The Planetary Theory of Copernicus

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I

The planetary theory of Ptolemy, the highest and final product of ancient science, dominated the entire Middle Ages. The Arabian scholars, as they did with all great scientific works of antiquity, made translations of it, and their foremost thinkers assimilated the theory and made new determinations of the numerical values by means of their own measurements; in this way Albattani discovered the motion of the solar apogee. From Moslem Spain barbarous Europe got its first notions of science in the 12th century, and the most important works were translated from Arabian into Latin; among them Ptolemy's work, since called *Almagest*. Gradually knowledge of his theory came up; in the 15th century Peurbach in Vienna wrote a book on the planetary motions. His pupil and collaborator, Regiomontanus, went to Italy to collect Greek manuscripts; he intended to make and print a new Latin translation of Ptolemy, which, however, was prevented by his early death in 1476. At Nürnberg where he had settled he made a number of observations with newly constructed instruments; still more and better ones were made in the following years by his friend the Nürnberg patrician, Bernhard Walther. Thus Western Europe began to reach and even to surpass the highest point attained in antiquity.

What, however, had been the final result there, here became the starting point of a new development. It was another world, it was other people who now in Europe were the bearers of the old science, different from the declining ancient world of serfdom. There was a tension of new energy in the free citizens of the late-medieval towns. A strong individualism pervaded the work of the artisans, the enterprises of the merchants, the ideas of the thinkers, displaying itself in art and literature, in church and religion, in travels, adventures, and discoveries, in research and science. They were not content with what was handed down from antiquity; new instruments were installed, new observations were made, new ideas sprang up in the minds. More than by anything else the coming of a new time was marked by the appearance of the new world system of Copernicus. At once, without intermediate steps, it sprang forward in full completeness, the rotation of the earth to explain the apparent rotation of the sky, as well as its yearly revolution around the sun to explain the irregular motions of the planets.

It is true that it was not published until 1543 only. But, as the author said in his dedication to the Pope, he had it ready four times nine years already, hesitating to publish it because he feared the criticism of ignorant people. Its basic theory had been formulated as early as 1506 in a short Commentary communicated in letters to friends; and it became widely known by an enthusiastic summary published in 1540 by Rheticus, who had come from Wittenberg to be instructed in the new doctrine. In the dedication and in the first chapters the author tells how he had come to assume the earth to be moving. The mathematicians themselves did not agree on the motions of the celestial bodies; some made use of concentric, others of eccentric circles, without arriving at a symmetrical structure. Then he found that some ancient philosophers, as Philolaus the Pythagorean, had assumed a motion of the earth; so he thinks he is also allowed to try whether by assuming a motion of the earth a more reliable representation of the revolutions may be found.

II

In the first chapters the arguments for the new system are given. First that the world is spherical and that the earth too has the figure of a sphere; and that the motions of the celestial bodies are uniform and circular or consist of circular motions; for only in this way all the former comes back in fixed periods. Since reason refuses to assume irregularities in what is arranged in the best order we have to assume that uniform motions appear to us irregular by difference of poles or because the earth is not in the centre of the circles. Most authors, surely, assume the earth to be at rest in the centre of the world; but in thinking it out we see that the question is unsettled. For every observed change originates either from the motion of the object, or of the observer, or of both. If the earth has a motion, this must appear, though in opposite direction, in all that is outside; and this holds especially for the daily motion. Since heaven contains all, it is not well conceivable that a motion should not be attributed to what is therein contained rather than to what is comprising and determining all. If then we assume that the earth is not in the centre of the world but at a distance not large enough to be measured against the sphere of the fixed stars, but comparable with the orbits of the planets, this could be a cause for the apparent irregularities in the motion of the planets.

The ancient philosophers assumed that the earth is resting in the centre, because all heavy matter tends to move to the centre of the world and remains there at rest; whereas the heavenly bodies revolve in circles. A rotation of the earth, Ptolemy says, would be contrary to it, and by the violent lateral velocity everything would be torn asunder. Objects falling down would not arrive at the right place because with great velocity it had been drawn away from below them; and the clouds and everything suspended would seem to move westward.

