COPERNICUS and the HELIOCENTRIC SYSTEM

We have seen the great importance attached by late mediaeval philosophers, and by the Church, to the cosmology of Aristotle. It is mainly for this reason that the work of Copernicus and Kepler had such a large impact- it directly challenged the prevailing orthodoxy, and thereby opened the way for the far more radical challenges to the mediaeval worldview which came later on. In what follows we look at both the life and achievements of Copernicus.

(1) LIFE of COPERNICUS (1473-1543)

Mikolaj Kopernik, or Nicolaus Koppernigk, was born on the 19th Feb 1473 in Torun, Poland; nowadays his latinized name Nicolaus Copernicus is used. His father, also called Nicolaus Koppernigk, had lived in Krakow before moving to Torun, where he set up a business trading in copper. Nicolaus Koppernigk Sr. married Barbara Waczenrode, who came from a well off family from Torun, around 1463. They had four children, two sons and two daughters, of whom Copernicus was the youngest. Copernicus's father died when he was 10 yrs old, and his uncle Lucas Waczenrode, a canon at Frauenburg Cathedral, became guardian to the four children. In 1488 Nicolaus was sent to the cathedral school of Wloclawek, where he received a standard Catholic education; 3 years later he began studies at the University of Krakow. He studied Latin, mathematics, astronomy, geography and philosophy, learning his astronomy from the "*Tractatus de Sphaera*", by Johannes de Sacrobosco (written in 1220). In these courses Copernicus learnt the conventional Aristotelian and Ptolemaic theories of the universe, and also much about what today we call astrology, ie., the calculation of horoscopes. Copernicus also pursued his own studies- signed copies of 3 of his private purchases still exist (these being a Latin translation of Euclid's Elements, published in Venice in 1482;, a copy of the second edition of the Alfonsine Tables, giving planetary theory and eclipses, printed in Venice in 1492; and Regiomontanus's Tables of Directions describing spherical astronomy, published in Augsburg in 1490.

Copernicus returned to Torun after four years of study at Krakow. By this time his uncle was Bishop of Ermland, and wanted Copernicus to pursue a career in the Church. Copernicus accordingly left for Italy, entering the University of Bologna on 19 October 1496, to start three years of study in canon law. While in Bologna Copernicus studied Greek, mathematics and astronomy, in addition to his official course of canon law. He also rented rooms at the house of the astronomy professor Domenico Maria de Novara, and began to undertake research with him, assisting him in making observations. On 9 March 1497 he observed the Moon eclipse the star Aldebaran.

While he was in Bologna, his uncle put his name forward for the position of canon at Frauenburg Cathedral. On 20 October 1497, Copernicus received official notification of his appointment as a canon and of the comfortable income he would receive, even before returning. He was officially installed as a canon of the Ermland Chapter on 27 July 1501; however, because had not completed his degree in canon law at Bologna, he asked to be allowed to return to Italy both to finish his law degree and to study medicine. Copernicus was granted leave on 27 July 1501 to complete his studies in Padua. Padua was famous for its medical school and while he was there Copernicus studied both medicine and astronomy. In the spring of 1503 he decided formally to obtain his doctorate in Canon Law, but he did not return to Bologna but rather took the degree at the University of Ferrara. After receiving his doctorate, Copernicus stayed in Ferrara for a few months before returning to Padua to continue his studies of medicine.

When he finally returned to Poland in 1503, Copernicus was again granted leave from his official duties as a canon in the Ermland Chapter at Frauenburg, so as to be physician to his uncle, and for the next 5 years he acted essentially as his uncle's secretary and physician. During this period he lived at Heilsberg Castle, a few miles from Frauenburg, the official residence of the Bishop of Ermland. In 1512 his uncle died, and Copernicus thereupon resumed his duties as canon in Frauenburg. He was mainly occupied here with administrative and political affairs, and with providing medical assistance to local citizens. However he now also had considerable time to devote to his study of astronomy, and he had at his disposal an observatory situated in one of the towers in the town's fortifications. By this time his reputation as an astronomer was well established, for when in 1514 the Fifth Lateran Council decided to improve the calendar in 1514, one of these experts chosen by the Pope to give advice was Copernicus (to which Copernicus responded by letter).

In 1516 Copernicus was given the task of administering the districts of Allenstein (also known as Olsztyn) and Mehlsack. He lived for 4 years in Allenstein Castle while carrying out these duties; and during this time, in 1517, he developed a plan for reform of the currency. When war broke out between Poland and the Teutonic Knights towards the end of 1519, he returned to Frauenburg. During the war, Copernicus was sent to peace talks in Braunsberg as one of a 2-man delegation representing the Bishop of Ermland. These talks failed and Frauenburg was besieged. Later, in 1520, Allenstein castle was also besieged, and Copernicus was involved in organising the defenses. Finally, in 1521, an uneasy peace was achieved. As a reward for his defence of Allenstein, Copernicus was appointed Commissar of Ermland and given the task of rebuilding the district after the war. His friend Tiedemann Giese, another canon in the Chapter (and later Bishop of Chelmno), assisted him in this. As part of his reconstruction plan, Copernicus put forward his earlier scheme for currency reform, presenting this to the Diet of Graudenz in 1522 (which in the end were not adopted by the Diet).

