WHEELS WITHIN WHEELS - THE COMPLICATION OF ASTRONOMY

Although Aristarchos' observations had no immediate effect on Greek cosmology, the Greek astronomers of the next few centuries continued to make even more careful observations of celestial phenomena. The improved observations made it clear that the heavenly cycles were not simple uniform circular motions, and cosmology became submerged in a battle to "save the appearances"; that is, to reconcile the growing awareness of celestial complexity with the conceptual purity of spheres and uniform circular motions.

1. Hipparchos of Nicaea

Hipparchos brought the art of observation to the greatest refinement achieved by the Greek astronomers. He worked between about 162 and 126 B.C.; as with Aristarchos, his main works have been lost but we know of his achievements through later scholars.

Hipparchos determined the times of solstices and equinoxes by observation and computed the elapsed time between them and observations by Aristarchos about 150 years earlier. He concluded from these data that the interval between successive appearances of the Sun at a given solstice or equinox was slightly less than 365 1/4 days (by about 1/300 day). He also knew that the "Babylonian" year - the time taken by the Sun to return to the same apparent place among the stars - was longer than 365 1/4 days. He correctly concluded that the difference meant that the place in the sky at which the Sun stands at the time of a given equinox moves slowly relative to the stars. This phenomenon is known as the precession of the equinoxes.

At an equinox, the Sun stands at one of the two crossovers of the ecliptic (its apparent path relative to the stars) and the celestial equator (the projection among the stars of the Earth's equator - Figure 1). Hipparchos' measurements showed him that each time the Sun crossed the equator in a given direction it was at a slightly different place among the stars - only thus would repetition relative to the equator and repetition relative to the stars take different lengths of time. This meant that either the ecliptic, or the celestial equator, or both, must gradually change location against the stellar background. As seen from Earth, this would mean that the star sphere appeared either to drift relative to the ecliptic, or relative to the equator, or both.

In compiling an accurate catalogue of the positions and brightnesses of

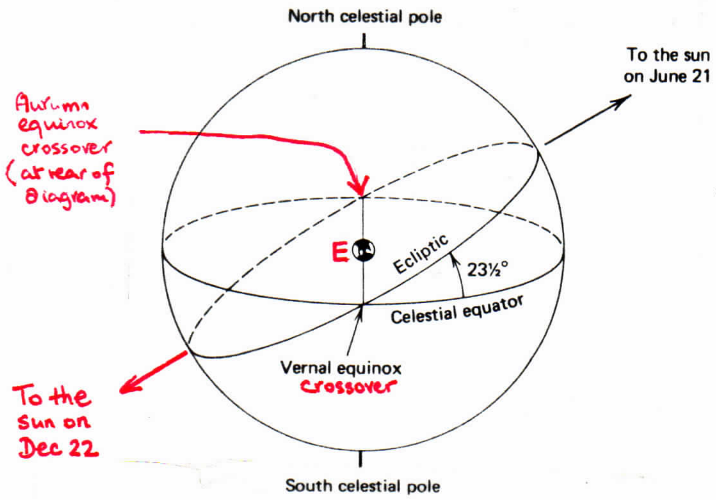

North celestial pole
To the sun
on June 21
Autumn
equinox
crossover
(at rear of
diagram)
E
Ecliptic
23½°
Celestial equator
Vernal equinox
crossover
To the
sun on
Dec 22
South celestial pole

Fig. 1

850 stars, Hipparchos checked the apparent positions of bright stars in the sky relative to the equator and the ecliptic. By comparing his observations with those of the same bright stars made in Aristarchos' time, he found that the slow apparent motion of the star sphere was entirely across the equator; the stars appeared not to drift across the ecliptic. In terms of the Aristotelian cosmology, Hipparchos' observations meant that a slow but steady extra wobble had to be added to the motion of the supposedly perfect outermost sphere, which contained the stars; also that this motion was exactly matched in the motion of the Sun, so that the ecliptic did not change its orientation relative to the stars. This arbitrary increase in complexity was not the only one to arise, however.

Hipparchos also found that the four seasons were not of equal length; for example Spring (the interval between the Spring Equinox and the Summer Solstice) was 94 1/2 days long while Summer (the interval between the Summer Solstice and the Fall Equinox) was 92 1/2 days. If the Sun travelled around the ecliptic at a steady rate, all four seasons would necessarily be exactly the same length. The inescapable conclusion was that the Sun must appear to move at a variable rate around the ecliptic, fastest in Fall and slowest in Spring, the variation being about 8%. Hipparchos concluded that if the Sun actually moved at constant speed around a circle, then to generate the observed variation the centre of that circle must be offset from the Earth, as in Figure 2.

Observations of the intervals between eclipses of the Moon showed him that the Moon also moved at an (even more complicated) variable rate around its apparent path, as if travelling uniformly around a circle whose centre was itself in motion around the Earth.

There is no evidence that these discoveries led Hipparchos to question the basic cosmological assumption that the heavenly bodies should move uniformly around circles. Rather, in seeking to describe the appearances of the heavenly motions, he supposed merely that the perfect circles were not centred on the Earth. This was an unpleasing, but minor complexity.

The planets were much worse.

2. The Motions of the Planets

It had been known since the earliest days of astronomy that the five other wanderers across the star sphere - Mercury, Venus, Mars, Jupiter and Saturn - were stellar in appearance but most unstellar in movement. For example, Figure 3

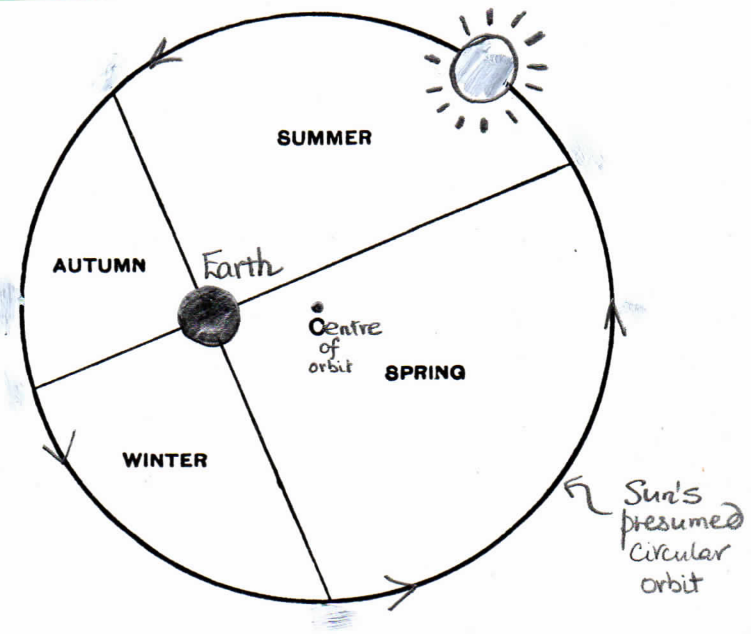
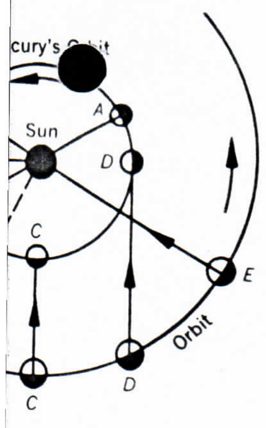