If, however, one assumes a rotation of the earth, he certainly is convinced that it is a natural and not a violent motion; and with what happens by nature, not by outer violence, everything remains in the best order. Why does not Ptolemy fear the same thing with heaven that with him has to rotate at a much more tremendous velocity? Since the earth is a globe enclosed between its poles, why not attribute to her the motion that is natural for a sphere, rather than assume that the entire world, of which the boundaries are unknown, is moving? A large part of the air, in which the clouds are floating, is drawn along with the earth, so that they to us appear to be at rest; whereas the remote realms of the air, in which the comets are seen, is free from this motion. It must be added that the state of immobility is considered to be more noble and divine than unrest and variability, hence belongs rather to the entire world than to the earth.

Since now there are no objections to a motion of the earth, we have to investigate whether she has more motions and may be taken for a planet. That she is not the centre of all circular motions is shown by the irregularities of the planets and their variable distances, that cannot be explained by circles around the earth. There are other centres besides the centre of earthly gravity; gravity is the tendency of cognate particles to combine into a sphere, and we have to assume that the same tendency is present in the sun, the moon, and the planets and gives them their spherical figure, whilst they describe their circular orbits. If we assume the immobility of the sun and transfer its yearly revolution to the earth, the morning and evening risings and settings of the stars fit in the same way, and the oscillations and stations of the planets appear to be motions of the earth. Then the sun occupies the centre of the world.

The succession of the planets was always assumed from their period of revolution, Saturn, Jupiter, Mars. The old contest whether Mercury and Venus should be placed above or below the sun, is now solved in this way that both, as already Martianus Capella wrote in antiquity, revolve about the sun. For the other three also the sun must be the centre, because in opposition, as is shown by their greater brightness, they come nearer to us and in conjunction are fainter and more remote. Between these two groups the orbit of the earth is situated, with the moon and all that is below the moon. At the outside, highest and most remote, is the sphere of the fixed stars, so large that the dimension of the earth's orbit is negligible against it, and immobile. Then follow Saturn, Jupiter, and Mars finishing their orbits in 30, in 12, in 2 years, then the earth with one year, then Venus and Mercury with 9 months, and 80 days. In the centre of them all stands the sun. "Who in this beautiful temple would wish to put this lamp at a better place than from where it could illuminate them all? Thus the sun, sitting as on a royal throne, leads the surrounding family of stars."

These are, in short, the arguments given by Copernicus for his new world system. As to their character they belong to the ancient philosophy of Aristotle, with its distinction of natural and artificial motions. In criticising Ptolemy's and Aristotle's view of the immobility of the earth he proceeds from the same fundamental points of view. The real power of the new system, of course, consists in its far greater simplicity, doing away with the epicycles and ascribing a single orbit to each of the planets.

For the earth, however, he could not be content with its yearly circle. To revolve in a circle meant for him, just as for the ancients, to be attached to a revolving radius, hence a turning of always the same side to the centre. In that case the North pole, if once inclined to the centre, had to remain so always. In order to have the axis always in the same direction in space a special third motion was necessary—called by him "declination"—a yearly conical motion of the axis. By making its period a trifle different from the year there resulted a slow displacement of the pole relative to the stars, the precession of the equinoxes, which formerly was considered as a special motion of the eighth sphere of the stars.

III

Copernicus did not intend to give merely an enouncement of the new fundamental principles; his book should replace Ptolemy's work in giving the entire exhibition of the world structure along these new lines. Hence he begins with a geometrical part, propositions and formulas of trigonometry and spherical astronomy, a table of sines for each angle, and a catalogue of stars, taken from Ptolemy, but reduced to another form. For precession to him, as to his medieval predecessors, is a complicated phenomenon. He accepted in good faith Ptolemy's assertion that at the time it was 1° in one hundred years, and he knows that afterwards it was found to be larger; so he assumes it to be variable in a period of 1700 years. This means that the length of a year also is irregularly variable. Since the vernal equinox thus is receding irregularly he does not count his longitudes from this point but from a fixed star, the first star in the Ram, γ Arietis (that in 1520 had a longitude of 25° 32′ relative to the true vernal point). He assumes that the decrease of the inclination of the ecliptic (23° 51′ in antiquity, 23° 28½′ after his own measurements) is periodical in 3400 years; combined with the variable precession it is rendered by a complicated motion of the earth's axis in that period, additional to its regular "declination."