Copernicus thereupon returned to Frauenburg to a rather quiet life. For the next 2 decades his life was devoted to administrative duties and to his astronomical work. During most of this time his situation was very stable, although problems were caused by his refusal to become a priest- in 1531 his bishop even threatened to take away his income if he did not enter the priesthood, although this threat apparently never materialised.

The great insights for which Copernicus became famous were already clear to him long before he ever made them fully know to the world. Around 1514 he distributed a little book, in several hand written copies, to a few friends. This work was anonymous- no author is named on the title page. The book, entitled "*Commentariolus*" (usually translated as the "Little Commentary") already it set out Copernicus's theory of a heliocentric universe, based on 7 'axioms'. These axioms place the sun near the centre of a universe in which the planets, including the earth, revolve around it, with the stars much further away. The movement of the sun and stars in the sky is correctly explained, as is the retrograde motion in the sky of the planets- all this is discussed in more detail below. Even when he wrote his *Commentariolus* Copernicus was planning to write a major work, and it is likely that he began writing his major work, the "*De Revolutionibus*", in the following year. However even once this was finished (a demanding task, since it involved him in rather painstaking study of the actual motion of the planets), Copernicus was very reluctant to publish. The reason for this is well known- in spite of encouragement form his friends, some of whom were quite influential (eg., Tiedemann Giese, or Cardinal Shoenberg of Capua), he feared the reaction of the young Catholic zealots of the district, to whom he was already suspicious because of his lack of fervent opposition to the new Lutheran doctrines. Note that Copernicus's fears did not extend to the whole Catholic church - in fact he was throughout his life a committed Catholic, and he had already published a brief popular account of his ideas in 1530, which had been circulated widely, and eventually had even been the subject of a lecture given in Rome. Pope Clement II had at that time approved of the ideas expressed, and even transmitted a request via the Polish Cardinal that the ideas be published in full. Thus Copernicus's reluctance to publish was clearly more connected with his own local situation, far from Rome.

However in May 1539 a young visitor arrived in Frauenberg to study with Copernicus. This was Georg Joachim Rheaticus, a young professor of mathematics and astronomy at the University of Wittenberg. Rheaticus spent about two years with Copernicus, taking some risk - for he himself was a Protestant visiting a Catholic canon, in what was then (and now) a Catholic stronghold. However history can be grateful to Rheaticus for doing so, since without his visit, it is possible that Copernicus's work might never have been published. In September 1539 Rheticus visited the mayor of Danzig, and acquired from him funds to help publish the "*Narratio Prima*" or "First Communication" (this was an abbreviation of the full title "First Communication to Johann Schner on the Books of the Revolutions of the learned gentleman and distinguished mathematician, the Reverend Doctor Nicolaus Copernicus of Torun, Canon of Warmia, by a certain youth devoted to mathematics"). In this short work Rheaticus enthusiastically reviewed the theory of Copernicus, in a very readable way.

The publication of the *Narratio Prima* encouraged Copernicus to publish the full mathematical details of his theory, which he had promised 27 years earlier in his *Commentariolus*. On 9 June 1541 Rheaticus was able to write that Copernicus had finally given his assent for the publication of "*De Revolutionibus, Libri VI*", and on 29 August 1541 the manuscript was ready for the printer. Rheticus took the manuscript with him on his return to Wittenberg, and gave it the printer Johann Petreius in Nremberg. Petreius was unable to supervise the printing, and so he asked Andreas Osiander, a Lutheran theologian, to undertake the task. In a now famous addition, Osiander inserted a 'letter to the reader', in place of Copernicus's original Preface, in which he claimed that the results of the book were not intended as the truth, rather that they merely presented a simpler way to calculate the positions of the heavenly bodies. This 'letter' was unsigned, and the true identity of its author was not revealed publicly until 50 years later, by Kepler. Osiander also changed the title, to "*De revolutionibus orbium coelestium*", thereby insinuating that the work treated only the motions of the heavenly bodies, and not that of the earth.