SUMMER
AUTUMN
Earth
Centre of orbit
SPRING
WINTER
Sun's presumed circular orbit

Figure 2

Fig. 3



ıd the earth in their orbits rn the book to look along ıe earth and Mercury, and y's changing position with At positions *A* and *E*, Mer- sun and hidden by it. At is directly in front of the ıible. The orbit of Venus is een those of Mercury and

2:00. But it does not ved along one-twelfth o hands line up again. n the hour hand has between the lining up

e ear period = one ıands (1.09 hours) to iter's period may be ould not surprise you about 12 years. The by similar reasoning . Copernicus showed out 30 years.

e 4-5 shows the sort stial sphere on which shown, and each dot of the stars at two-

February 15 (M_1) as nidpoint on the loop ons were made two *ne-sixth of its orbit* arth when Mars ap-

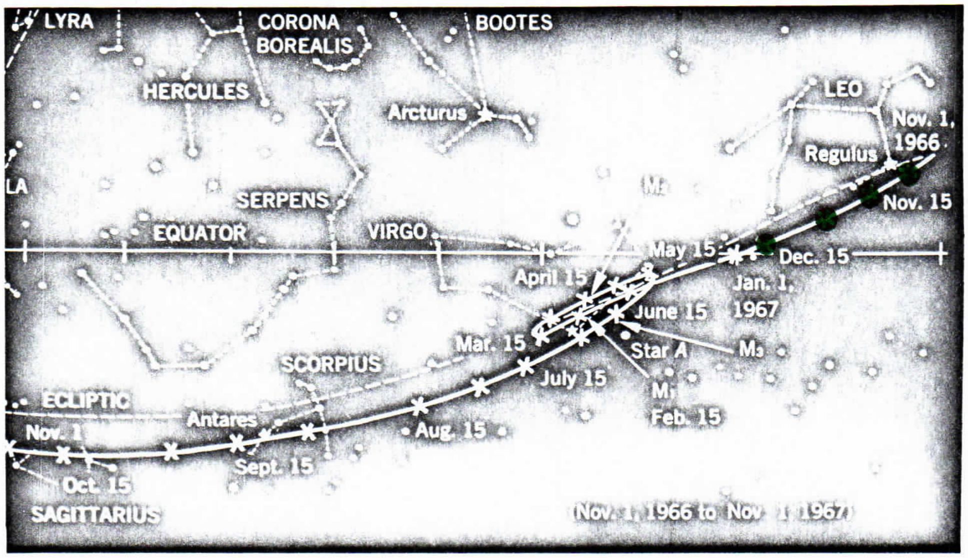


Fig. 4-5 The path of Mars (Nov. 1, 1966 to Nov. 1, 1967).

peared at M_1 can be plotted at E_1 and its position when Mars appeared at M_2 can be plotted at E_2.

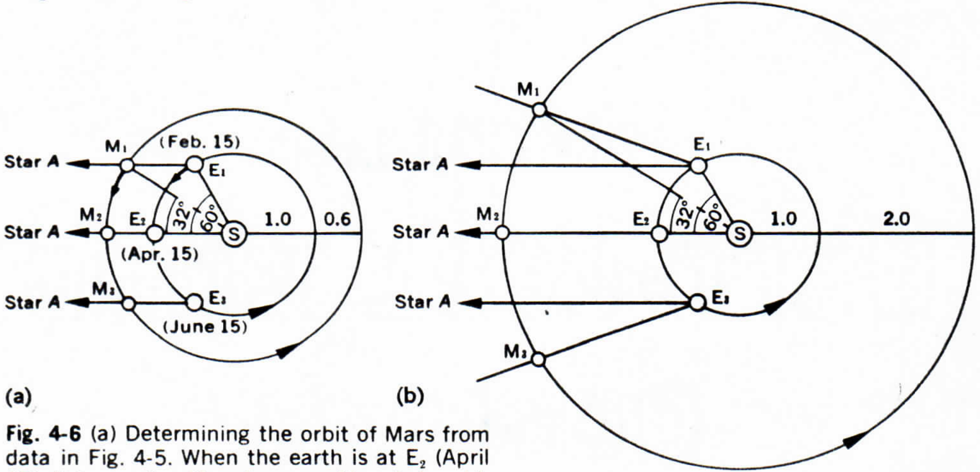


Fig. 4-6 (a) Determining the orbit of Mars from data in Fig. 4-5. When the earth is at E_2 (April 15), it is passing Mars because Mars is in mid-loop in the sky. Therefore, earth, sun, and Mars are lined up (SE_2M_2). Mars is seen near Star A in the sky, as in Fig. 4-5, so the line-up is SE_2M_2 Star A. Two months earlier, on February 15, the earth was 60° farther back on its orbit at E_1 and Mars was about 32° back on its orbit at M_1. But Mars was seen near Star A then, too, so the line-up was E_1M_1Star A (parallel to SE_2M_2Star A, because Star A is so far away). On June 15 the earth is at E_3 and Mars at M_3, again near Star A in Fig. 4-5, so the line-up E_3M_3Star A is again parallel to SE_2M_2Star A. When Mars' orbit is drawn to fit these observed directions, it must be 1.6 times larger than the earth's orbit. (The ratio is more accurately 1.52 as given in Table 4.) (b) If you draw Mars' orbit three times larger than the earth's, *the observed directions E_1M_1, E_2M_2, and E_3M_3* do not come out lined up with Star A.

illustrates the motion of Mars in a typical year (1966/7). Mars began the year moving Eastward against the stars, at a rate which gradually decreased - until it momentarily stopped among the stars in March and looped back towards the West on a different path! The Westward motion came to a halt in mid-May, whereon the planet accelerated off towards the East once more.

Such retrograde loops were known to be performed regularly by all five planets. The major differences were in the sizes of their loops and the fact that Mercury and Venus appeared to oscillate back and forth around the position of the Sun in the sky whereas Mars, Jupiter and Saturn carried out their loops when opposite the Sun in the sky. Of the latter three, Mars had the biggest, yet fastest, retrograde loops while Saturn had the smallest yet slowest; all three appeared uncommonly bright while performing the mysterious loops.

In these strange facts lay a vital cosmological clue - but the Greeks did not perceive this. Instead they saw apparently needless complexity in the skies. While preserving their basic tenet of uniform circular motions for all heavenly bodies, they were forced to complicate the geometry of the assumed circles in the effort to "save the appearances". The theoretical model was arbitrarily made more complicated to fit the unexpected details of what was observed.