The apparent motion of the sun along the ecliptic discloses the real motion of the earth. Copernicus represents it by an eccentric circle, and after Hipparchus' method he derives its orbit from the duration of the seasons as he had observed them. He finds the sun's apogee at 96° 40′ and an eccentricity of 0.0323. The first result confirms the motion of the apsides; Ptolemy had found the longitude of the apogee 65° 30′, the Arabian astronomer Albattani (in 879) had found 82° 17′, Arzachel (in 1069) 77° 50′, relative to a fixed equinox. Copernicus thinks a real retrogression between these Arabian astronomers not probable. "I confess that nothing is so difficult as observing the apogee of the sun, because here large values must be derived from very small, hardly perceptible quantities." Yet he assumes an irregular progression, again putting his faith in Ptolemy's statement that since Hipparchus no change had occurred. Moreover he assumes that the differences in eccentricity, $1/24 = 0.0414$ by Hipparchus and Ptolemy, 0.0347 by Albattani, and 0.0323 by himself, indicate a real progressive change.

To render all these irregularities for which he assumes the same large period of 3400 years, the motion of the earth has to be more complicated. The centre of its circular orbit has not a fixed position relative to the sun but describes a small circle (with radius 0.0048) bringing it nearer to and farther from the sun, so that the eccentricity varies between 0.0414 and 0.0318, and the apogee, relative to the stars, oscillates $7\frac{1}{2}°$ to both sides. Thus the longitude of the sun must be derived by a rather complicated computation, for which tables are constructed. "If, however, some one should be of the opinion that the centre of the yearly circle is fixed as centre of the world, and that the sun is movable, having the two motions which we derived for the centre of the eccentric circle, everything would fit with the same numbers and the same computation. . . So there remains some doubt about the centre of the world, and that is why from the beginning we expressed ourselves in an uncertain way as to whether it is situated inside or outside the sun."

IV

In elaborating the orbits of the planets Copernicus follows a different line of thought from Ptolemy. That the variations in angular velocity show an eccentricity twice as large as do the variations in distance of the epicycle's centre, was explained by Ptolemy by means of an eccentric *punctum aequans* from where the motion should appear uniform. Copernicus' fundamental principle is that all motions consist of uniformly described circles. He thinks it is not allowed to disregard this principle, as is actually done with the assumption of such an equant, since thereby in reality the motion is not uniform, "Certainly the uniform motions of the epicycle must take place relatively to the centre of the deferent, and the motion of the planet relatively to the radius toward that centre. It is then tolerated [in the old theory] that a uniform revolution could take place about a foreign centre. . . This and similar things have induced us to adopt another kind of deductions, in which uniformity and the foundations of science have been preserved."

In a most ingenious way Copernicus succeeded in discarding the *punctum aequans* and avoiding non-uniform motion, namely by replacing it by an epicycle. He faced the problem that in aphelion and perihelion (in 1 and 3 in the Figure) the distances to the sun should be affected by the single eccentricity e, whereas at 90° anomaly (in 2 and 4) the direction sun-planet should be affected by the double or total eccentricity $2e$. He solved it by making the distance of the sun from the centre of the circle $1\frac{1}{2}e$ and having the planet revolve in addition along

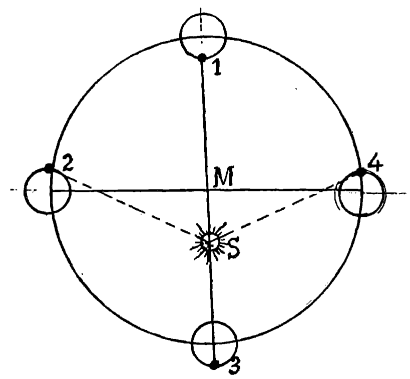

FIGURE 1

a small epicycle of radius ½*e* (revolving once, relative to the radius, according to the ancient conception; twice, after modern conception of absolute direction in space). Then in aphelion and perihelion, as the Figure shows, the two effects, of eccentricity and epicycle, subtract, whereas in the sideward positions they add. Thus by combining an eccentric place of the sun with an epicycle of radius ⅓ of the eccentricity he attains the same goal as Ptolemy did with his equant, and he attains it by means of entirely uniform circular motions.

