time taken for the 6 signs to rise, at the beginning of which the sun is situated, marks the length of daylight, because at the end of it the sun is setting; the rising times of the zodiacal signs form a very important part of ancient astronomy and in fact gave the impetus to the discovery of trigonometry, yet another of the achievements that must be credited to Hipparchus - but this is not the place to go into this question.

So far, then, so good, but there is still one easily observable phenomenon that is left unexplained - namely the inequality of the astronomical seasons, the fact that the sun takes (in round numbers) 94 days to go from the vernal equinox to the summer solstice, 92 days from there to the autumnal equinox, 89 days from there to the winter solstice, and 90 days back again to the vernal equinox. If the sun's actual course was homocentric with the earth and if its velocity was uniform round it (both these conditions being highly desirable on *a priori* grounds), then these inequalities could not be accounted for. The solution of this problem marks the real beginning of Greek mathematical astronomy. There was one false start, as it were, or we might call it more justly a gallant failure. I refer, of course, to Eudoxus' system of concentric spheres, whereby he tried to account for the observed movements of the sun, moon and planets by postulating for each a set of spheres (the sun required 3) so arranged that the poles of the inmost were carried round by the rotation of the next outer sphere (which had different poles and rotated at a different speed) and so on, the celestial body itself being supposed to be on the equator of the inmost. It was a brilliant piece of mathematical reasoning - far too complicated for me to attempt to describe in detail here - but it just would not *do*. Despite the fact that Callippus, his pupil, added 6 spheres to Eudoxus' total of 27 in an attempt to reconcile the theory with the growing number of more accurate observations, and despite the fact that Aristotle accepted it in principle (*Met.* A 1073 b 17) but with characteristic zeal transformed what was a mathematical abstraction into a physically connected piece of celestial machinery (thereby making it even more complicated by the addition of another 22 back reacting spheres) - despite all this or rather because of all this, the system *still* would not do. It failed, for example, to account for the facts that the looped courses the planets are observed to trace out in the sky are of varying sizes at different times, and that the brightness of the planets varies, thus indicating that they are not at constant distances from the earth. It was not long before it was superseded by the theory of epicycles and eccentric circles, two concepts which dominated planetary theory for some 1800 years, until Kepler proved that the orbits were not circles or combinations of them, but ellipses.

The first man to work out the geometry of epicycles and eccentrics was Apollonius of Perge in Pamphylia c. 230 B.C., but it was Hipparchus in the next century who was responsible for the systematic application of them in astronomy to represent the motions of sun and moon, and Ptolemy who finally completed the theory for the planets. Now an epicycle is a small circle, the centre of which moves round a larger circle called the deferent and the celestial object is envisaged as being located on the circumference of the epicycle. An eccentric is a circle the centre of which is offset relative to the centre of another circle, in this case the earth. To account for the sun's motion, which displays only one irregularity, namely the inequality of the seasons, either of these two hypotheses will suffice. If you choose the radii of your circles and the direction and speed of rotation of your epicycle correctly, then the resultant apparent

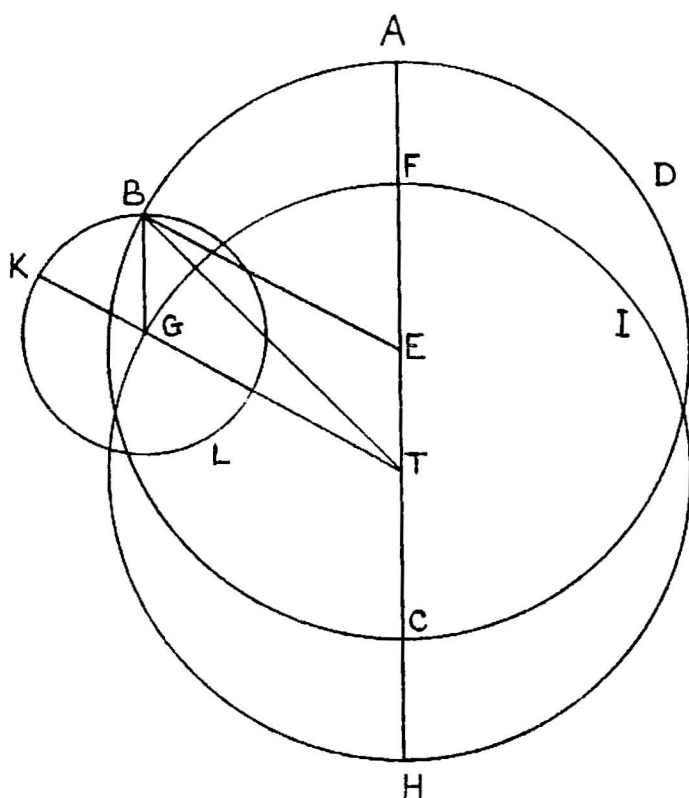


FIG. 5

motion of the sun, as seen from the earth, will be such as to exhibit the observed inequalities in the length of the four seasons. Fig. 5 shows the equivalence of the two theories.