3. Claudius Ptolemy and the Almagest

The three centuries after Hipparchos added no fundamentally new phenomena to these problems. The Greek culture was declining and the more militaristic and empirical Romans were dominating the Mediterranean. Around 140 to 150 A.D. the Alexandrian astronomer Claudius Ptolemy, armed with Hipparchos' data and some later measurements, compiled in one treatise - his "Almagest" - all that was then known about the celestial cycles. This included the motions and variations in brightness of the planets, the detailed motions of the Sun and Moon and the precession of the equinoxes, as well as a catalogue of the positions of 1022 stars relative to the ecliptic, with estimated brightnesses (or "magnitudes") for each. A vital part of the book was its systematisation of predictions of the locations of the Sun, Moon and planets - a set of recipes for computation of their positions relative to the stars at any given time. Ptolemy constructed these recipes within the conceptual background of Aristotelian geocentric cosmology. He wrote:

> "We believe that the object which the astronomer must strive to achieve is this: to demonstrate that all the phenomena in the sky are produced by uniform and circular motions ... ".

The prediction of the celestial phenomena had to be couched in terms of the "perfect" forms of motion held to be appropriate for heavenly objects, by now for over 600 years. The geometrical monstrosity which ensued demonstrates the extreme lengths to which the later Greeks were prepared to go in order to reconcile the observed phenomena with the principle of uniform circular motion.

The basic ingredients of the scheme were the epicycle and the deferent, used by Hipparchos before Ptolemy, but brought in the "Almagest" to the form which events would have dominate European astronomical thought for the next 1500 years. The nonuniform apparent motion of a heavenly object around the Earth was regarded as composed of two parts - uniform motion of the object on a small circle (the epicycle) around a point which itself moved uniformly around a larger circle centred on the Earth (the deferent - Figure 4). The resultant combined motion was a variable-speed loop-the-loop (or oval, depending on the relative sizes of epicycle and deferent and the relative rates of motion around them). By adusting all four parameters - two circle sizes and two rates - the peculiar apparent motions of the Sun, Moon and planets could be matched. The variation in distance from the Earth could also explain the variations in brightness of the planets.

At least, the phenomena could be approximated; but even this complicated a model could not in fact produce sufficient agreement with the observations available to Ptolemy. To improve the agreement with the data Ptolemy was forced to make the epicycle centres travel at a variable rate around their deferents. To avoid naked conflict with the basic presumption of uniform motions Ptolemy then "invented" a point called the "Equant" (Figure 5) within each deferent. The centre of the epicycle was to travel around the deferent so that it swept out equal angles around the Equant in equal times; its motion was thus "uniform" as seen from the Equant. But neither the Equant nor the Earth were at the geometrical centre of the deferent - they stood equally on each side of it as in Figure 5. Adjusting the location of the Equant provided Ptolemy with yet another variable parameter which he could juggle to fit the observed motions.

The artificiality of this system is obvious to modern eyes. It did mere lip-service to the original concept of uniform motion on a circle. The Equants were invented merely to be the points about which the motions of the epicycle centres would appear uniform; these motions were not circular about

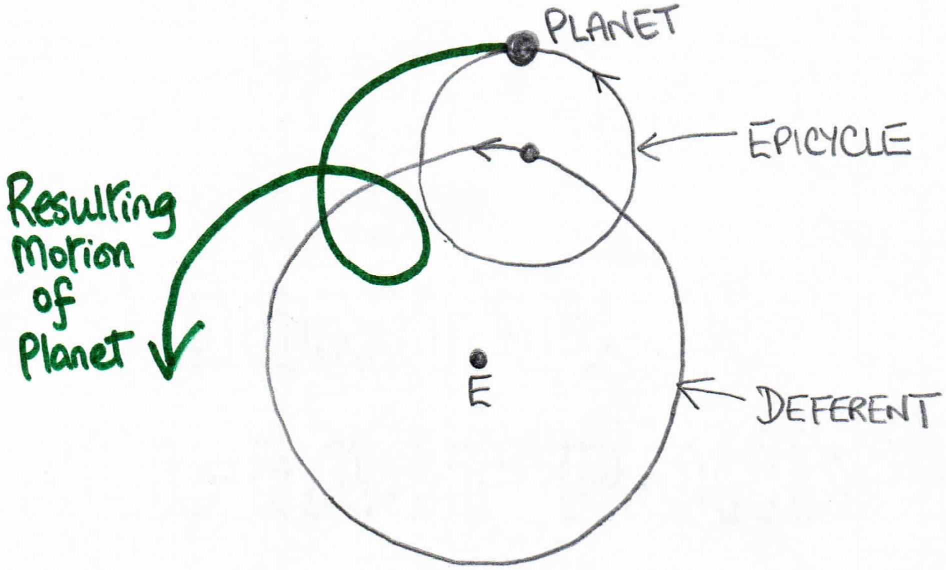
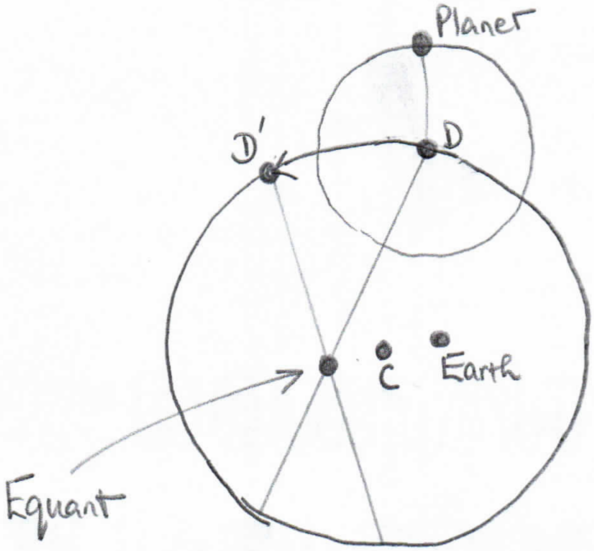


Fig. 4



Centre of epicycle travels from D to D′ so that equal angles around Equant are swept out in equal times. Equant is offset from centre of Deferent (C). Earth (E) is equally offset in direction opposite to Equant

Fig. 5

either Equant or Earth. How could Ptolemy have been satisfied with such subterfuge?

He may well have wished for something simpler, but he was intent on providing a good basis for predictions of the heavenly configurations and so could not stop at an inaccurate model. He also lacked any guiding notion of why the motions of heavenly objects should take any particular form other than the presumed circles. For in the Aristotelian world-view, still prevailing, the motions of heavenly objects could not be related to any terrestrial experience. Ptolemy explicitly rejected the non-Aristotelian alternative which later opened the door to fresh thinking about the forms of the motions, because these alternatives involved rotation of the Earth. Indeed he wrote:

> "Some philosophers think that nothing prevents them from assuming that the Heaven is resting and that the Earth in nearly a day rotates from West to East ... they did not perceive how very ridiculous this would be with regard to the phenomena around us and in the air ... we would never see a cloud, or anything that flies or is thrown, move towards the East, because the Earth would outdo them in motion towards the East so that all the others, outdistanced, would appear to move towards the West".

The rotation of the Earth seemed to conflict with the observations of motions near it, and so the way was barred to cosmologies such as that of the long-dead Aristarchos. The main features of Ptolemy's system are outlined in Figure 6; the details of the Equants are omitted, for clarity. A particularly notable feature of the system is the fact that the movement of the epicycles of Mercury and Venus had arbitrarily to be locked to the movement of the Sun - to prevent Mercury and Venus from straying too far from the Sun in the sky, in conflict with observation. Thus the Sun seemed somehow to influence the motions of these two planets, but not the others. Here again was a detail which might have illuminated the way through the fog; but to Ptolemy it remained obscure.