After this principle he makes a new computation of Ptolemy's data for the oppositions of Saturn, Jupiter, and Mars. In concordance with Ptolemy it is not the opposition to the real sun but to the mean sun that is used; this means that not the sun itself but the centre of the earth's orbit is taken as the centre of the world, around which the planets describe their orbits. The point S in our Figure does not, as was supposed above, represent the sun, but the centre of the earth's orbit. It seems as if, in thus working out the theory, adhering to Ptolemy's method of treating the problem, the magnificent words on the royal throne of the sun had been forgotten, or perhaps not yet written down. He arrives, of course, at the same numerical results, transformed only to his system; hence for eccentricity and radius of epicycle he finds for Saturn 0.0854 and 0.0285, for Jupiter 0.0687 and 0.0229, for Mars 0.1500 and 0.0500; and also his longitudes of apogee reduced to his fixed ecliptic correspond up to the nearest minute to Ptolemy's.

Ptolemy's values could not be relied upon for modern times; the change in the sun's apogee (*i.e.*, the earth's aphelion) was noted already. So Copernicus' chief task was to provide for better data by means of his own observations. For each of these planets he derived three oppositions from observations between 1512 and 1529. In computing the orbits he had, just as Ptolemy, to proceed by successive approximations: first assuming a single eccentric circle, then assigning ¼ of the eccentricity found to the radius of the epicycle and correcting the observed longitudes for the effect of the motion on the epicycle; the distance SM thus found provides by its ⅓ part a better value for the epicycle's radius, and so on.

For Saturn the computation is given in full detail; starting from a total eccentricity of 0.1200 he arrives finally at a distance 0.0854, epicycle 0.0285, in total 0.1139, exactly corresponding with Ptolemy (who gives 6⅚ sexagesimal = 0.1139), with apogee at 240° 21′. The value of Ptolemy, reduced to the fixed ecliptic, was 226° 20′, hence the line of apsides relative to the stars has advanced 14° in the 1400 years elapsed. For Jupiter he was led astray by an error of computation; so he assumes Ptolemy's value for the eccentricity and derives therewith the longitude of the apogee 159°, which is 4° 30′ advanced relative to Ptolemy's value. For Mars he gives only his final result: the epicycle radius 0.0500, and the eccentricity 0.1460 (with apogee at 119° 40′), hence not exactly in accordance with his premises; an exact recomputation should have given 0.0488, 0.1463, and 119° 14′. Ptolemy had the apogee at 108° 50′, "hence it has advanced by 10° 50′. The distance of the centres we found to be 0.0040 smaller than he did. Not that Ptolemy or ourselves have made an error, but as a clear indication that the centre of the orbit of the earth has come nearer to that of Mars, whereas the sun stayed at her place." Here it must be remarked that this difference corresponds to 14′ only in the first opposition; and it seems questionable whether his instruments could warrant such a small quantity. For all these planets his results provided him with exact longitudes for modern times, from which, by comparison with the ancient ones, more accurate values of the period of revolution could be derived.

A fourth observation outside opposition was needed of course to determine the ratio of the planet's to the earth's circle. A modern note is heard here in the title of the chapter: "On the parallax of Saturn, as it follows from the yearly orbit of the earth, and on its distance." What formerly appeared as an epicycle is now rightly called a parallax. But then, in the elaboration, he again reverts to Ptolemy by giving in his result the earth's orbit in terms of the planet's: 0.1090, 0.1916, 0.6580, for Saturn, Jupiter, Mars,—little different from Ptolemy's values—instead of expressing the size of the planet's orbits 9.17, 5.22, 1.520, in that of the earth's as their unit.

V

For Venus and Mercury Copernicus' theory is more complicated. We might expect, on the contrary, that the new world system, with a smaller eccentric circle for the planet within the larger eccentric circle of the earth, would give a simpler representation of the phenomena than Ptolemy's theory. But first by his insistence upon the centre of the earth's orbit instead of the sun itself as the world centre, Copernicus made his task more difficult and his system more complicated than was necessary. Moreover he links himself so closely to Ptolemy that his exposition seems to be a copy of his predecessor in somewhat altered language. He proceeds from the same observations, adding for Venus only one of his own to have a modern longitude that may afford a more accurate period of revolution; he expounds the same theory with the same numerical data, only transcribed into another form analogous to the other planets. Since the sun is standing nearly in the centre of the circle of Venus, and Copernicus refers the motion of Venus to the centre of the earth's orbit it is the eccentricity of the latter that appears as eccentricity of the former which, again, has to be divided into ¼ and ¾ the amount. "This star, however, has something different from the others in law and measure of its motions, which can, I think, better and more easily be represented by an eccentric circle upon another eccentric circle." This means that instead of having a small epicycle the centre of which is describing a large circle he has the centre of the large circle describing a small circle, varying between the distances e and $2e$ from the world centre—which, geometrically, comes down to an entirely identical effect. But it means at the same time that this small circle is described in half a year, hence the place thereon is dependent on the place of the earth in its orbit. It looks like a singular falling back into geocentrical ideas, that the real motion of Venus on its circles is determined by the motion of the earth; but it was an unavoidable consequence of his taking the centre of the earth's orbit as the world centre.