Here T is the centre of the world and of a circle FGHI, the deferent, on which moves the centre G of a smaller circle KBL (the epicycle) round which the sun actually moves in a direction (KBL) opposite to that in which the epicycle's centre G moves round the deferent (FGHI). In the same figure, but on the eccentric hypothesis, E is the centre of the eccentric circle round which the sun moves in the direction ABCD, with a radius (EA) equal to that of the deferent (TF) in the previous hypothesis. If,

after a given time, the sun starting from A has reached a position B on the eccentric, it will have traversed the arc AB subtended by the angle AEB; but to a terrestrial observer this arc will appear to be subtended by the smaller angle ATB. Hence the sun's apparent movement at this part of its course (near apogee) will be slower than its mean movement; conversely, at perigee (near C), the apparent movement will be greater than the mean.

On the epicyclic hypothesis, the sun is assumed to be carried round the epicycle with the same angular velocity but in the opposite direction to that which the epicycle (or rather its centre G) moves round the deferent, and this angular velocity is the same as that with which the sun moves on the eccentric. Thus, in effect, the two movements, of the sun on the epicycle and of the latter on the deferent, cancel each other out and to an observer on the earth produce exactly the same effect as the eccentric hypothesis. For if, after the same length of time as before, the centre of the epicycle has traversed the arc FG on the deferent (such that angle FTG = angle AEB), and the sun itself the arc KB on the epicycle (such that angle KGB = angle GTF), then obviously the sun's apparent position will again be measured by the angle BTA as in the eccentric hypothesis. The radius BG of the epicycle = the eccentricity ET and must always be parallel to the line of apsides AFETCH, while the apogee K of the epicycle lies always on the radius of the deferent TG produced.

In actual fact, for the sun, the eccentric hypothesis was preferred being basically simpler than the other. Now both epicycle and eccentric are essentially mathematical devices for explaining

apparent irregularities as seen from the earth in what ought to be uniform courses; but these devices must, of course, be used in conjunction with the concept of the *mean* sun, moon or planet which (ex hypothesi) is assumed to move with uniform velocity and complete its orbit in the requisite period for the particular body. This mean sun (since we are talking about the sun at the moment) is an imaginary body and is to be contrasted with the true or apparent sun which is what is actually observed. The periodic time for the sun is one year - that is the time that the sun takes for one complete circuit of the ecliptic, i.e. a 360° revolution. The establishment of the length of the year, as accurately as possible, is the essential observational basis without which neither epicycles nor eccentrics are of the slightest use. Hipparchus, followed by Ptolemy, by comparing his own observations of solstices and equinoxes with earlier ones (especially some observed by Aristarchus, c. 280), decided that the tropical year was $1/300^{\text{th}}$ of a day less than $365\frac{1}{4}$ days, i.e. 365 days 5 hours 55 minutes - about $6\frac{1}{2}$ minutes too long according to the modern figure. Expressed in the normal sexagesimal notation (whereby each day is divided into 60ths, each of these into further 60ths and so on - this was standard practice for all astronomical calculations), this becomes 365 d. 14' 48"; dividing this into 360° , we get $0^\circ 59' 8''$ and this is the amount in degrees of the *mean* daily movement of the *mean* sun (ἡ ὁμολη κίνησις). A table can then be constructed of this mean motion in years, months, days and hours; Ptolemy gives this in *Almagest* iii, 2. If you relied on this alone for calculating the position of the sun you would, of course, obtain wrong results, because the sun is seen from the earth *not* to move with uniform speed in all parts of its orbit. This is where the epicycle and eccentric theories come in; they are designed to account for the apparent irregularities by providing the corrections that have to be applied to the mean motion in order to obtain the true position of the sun - but first you must have your mean motion and this is determined by observations over as long a period as possible. The same principle of mean movements then corrected by mathematical refinements holds good for the lunar and planetary theory also. I stress this principle, because it seems to me that most of the textbooks of the

history of astronomy or ancient science do not make it sufficiently clear - epicycles and eccentrics are treated as a sort of magical formula which needs no further explanation.