4. Decline

Ptolemy's "Almagest" became the last word of Greek astronomy not because it represented an unsurpassable pinnacle of astronomical achievement but because the culture which had produced it was about to fall apart. The Mediterranean society had been built up on slavery and gold and silver coin. Commercial paralysis from the exhaustion of the Spanish mines, pestilence brought in from Asia in 188 A.D., and the overthrow of the ruling classes by the peasants and their soldier-leaders brought the intellectual life represented by Ptolemy to an

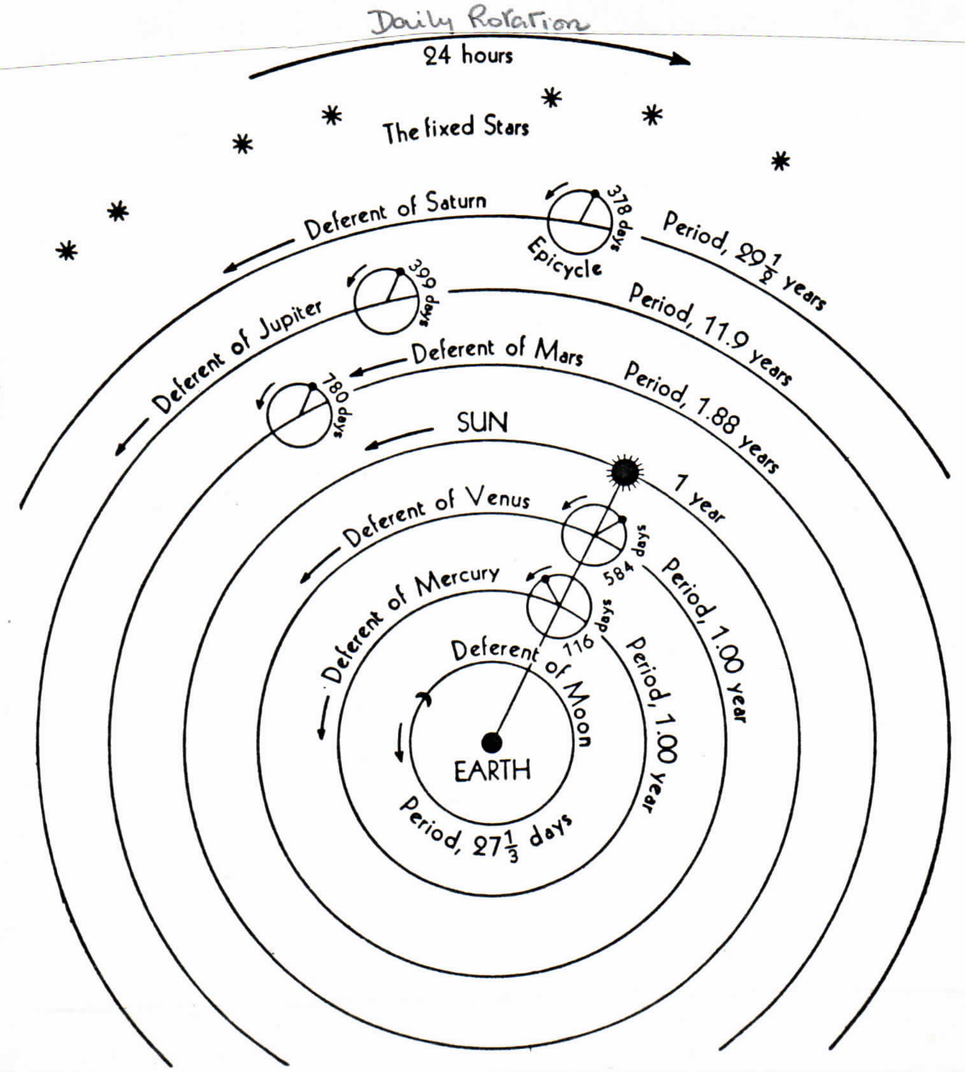


Fig. 6 Ptolemy's system (~A.D. 150)
Epicycles and Deferents not to scale, Equants not shown
Note the Earth - Mercury - Venus - Sun connection

end within two centuries of the writing of the "Almagest".

By the Seventh Century A.D. the expanding Arab Moslem culture represented the only major continuance of scientific learning in the Western world, and the Arabs did not innovate. They translated the surviving Greek texts and continued measurements of astronomical phenomena in the Greek tradition (but with less accuracy than Hipparchos' observations). Astronomy did not fall back far under the Arabs, but neither did it advance.

The Eleventh Century saw a renaissance of intellectual life in Europe. Contact with the Islamic world led to rediscovery and retranslation of the Greek texts which were by then up to 1600 years old, yet which contained what seemed to the Europeans to be a highly sophisticated world-view. In the intervening millenium even the concept of a spherical Earth had disappeared from European thinking - it was rediscovered not by fresh investigation of the contemporary world but by reading the observations and insights of men who had lived further in the past of these renascent Europeans than the Eleventh-Century Europeans are from us!

Consider what would be the impact today if we discovered some 1000-year-old texts containing astronomical information we have yet to discover for ourselves, scientific ideas beyond the knowledge of today's experts, and mathematical methods unknown to our scholars. The old texts were not simply read and assimilated overnight - they were venerated. To their readers, the Golden Age of learning appeared to have been in the past, while contemporary knowledge was limited and untrustworthy. The wealth of ancient ideas was to be studied and re-understood, not questioned.

The reassimilation was not always easy. The Castilian King Alfonso X ("Alfonso the Wise") remarked as he was introduced to the Ptolemaic system:

> "If the Lord Almighty had consulted me before embarking upon the Creation, I should have recommended something simpler".

Nevertheless it was under the aegis of King Alfonso that a set of astronomical tables was produced in 1252 A.D. using the Ptolemaic system for the computation of planetary configurations. The Alfonsine Tables became the standard tables of numerical astronomy for 300 years.

5. Canon Koppernigk of Frauenberg (Copernicus)

On the last page of the copy of the Alfonsine Tables owned by Nicolas

Koppernigk, a canon of the cathedral at Frauenberg in what is now Poland, is a handwritten annotation:

> "Mars surpasses the numbers by more than two degrees; Saturn is surpassed by the numbers by 1 1/2 degrees."

Koppernigk (Fig. 7), born in 1473, had been appointed by his uncle to a sinecure canonry at Frauenberg in 1497. Assured of a lifetime income for less-than-arduous duties he promptly departed for Italy where he remained until 1506 obtaining a university education in canon law, astronomy, mathematics and medicine. In February and March 1504 there occurred a most unusual astronomical configuration - all five visible planets entered the constellation of Cancer, producing a rare series of close approaches in the sky. Such close approaches provided the most critical data for the definition of a planetary model such as Ptolemy's and were carefully watched by astronomers. Koppernigk's notation in his copy of the Alfonsine Tables corresponds to these events; the Tables mispredicted the times of the close approaches in 1504 by as much as ten days, and the extent of the errors was duly recorded by the canon.