For Mercury in the same way Copernicus copies Ptolemy's argument and the derivation from the eight elongations, with the false apogee at 183° 20′ and the other unreliable data derived from the difficult observations. But as to their theoretical representation he was in a worse position than Ptolemy. What with Ptolemy was the yearly deferent of Mercury that could be fashioned according to the demands of the observations of Mercury, in the new system had been turned into the earth's orbit, which could not be changed for the sake of Mercury. The small orbit of Mercury itself had to pay for all the appearances, and it could be done only by having Mercury's course in space dependent on the earth. To represent it by uniform circles a complicated structure had to be devised. The centre of Mercury's circle describes in half a year a small circle with radius 0.0212 in such a way that its maximum distance to the world centre (0.0736) is reached when the earth passes Mercury's line of apsides, its minimum (0.0312) when it is 90° different in longitude. Moreover the radius of Mercury's circle is variable in the same tempo between 0.3573, for the earth in the apsides-line, and 0.3953, for the earth at 90° distance. This is a linear oscillation of Mercury outward and inward on the radius; but such a linear oscillation can always be represented by a combination of two equal opposite circular motions.

To find the longitude of Mercury at a modern date and derive a more exact period of revolution new observations had to be made. But he was not able to do so. "This way to investigate the course of this planet has been depicted to us by the Ancients, but favoured by a clearer sky, since the Nile does not breed such vapors as the Vistula does here. Nature denied this facility to us who are living in a harsher country, since the sky is seldom pure, and moreover, owing to the more inclined position of the celestial sphere the possibility to observe Mercury is more rare. So this planet has caused us much trouble and labor in investigating its irregularities. For this purpose we have made use of carefully made observations at Nürnberg." These were observations made in 1491 and 1504 by Bernhard Walther and Johannes Schoner. He is able to represent them by an apogee at 211° 30′, having advanced relative to the stars by 28° 10′ since antiquity.

VI

The last Book in Copernicus' work, as in Ptolemy's, is devoted to the inclinations of the orbits. Ptolemy had to determine for each planet two inclinations; he found them different, but had he made use of exactly correct observations he should have found them equal. Copernicus is at a disadvantage having only one inclination to determine; since, however, he takes over the observational data of Ptolemy's there is no other way for him than to assume it to be variable. Thus he says: the latitude "changes most there where the planets near opposition to the sun show to the approaching earth a larger deviation in latitude than in other positions; in the Northern hemisphere to the North, in the Southern to the South. This difference is larger than what would be accounted for by the sole approaching to or removing from the earth. From this we recognize that the inclinations of the orbits are not fixed but are varying by oscillating movements connected with the earth's motion." He does not make use of Ptolemy's original data but of his tables, modified in some cases by his own observations, and he deduces that the inclination of Saturn's orbit oscillates between 2° 44′ and 2° 16′, of Jupiter's between 1° 42′ and 1° 18′, and that of Mars between 1° 51′ and 0° 9′; always in this way that maximum and minimum occur at opposition and conjunction, hence are determined by the position of the earth.

With Venus and Mercury matters are still more complicated, as they were for Ptolemy too. The line of nodes of the inclined orbit is assumed to coincide with the line of apsides, and the orbit oscillates about this line. Inclination is largest, 3° 29′ for Venus and 7° for Mercury, when the earth stands in the line of nodes, so that it appears as a large latitude in the elongations; and smallest (2° 30′ and 6° 15′) when the earth and the planet both stand sideways and it appears in conjunction.

These two effects, called "obliquatio" and "declinatio" mingle in intermediate positions. Moreover he adopts Ptolemy's additional constant deviations (10′ to the North for Venus, 45′ to the South for Mercury) but represents them by oscillations of the line of nodes, called "deviatio," of which only the extreme effects can be observed. Except for the latter his Tables for the latitude of Venus and Mercury are identical with Ptolemy's.