Anyway, to return to the sun - what is required now is to calculate the corrections that must be added to or subtracted from (hence called προσθαφαιρέσεις) the mean motion in order to find the true place of the sun. This involves the determination of the eccentricity and the apogee by means of a diagram like that of Fig. 6. Here ABGD is the (ideal, mathematical) ecliptic, centre E (the observer), A representing the vernal equinox,

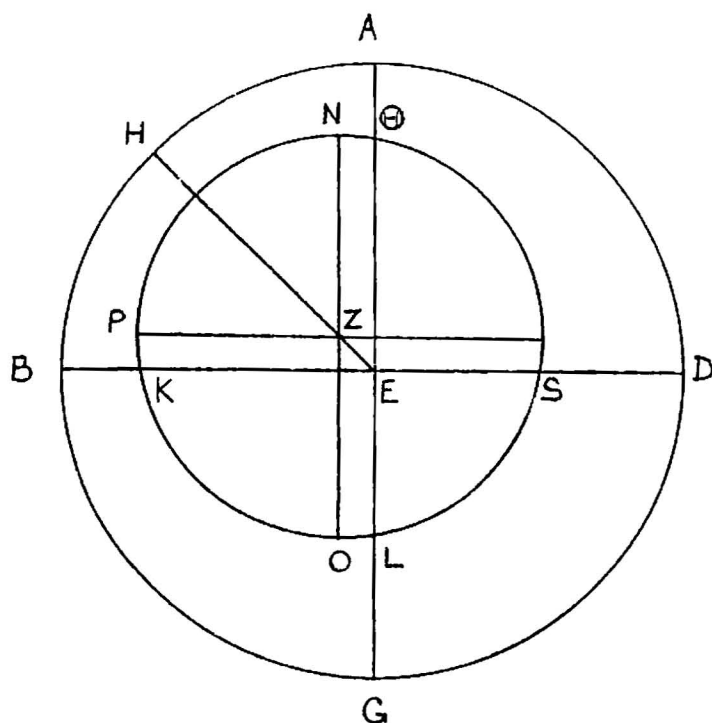


FIG. 6

B the summer solstice, G the autumnal equinox, and D the winter solstice; the sun's eccentric circle (deliberately exaggerated in the drawing, of course) is NPOS centre Z. H is the point of apogee. What has to be determined is ZE, the eccentricity and either the arc AH or HB to fix the position of H (A is 0° Arietis, B is 90° or 0° Cancrī, G is 180° or 0° Librae or $\chi\eta\lambda\omega\nu$, D is 270° or 0° Capricorni). I won't go through the calculation in detail; the arcs ΘK and KL are known as the result of observing that the sun takes $94\frac{1}{2}$ days to go from A to B and $92\frac{1}{2}$ days from B to G - since the mean sun traverses $0^{\circ}59'8''$ in one day, the total arc ΘKL amounts to $184^{\circ}20'$. Given this datum, by dropping suitable perpendiculars, one can prove that the apogee, H, is at $5^{\circ}30'$ Geminorum (long. $65^{\circ}30'$). This, according to modern calculations, is reasonably accurate for Hipparchus' time; Ptolemy should have found it at 11° Geminorum, because the position of the apogee gradually changes (partly owing to the effect of precession), but since he was using Hipparchus' data (which he claimed were exactly the same as he himself had observed) it is not surprising that he found the same result. There is other evidence, too, that Ptolemy was not such an accurate observer as Hipparchus.