There was need to reform the Tables. There was also need to reform the calendar, as the "slippage" between the Julian calendar and astronomical observations of the true solar calendar had by then accumulated to nearly eleven days (see Chapter Two). As a functionary of the Catholic Church trained in mathematics and astronomy, Koppernigk was concerned about such matters.

He sought to update and improve the Ptolemaic system, which he considered "neither sufficiently absolute nor sufficiently pleasing to the mind". His attack on the problem was firmly Aristotelian in concept. In his "Commentariolus", an introductory outline of his proposed revisions written around 1510-1514, he notes that

> "Our ancestors assumed a large number of celestial spheres for a special reason: to explain the apparent motion of the planets by the principle of regularity."

Koppernigk's first criticism of Ptolemy was that he had not validly used this principle - he considered Ptolemy's Equants to be a sham which should be dispensed with:

> "Having become aware of these defects, I often considered whether there could perhaps be found a more reasonable arrangement of circles from which every apparent inequality would be derived and in which everything would move <u>uniformly about its proper centre</u>, as the rule of absolute motion requires."

Copernicus. *(Yerkes Observatory.)*

Fig. 7

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COPPERNICUS.

[*To face p.* 94.

Ptolemy was not merely inaccurate - he was also not rigorously Aristotelian enough for Koppernigk! Because he discarded Ptolemy's equants, Koppernigk was forced to invent further epicycles to "save the appearances". Still he perceived a simplification that had apparently escaped Ptolemy - if the Earth and planets were assumed to circulate around the Sun, the retrograde loops could be explained as an appearance produced by combining the motions of the planets with the motion of the Earth (Figure 8). Furthermore, the affinity of Mercury and Venus for the direction of the Sun could be explained if their orbits lay interior to that of Earth (Figure 9). And if, after all, the Earth moved, as Aristarchos had claimed almost 1800 years earlier, then Hipparchos' precession of the equinoxes could be produced by a motion of Earth's poles relative to everything in the sky; this was simpler than the correlated behaviour of the stars and the ecliptic which had been visualised earlier (see under 'Hipparchos' above). Koppernigk's rearrangement also meant that the motions of the planets became steadily slower with increasing distance from the centre of the System, an elegance which he appreciated. The mathematically-trained canon saw these to be powerful simplifications, and they constitute his major contribution to cosmology. He could not however ignore the objections raised against Aristarchos by the Aristotelian school, whose teachings he accepted. Did the Earth really move?

For all Koppernigk's insight in seeing the geometrical simplification possible in a heliocentric model, he had little to offer against arguments (now almost 2000 years old) that real motions of the Earth would imply gross effects at its surface which patently did not take place. Koppernigk did not refute these arguments, but tried to side-step them with the following doublethink (from his "Book of the Revolutions", published in 1543):

> "Now if one should say that the Earth moves, that is as much as to say that the motion is natural, not violent; and things which happen according to nature produce the opposite effects to those which occur by violence. Things subjected to any force or impetus, gradual or sudden, must be disintegrated, and cannot long exist. But natural processes being adapted to their purpose work smoothly."

In other words, he was prepared to say that the nature of a motion depended on how it was initiated; "natural" motions involved no forces and so could not produce the disruptive effects that had been predicted. At this point Koppernigk blinded himself to what finally proved to be the nub of the whole issue - the description of motion and its relationship to the everyday

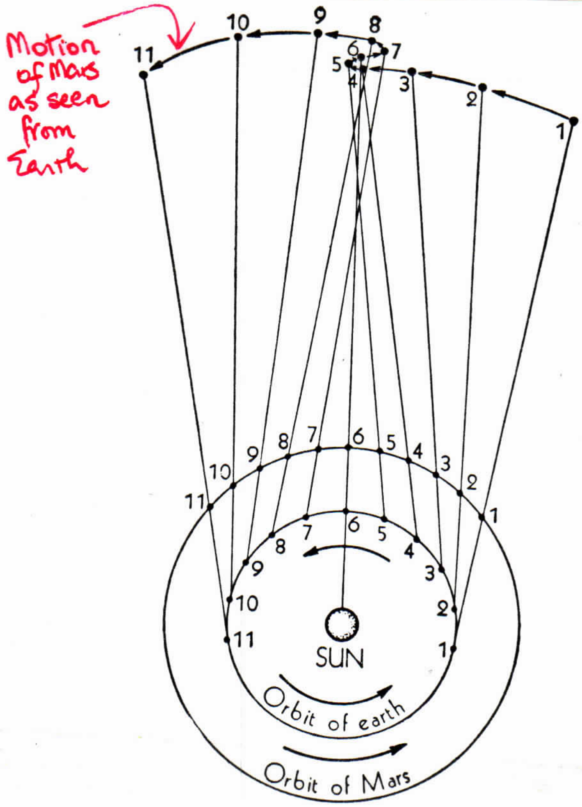
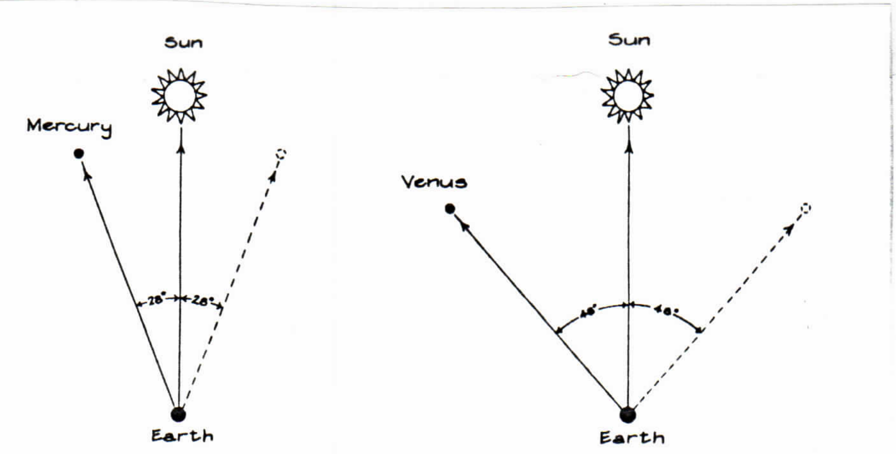


Fig. 8

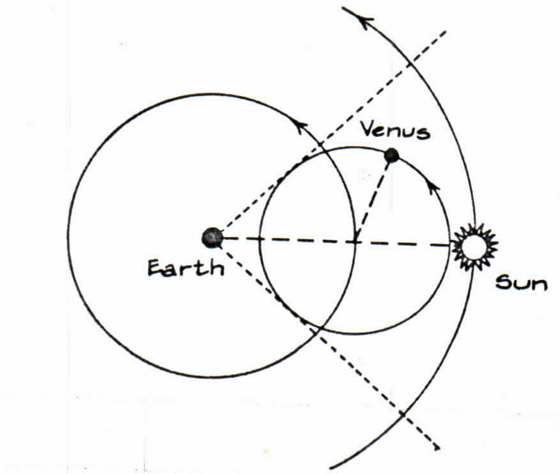
Explanation of retrograde motion of Mars in Copernican system. As Earth swings past Mars in orbit, the Earth-Mars line swings Westwards on the sky between configurations 5 and 7.