Thus it appears that Copernicus in his theory of the latitudes of the planets as well as in the longitudes of Venus and Mercury takes over nearly literally Ptolemy's theory with all its inadequacies, only expressed in a different way to adapt them to the heliocentric basis. So the earth plays a special role in his world system, in partly regulating and directing the motion of the other planets. All this as a consequence of his unjustified trust in Ptolemy's data of observation and his taking the centre of the earth's orbit as the center of the world.

VII

To anybody who knows that modern astronomy begins with Copernicus, a closer study of his book "De Revolutionibus" must bring an extreme surprise, or rather disillusion. This the work that rocked the foundations of astronomy, that proclaimed the modern world system, that brought about a revolution in science and in human world view—and yet so antique in its detailed elaboration. It looks like such an unassimilated mixture of new and old that its seems hardly credible that it should be the work of one and the same person.

The new side is the expounding of the heliocentric system in the first chapters. Thereby the foundations not only of astronmy but of the entire human world conception are revolutionized. With the earth pushed away from its central position in space, man was pushed away from his central place in the world, where he considered himself the aim and object of creation. Since the latter was embodied in Church doctrine and religion the new system soon played a part in the great spiritual struggles of the time. A wider world, no longer enclosed within a narrow celestial sphere, opened itself to the view of man, an unlimited space full of stars, all of them suns, maybe accompanied by planets with other inhabitants—a bewildering vision of the numerousness of worlds. Though the first exponents of this vision had to suffer for their cause, this could not prevent that the new knowledge gradually spread into all classes of the people, and the name of Copernicus became a war cry in the fight for new enlightenment.

And when then we dive into the further chapters of this revolutionizing book we feel ourselves transferred entirely into the sphere of antiquity. In every detail, in every next chapter, it tries to cling almost anxiously to the time-honored example of old Ptolemy. Nowhere the breath of a new time is felt. Nowhere a trace of the daybreak of a new epoch of scientific research.

Indeed it did not break. There is no such antagonism between the first and the later chapters as seems at first sight. The first part too breathes the spirit of antiquity. It was pointed out already that all his arguments for the earth's motion are based on Aristotelian philosophy. He himself does not consider his work as a break with the classic world-view. He appeals to predecessors in antiquity; he speaks of the Pythagorean Philolaus who made the earth describe an orbit, and mentions Heraklides and Ekphantos and the Syracusean Nicetas who made the earth revolve about an axis. In the later part of the 16th century, out of the need of leaning upon recognized authority, in the struggle of the world systems the "ptolemean" and the "pythagorean" systems were opposed to one another, though Philolaus' doctrine was quite different. The contest went on entirely within the realm of ancient science, which now in its full extent was opened to the Western world in that great spiritual movement which we call "Renaissance."

The Renaissance was the opening up and assimilating of the classic culture by the peoples of Europe. Medieval development now had made them ripe to enter into the spiritual inheritance of the Greek and Roman world. It was to them the acme of human civilization, the admired ideal of life, art, and science, which they passionately studied and tried to imitate. The Renaissance was the enrapturing revelation of all the beauty and wisdom of the ancients and the fervent desire to follow them in their course. Thus it was felt as the rebirth of brilliant culture after medieval ignorance and barbarity. Only after it had been assimilated and had settled a new development along new paths was possible.

We often make ourselves the wrong picture of the unfolding of science in the 16th century by seeing it as one process of spiritual revolution. We have to distinguish two different steps which, roughly, may be centered about the years 1500 and 1600 A.D. With the first we stand in the midst of the Renaissance, with its first rise and flowering of scientific discovery. But not till a century afterwards had science found its new way of critical and experimental research which in a continuous progress should lead her to modern heights. Modern science does not begin with Copernicus but with Simon Stevin and Galileo, with Tycho Brahe and Kepler.

Copernicus was entirely a child of the Renaissance. His youth brought him to Italy, the centre of its fervent unfolding, where he partook in its strong impulses. Returned to his fatherland at the Vistula he got, through his uncle the bishop of Ermland, a place in the Chapter at Frauenburg, where he could devote himself to his astronomical studies free from care. Here he could occupy himself at leisure with Ptolemy and the other ancient writers, and work out his new ideas for improving the planetary theories.

His was the great renovating deed of a profoundly musing mind, unconscious of the ensuing revolutionary consequences. The time had not