The next step is to find the values of the angle TBE (in Fig. 5) which represents the difference between the sun's movement as viewed from the earth T and its own uniform motion round the eccentric circle (or the epicycle) as given by the table of mean movement. Clearly, when the sun is in the semi-circle ABC (vernal equinox to autumnal equinox, 0° - 180°) the correction must be subtracted from the mean position and added when the sun is traversing the opposite part of its course (the maximum irregularity, $2^{\circ}23'$, occurring at the solstices). Then a table of $\pi\rho\sigma\theta\alpha\chi\alpha\rho\acute{\epsilon}\sigma\epsilon\iota\varsigma$ is drawn up, and this, used in conjunction with the table of mean motion, enables the sun's true position to be found at any given time. Finally, Ptolemy shows, by working backwards from what he says is one of his most accurately observed equinoxes in 133 A.D. (actually it seems to have been 31 hours too late), how to calculate the position of the sun at midday on 1st Thoth = 26 Feb. 747 B.C. This date marks the beginning of the era of Nabonassar, which was chosen as the epoch for all the Hipparchian-Ptolemaic solar, lunar and planetary tables; you have to start from somewhere and this date was a reasonable choice, since no Babylonian astronomical observations (which played a vital part in Greek mathematical astronomy) were available before this year. To reckon the lapse of time between astronomical observations, the Egyptian year of 12 months of 30 days + 5 additional ('epagomenal') days was always used; this 'wandering' year (so-called) soon became out of step with the seasons (each date making a complete circuit in 1460 years), but this was of no consequence to the Hellenistic astronomers, who were only interested in a rigid and exact time-scale, which was precisely what the Egyptian system provided (Neugebauer calls it "the only intelligent calendar which ever existed in human history"). Given the length of time in years, months, days and hours, then by subtraction of whole circles (i.e. multiples of 360°) the sun's motion in degrees measured on the ecliptic can readily be determined from the tables.

So much then for the theory of solar movement. I have spent what may seem a disproportionate amount of time on it, because (a) the sun is obviously of fundamental importance in astronomy, and (b) its theory demonstrates the mathematical principles of Greek astronomy in their simplest forms. Knowledge of the sun's position is a basic requirement for the computation of eclipses, for example, and eclipses were used to determine the moon's position with far greater accuracy than could be achieved by direct observation; very sensibly, the Greek astronomers placed more reliance on their superlative mathematical techniques than on their observational methods.

Now the motion of the moon is incredibly complicated - just how complicated is beautifully explained by Neugebauer in chap. 5 of that brilliant work (indispensable for the historian of ancient science) *The Exact Sciences in Antiquity*, 2nd ed. 1957. The motions of the planets are even more complicated. The mathematical theory to represent these motions therefore becomes necessarily more complex; but the basic principles of mean motion and then the application of epicycles and eccentrics and combinations of the two devices remain the same - and, as with the sun, it is observation over as long a period as possible that provides the essential parameters for the elaboration of the theory. For the moon, which deviates in latitude about 5° each side of the ecliptic, Hipparchus at first thought that a simple epicycle carried on a deferent homocentric with the ecliptic would suffice to account for the phenomena; but he himself noticed that, although this construction agreed with observations of the moon's position at syzygy (new and full moon) it failed to agree at quadrature (first and last quarter), and furthermore the discrepancy was not constant but varied from 0° to a maximum of $2\frac{1}{2}^{\circ}$. It is one of Ptolemy's greatest contributions to astronomy that he succeeded in accounting for this second inequality (called in modern terminology, the evection) of the moon's motion. He did it by postulating that the centre of the deferent was not the earth but eccentric to the earth on a line joining perigee and apogee, the line of apsides; the effect of this combination of the two devices was that the moon moving on the epicycle, *as seen from the earth*, appeared to describe an elliptical orbit. There is actually a third inequality (called variation) which Ptolemy attempted to deal with by further complicating the theory by supposing that the line of apsides of the epicycle, instead of passing through the earth, is always directed to a point offset from the earth the same amount as the centre of the deferent but on the opposite side - this gives him yet another table of corrections to apply to the mean motion. The net result in the case of the moon was that theory could be reconciled with observation to within the limits of error of the available instruments.

For the planets, Hipparchus was unable to advance any satisfactory theory, owing to lack of sufficient observations; he knew that the traditional Eudoxian system of concentric spheres was inadequate and he surmised that it was combinations of epicycles and eccentrics that would eventually give the right answer - but this problem he had to leave to his successors. As Ptolemy (who calls Hipparchus *φιλαληθέστατος* and *φιλόπρονος*) tells us (*Alm.* ix, 2), "not having at his disposal the large number of accurate observations which he himself provided for me" Hipparchus confined himself to pointing out the discrepancies between contemporary theory and what was actually observed and did not attempt a comprehensive explanation. Note again the vital importance of observations over as long a period as possible in order to provide the basic parameters for the mathematical theory; Ptolemy was fortunate in having Hipparchus' results to build on. Books 9-13 of the *Almagest* deal with the planets and here Ptolemy displays a consummate mastery of mathematical techniques and of the observational material. He treats each planet as a separate problem, varying his treatment to suit the special circumstances of each case. Epicycles and eccentrics are the basic devices used; in addition he makes further use of the concept of an imaginary point located on the opposite side of the centre of the deferent with regard to the earth, that we have already seen used in the last refinement of the lunar theory. Fig. 7 shows the basic construction for Venus, Mars, Jupiter and Saturn (borrowed from Derek Price's *Equatorie of the Planetis*, 1955, p. 100). Here E is the imaginary point, later known as the equant; the two most important angles are ATM, which governs the position of the epicycle centre on the eccentric circle, and POB which governs the position of the planet on the epicycle, round which it is assumed to move with constant angular velocity.