a) <u>The observation</u> – Mercury never appears more than 28° away from the Sun in the sky

Venus never appears more than 48° away from the Sun

b) <u>Interpretation in Ptolemaic system</u> – centre of Venus' epicycle is mysteriously controlled by Sun



c) <u>Interpretation in Copernican system</u> – orbit of Venus lies inside orbit of Earth

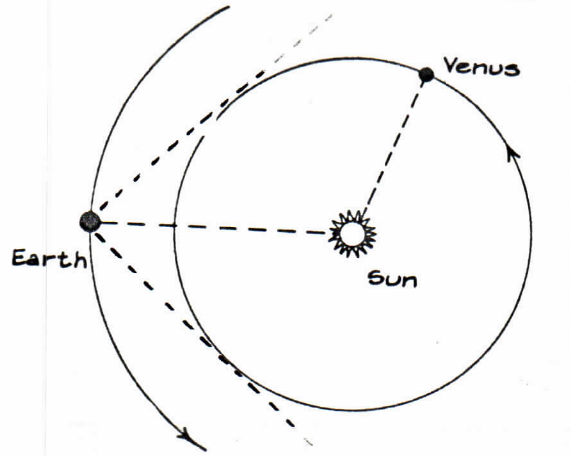


Fig. 19

concept of force, or effort. He adopted rigorously Aristotelian thinking about motions while moving away from the corresponding thinking about planetary geometry. In the same "Book of the Revolutions" he came close to a breakthrough again with his statement that:

> "We must admit the possibility of a double motion of objects which fall and rise in the Universe, namely the resultant of rectilinear and circular motion. Thus heavy falling objects, being specially Earthy, must doubtless retain the nature of the whole to which they belong."

Here Koppernigk stood next to the conceptual bridge - the concept of inertia - which was to lead others to the other side of the intellectual chasm; but the fog persisted, and he turned away only paragraphs later to the following philosophical argument:

> "Further, we conceive immobility to be nobler and more divine than change and inconstancy, which latter is thus more appropriate to Earth than to the Universe. Would it not then seem absurd to ascribe motion to that which contains or locates, and not rather to that contained and located, namely the Earth?"

Evidently the ancient conceptual bonds were still too heavy for Koppernigk to shake them off.

His adoption of a heliocentric system (Fig. 10) for the description of the heavenly motions freed him from the grossest nonuniformities which challenged Ptolemy - but Koppernigk's final model, published in the year of his death as the "Book of the Revolutions", was even more monstrous than the one it replaced. Having eliminated Ptolemy's epicycles he was briefly ahead in terms of simplicity, but discarding the Equants as well forced him to invent new epicycles in order to fit the data. Worse still, by using more recent data in addition to Hipparchos' very careful work Koppernigk introduced bad data (poor measurements, misidentifications of planets, errors in copying) recorded during the Arab stewardship of astronomy. The falsity of these data did not confuse later analysis, but Koppernigk's system became more and more complex as he continued to add further motions in the attempt to explain configurations that had never existed. By the time he was done, a total of 48 epicycles entered into his system, over four times as many as there were in Ptolemy's original model.

The "Book of the Revolutions" was not exactly a best-seller. Less than

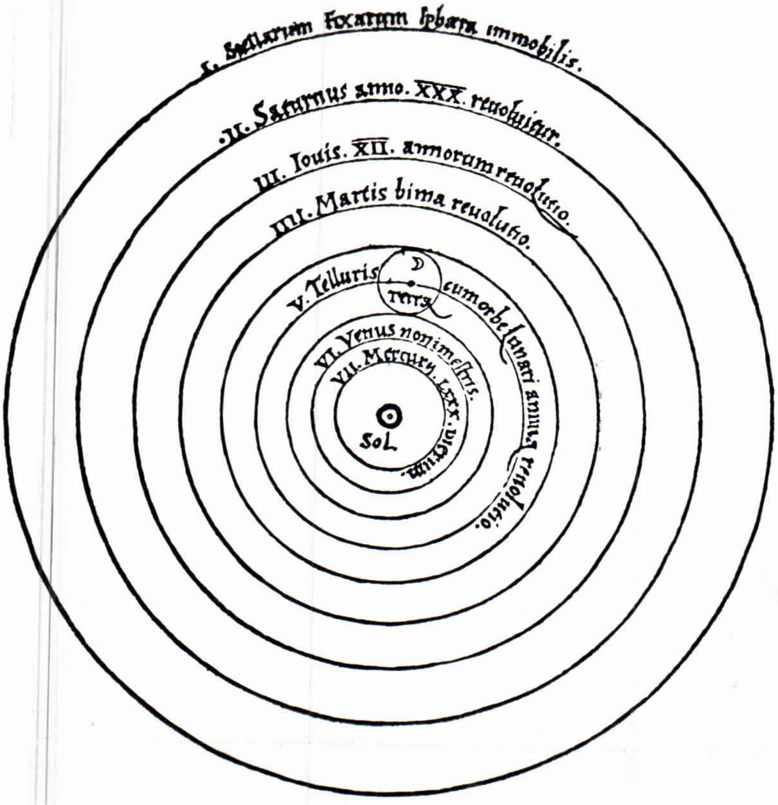


Fig. 10 The Copernican System, from the "Book of Revolutions"
Sol - Sun
Revolutio Telluris - Earth orbit
Revolutio Martis - Mars orbit
Revolutio Iovis - Jupiter orbit
Revolutio Saturnis - Saturn orbit
Sphaera Stellarum - Sphere of stars

N.B. The <u>epicycle system</u> is not shown in this diagram, which gives only the overall layout of the planetary orbits used by Koppernigk

Copernican System - from "De Rev"

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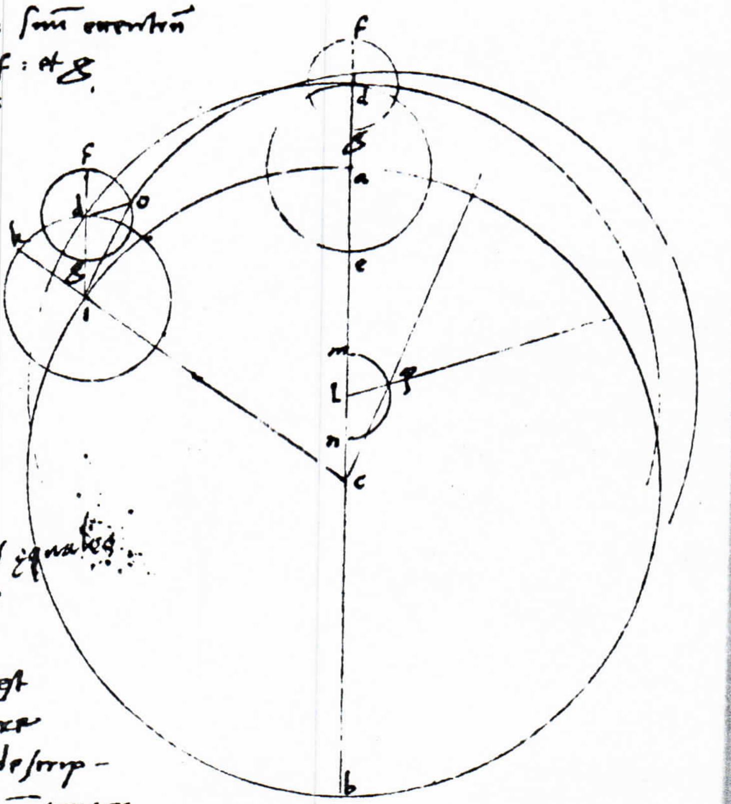

Quanta sit secunda Solaris inæqualitatis differentia Cap xx

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prima ac simplici illam anomaliam obliquitatis signiferi vel
eius similitudinem sequeretur : certas habebimus eius diffe-
rentias, si non obstiterit error aliquis observatorum præteritorum
Habemus enim ipsam simplicem anomaliam anno Christi MDxv
secundum numerationem grad clxv scrup ~~[illegible]~~ xxxix fere : et eius
principium facta retrorsum supputatione ~~sexaginta~~ lxiiii fore
annis ante Christum natum ~~et~~ colliguntur anni MDlxxx a quo ~~principio~~ tempore ad nos
Illius aut ~~magno~~ principii inventa est eccentrotes maxima ~~partium 4..~~ 417
quarum quæ ex centro orbis esset 10000 : nunc vero, ut
a nobis

A page from Koppernigk's manuscript, showing his complex epicycle system.

one-twentieth of the text was concerned with the crucial statement and defence of the heliocentric cosmology - the major part comprised dry mathematical details (in Latin) of his new computation system for the celestial motions. The first printing of a thousand copies was never exhausted, and was outsold hundreds of times over by other Sixteenth-Century astronomical treatises, including printings of the "Almagest". Although the concept of the Earth as but one of six planets (and not the centre of the Universe) clashed with the prevailing Christian theology, Koppernigk, whose views were well-known to his superiors in the church, was admonished far more clearly for retaining a housekeeper-concubine by the name of Anna than he was for his theoretical ideas. It was too easy to regard Koppernigk's work as no more than an improved system for planetary computations, and this interpretation was encouraged by a preface to that effect inserted in the published edition at the last moment by one Andreas Osiander who was in charge of the printing. Koppernigk is alleged to have seen the printed edition for the first time only on his death-bed, and though he was aware of the preface probably never approved it. Those few mathematical astronomers who did plough through the book may also have wondered about Koppernigk's belief in the reality of his system, for alternative computation systems with different epicycles were used when it was convenient to do so, and it is not clear which, if any, Koppernigk himself considered to be the real world.

Yet there can be no doubt that Koppernigk believed in the basic reality of his system, for he did reconsider the problem of the Earth's motion even though he failed to resolve it satisfactorily. In the end, the "Book of Revolutions" sparked the so-called Copernican Revolution in European scientific thought less by what it solved than by what it prompted others to question. As an example of the lack of impact of his monumentally tedious book in the years to follow, we may look at the work of the man who was unquestionably the greatest European astronomer in the years immediately following Koppernigk's death.

6. Tyge Brahe (Tycho)

Tyge Brahe (Fig. 11) was born in 1546, a little more than three years after Koppernigk's death, the son of a Danish nobleman. Impressed by the timely occurrence of the predicted solar eclipse of 1560, he began to study astronomy. By August 1563, though only sixteen, he was less than impressed at the state of that science. He had obtained copies of the Alfonsine Tables

Tycho Brahe (1546–1601)

Fig. 11

and the Prutenic Tables which were published in 1551 by the mathematician Erasmus Reinhold according to the Copernican prescription. He noted that the Tables predicted an upcoming close approach of Jupiter and Saturn, and, using an ordinary geometer's compass as a sighting aid, began to observe the angle between the two planets on 17th August 1563. On the morning of the 24th of August he found them so close that he could scarcely measure the angle between them; the Alfonsine Tables were a full month in error predicting this event, and the tables based on the Copernican system were several days out. The young Tyge determined to devote himself to deriving a new system for the description of the heavens, to be based on his own careful observations. He was destined to become the first European to better the accuracy of the astronomical observations made by Hipparchos 1700 years earlier.

In 1572, Tyge was living at the estate of an uncle who conducted alchemical experiments, and on the evening of November 11 Tyge was crossing the estate between the chemical laboratory and the house when he happened to glance skyward and make an observation that was to shake the astronomical world - there was a brilliant new star in the constellation of Cassiopeia. Tyge literally could not believe his eyes and it is recorded that he asked the servants who were with him, and some passing peasants, to confirm that they too saw the very bright star in the place he indicated! He had just finished constructing a sextant with arms some 5 1/2 feet long, with which to make accurate observations of celestial configurations, and he used this to determine the apparent place of the new object among the stars.

According to Aristotelian belief, the heavens were immutable. The brilliant new object should therefore not have been a true star, but perhaps an unusually bright and small comet. Such apparitions were thought to occur in the upper regions of the Aristotelian terrestrial sphere, so that they moved against the background of the stars. Tyge established clearly that the new phenomenon did <u>not</u> move against the stars, but travelled with them across the sky with great precision night after night. Clearly, then, it <u>was</u> a star. During the next sixteen months however it steadily faded into invisibility. Tyge's small book "Of the New Star", published in 1573, described his observations of it (Fig. 12) and speculated on its consequences for meteorology and astrology, but refrained from discussing its philosophical implications in detail.

Tyge had seen a supernova; in modern terms, not a new star but the violent explosion of an old one. In his day its significance was profoundly disturbing - the young Brahe may have been well advised to limit the discussion of it in his first book. For the new star constituted a glaring contradiction of the Aristotelian doctrine of the immutability of the heavens. Though he said little in public on this important point, it convinced Tyge of the role he could play in the development of astronomy, and set him on the road to widespread fame.

In 1756 King Frederick II of Denmark granted:

> "to our beloved Tyge Brahe, Otto's son, of Knudstrup, our man and servant, our land of Hveen with all our and the crown's tenants and servants who thereon live, with all rent and duty which comes from that and is given to us and the crown, to have, enjoy, use and hold, quit and free without any rent all the days of his life, and so long as he lives and likes to continue and follow his studia mathematices ..."

Tyge also received a grant for the construction of a house and observatory (Fig. 13). Hveen was an island off the coast between Copenhagen and Hamlet's Elsinore. With the grant of land and tenants King Frederick sought to ensure that Tyge's researches would be adequately supported without other distracting labour on his part, and that his discoveries would be made to the greater glory of the Danish kingdom. The combination of royal funding and Tyge's skill at constructing and using new instruments for astronomical measurement was to produce the body of data from which at last the answer to the cosmological puzzle would be extracted - but not by Tyge himself.