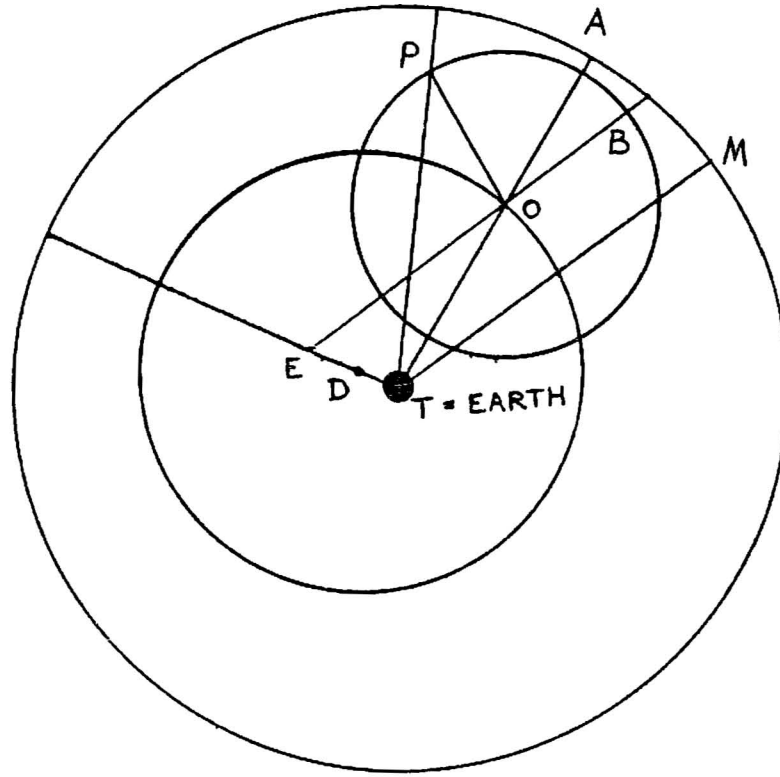


FIG. 7

EB and TM are kept always parallel. For Mercury, Ptolemy found it necessary to postulate further that the centre of the deferent D, instead of being stationary, itself describes a small circle of radius DE. From the point of view of the modern heliocentric theory, for the outer planets, Saturn, Jupiter and Mars, the epicycle corresponds to the motion of the earth (i.e. the annual rotation) and the eccentric to that of the planet itself round the sun; for the inner planets, Mercury and Venus, the situation is the reverse.

As you will readily perceive, this notion of an imaginary point, the equant, observed from which (and not from either the earth or the centre of the deferent) the centre of the epicycle is supposed to move uniformly, i.e. the line from the equant to the centre of the epicycle moves so as to traverse equal angles in equal times (because this is the *raison d'être* of the equant), this notion is, in fact, an elaborate form of cheating in respect to the time-hallowed principle (dating probably from the Pythagoreans) that the celestial bodies being divine must move in uniform circular orbits. The later commentators and the Neo-Platonists do not fail to point this out; it obviously bothered the philosophers, but not, I think, the mathematicians (despite Sambursky, who in *The Physical World of Late Antiquity*, 1962, p. 140 claims to detect "a curiously apologetic air" in Ptolemy). It would be a fascinating task (and very illuminating for the history of Greek thought) to trace the development of ideas about the nature and movements of the heavenly bodies against the background of contemporary thought from Homer and Hesiod through the Pre-Socratics, Plato, Aristotle, Hipparchus, Ptolemy and the Neo-Platonists up to mediaeval times; but that and other equally fascinating subjects, such as the influence of Babylonian astronomy on Greek, the rôle of astrology (vastly underrated, in my opinion), the relationship between theoretical science and technology in the ancient world - these I must leave to other occasions.