In Tyge's time accuracy in angular measurement was based on the construction of enormous sighting-devices (see Figure 14), with engraved brass scales and steel frames for stability. Tyge improved the method of engraving angular scales for precise measurement, and improved the visual methods of sighting on astronomical objects. He also understood that observations made using one instrument might be subject to errors peculiar to the design and engraving of that instrument, so that measurements should be made in as many ways as possible and cross-checked for consistency. He constructed a brass-finished globe five feet in diameter on which he engraved the accurate locations of the stars derived from his measurements; this globe may also have been used as a practical computer for the conversion of angular measurements from one system of sky co-ordinates to another. His measurements of star positions were

Fig. 13

-Uraniborg. From a collection of letters published by Tycho.

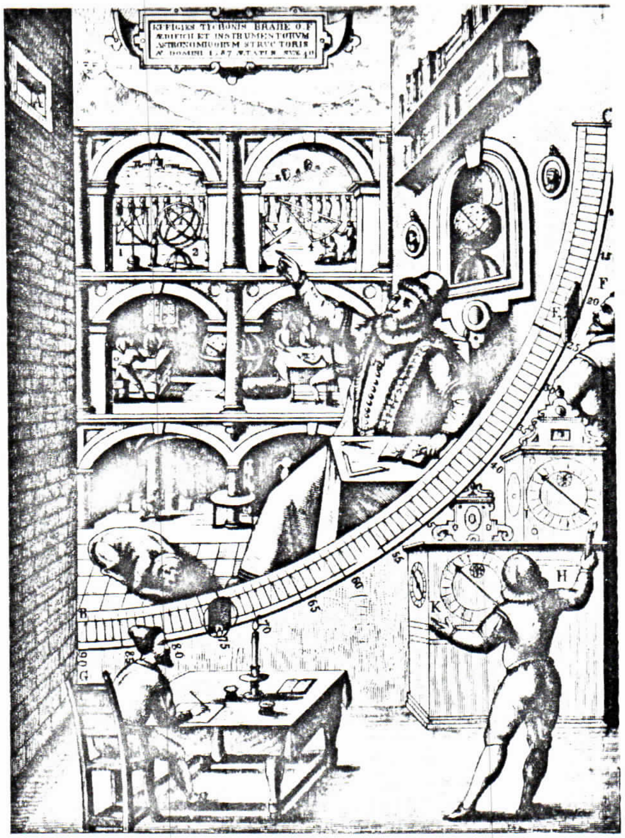

Fig. 14

Brahe at Uraniborg, observing with his great mural quadrant. *(Yerkes Observatory.)*

so accurate (to better than half an arc minute in each co-ordinate defining the position) that he discovered the small effect of the Earth's atmosphere on the displacement of star images near the horizon, and was able to untangle within a space of only a few decades some of the errors introduced by the bad data of the previous 1800 years. In Tyge Brahe the art of careful observation, with much attention to systematic elimination of possible instrumental errors, began to play its modern role in the development of science.

Yet this man who single-handedly transformed experimental astronomy rejected the Copernican heliocentric system. His personal copy of the "Book of the Revolutions" bears annotations which imply that Tyge was interested in the computational methods of Canon Koppernigk but not in his cosmology. Of the latter he was to remark "how could the fat and lazy Earth be capable of the motions ascribed to it by Copernicus?". Indeed, Tyge used his copy of Koppernigk's book as a diary in which to inscribe the development of his own world-system, which is shown in Figure 15. Tyge's model was actually a throwback to the time of the Greek astronomer Heraklides of Pontus, who studied under Plato and Aristotle in the Fourth Century B.C. In Heraklides' model the Sun revolves around the Earth, but the planets Mercury and Venus orbit the Sun - thus explaining their affinity for the Sun's part of the sky. In Brahe's system the <u>other</u> three planets also revolve around the Sun - only Sun, Moon and stars orbit the central Earth. To this basic conception he added epicycles, deferents and equants to fit his now much-improved observations.

His model is, in fact, mathematically equivalent to Koppernigk's, and with its better basis in observation it made better predictions of future celestial configurations. It also avoided the clash with the Aristotelian description of motion, leaving the Earth stationary at the centre of the Universe where both scholars and theologians were happiest to find it. But in the end Brahe was not quite true to the quality of his own data. One further concept was necessary to bring Koppernigk's heliocentricism and Tyge Brahe's precision of measurement together in a truly revolutionary theory of the world. That concept was to be provided by a mathematician with mystical leanings - Johannes Kepler, of Weil-der-Stadt in Germany.

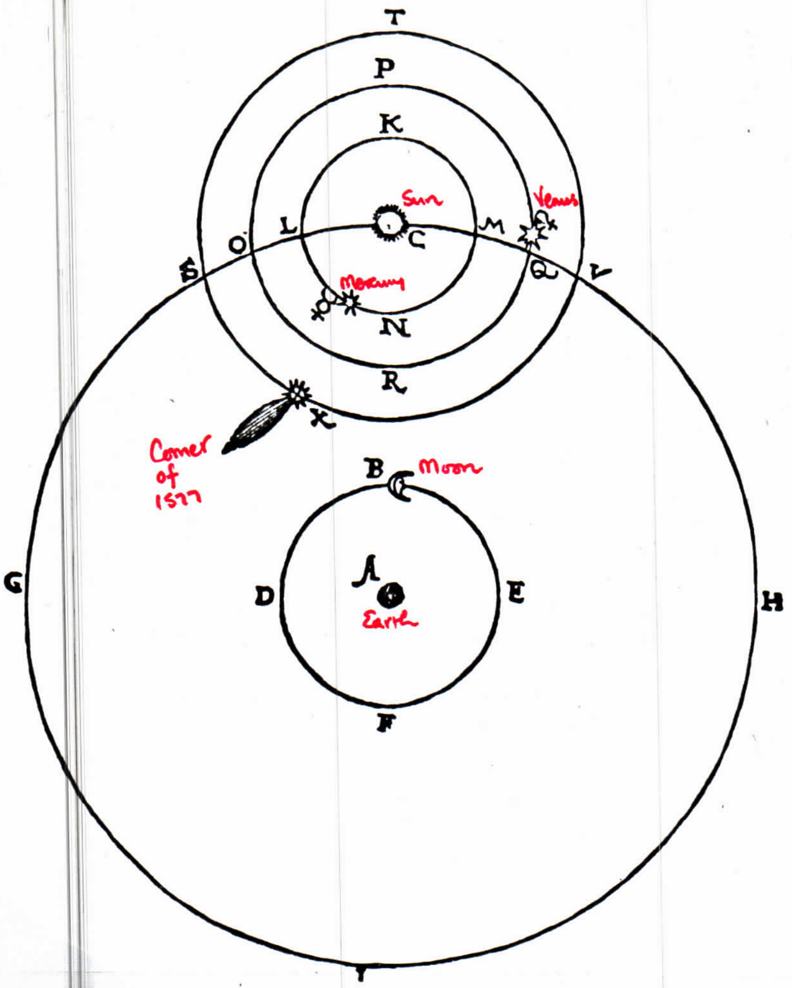

Fig. 15 –Tycho's system of the world. From his book on the comet of 1577.