Copernicus apparently first saw a copy of the 200 page printed book, on his deathbed. He died on 24 May 1543 of a cerebral haemorrhage. In is his dedication of the work to Pope Paul III (most of which is reprinted in translation from the Latin in the Supplementary Notes), he writes:

"*1. . . I debated with myself for a long time whether to publish the volume which I wrote to prove the earth's motion or rather to follow the example of the Pythagoreans and certain others, who used to transmit philosophy's secrets only to kinsmen and friends, not in writing but by word of mouth, as is shown by Lysis' letter to Hipparchus. And they did so, it seems to me, not, as some suppose, because they were in some way jealous about their teachings, which would be spread around. On the contrary, they wanted the very beautiful thoughts attained by great men of deep devotion not to be ridiculed by those who are reluctant to exert themselves vigorously in any literary pursuit unless it is lucrative. . .When I weighed these considerations, the scorn which I had reason to fear on account of the novelty and unconventionality of my opinion almost induced me to abandon completely the work which I had undertaken.*"

"*2. But while I hesitated for a long time and even resisted, my friends drew me back. Foremost among them was the cardinal of Capua, Nicholas Schnberg, renowned in every field of learning. Next to him was a man who loves me dearly, Tiedemann Giese, bishop of Chelmno, a close student of sacred letters as well as of all good literature. For he repeatedly encouraged me and, sometimes adding reproaches, urgently requested me to publish this volume and finally permit it to appear after being buried among my papers and lying concealed not merely until the ninth year but by now the fourth period of nine years. The same conduct was recommended to me by not a few other very eminent scholars. They exhorted me no longer to refuse, on account of the fear which I felt, to make my work available for the general use of students of astronomy. The crazier my doctrine of the earth's motion now appeared to most people, the argument ran, so much the more admiration and thanks would it gain after they saw the publication of my writings dispel the fog of absurdity by most luminous proofs. Influenced therefore by these persuasive men and by this hope, in the end I allowed my friends to bring out an edition of the volume, as they had long besought me to do.*"

(2) The HELIOCENTRIC THEORY of COPERNICUS

The basic ideas of Copernicus already appear in the 7 'axioms' of his first published work, the *Commentariolus*. These axioms were:

1. There is no single centre for all orbits in the universe.
2. The Earth's centre is not the centre of the universe, but only of the lunar orbit.
3. The centre of the universe is near the sun.
4. The distance from the Earth to the sun is imperceptible compared with the distance to the stars.
5. The daily rotation of the Earth accounts for the apparent daily rotation of the stars, which themselves are immobile.
6. The apparent annual cycle of solar motion is caused by the Earth revolving round it once every year.
7. The apparent retrograde motion of the planets is caused by the motion of the Earth around the sun, and from which one observes the planets.

Note that these are not really axioms but more statements of the main elements of the theory. We see that Copernicus already had his basic ideas. In his dedication of "*De Revolutionibus*" to Pope Paul III, he described the origin of some of his reasons for arriving at these conclusions- these reached back to his studies in Padua:

"*3 . . . I was impelled to consider a different system of deducing the motions of the universe's spheres for no other reason than the realization that astronomers do not agree among themselves in their investigations of this subject. For, in the first place, they are so uncertain about the motion of the sun and moon that they cannot establish and observe a constant length even for the tropical year. Secondly, in determining the motions not only of these bodies but also of the other five planets, they do not use the same principles, assumptions, and explanations of the apparent revolutions and motions.*

4. For this reason I undertook the task of rereading the works of all the philosophers which I could obtain to learn whether anyone had ever proposed other motions of the universe's spheres than those expounded by the teachers of astronomy in the schools. And in fact first I found in Cicero that Hicetas supposed the earth to move. Later I also discovered in Plutarch that certain others were of this opinion, for he says that: 'Some think that the earth remains at rest. But Philolaus the Pythagorean believes that, like the sun and moon, it revolves around the fire in an oblique circle. Heraclides of Pontus, and Ecphantus the Pythagorean make the earth move, not in a progressive motion, but like a wheel in a rotation from west to east about its own center.'

5. Therefore, having obtained the opportunity from these sources, I too began to consider the mobility of the earth. And even though the idea seemed absurd, nevertheless I knew that others before me had been granted the freedom to imagine any circles whatever for the purpose of explaining the heavenly phenomena. Hence I thought that I too would be readily permitted to ascertain whether explanations sounder than those of my predecessors could be found for the revolution of the celestial spheres on the assumption of some motion of the earth.

6. Having thus assumed the motions which I ascribe to the earth later on in the volume, by long and intense study I finally found that if the motions of the other planets are correlated with the orbiting of the earth, and are computed for the revolution of each planet, not only do their phenomena follow from this but also the order and size of all the planets and spheres, and heaven itself is so linked together that in no portion of it can anything be shifted without disrupting the remaining parts and the universe as a whole."

However, as Copernicus realised, it was not enough to simply assert his new theory - it had to be established by comparing its predictions with the actual observations of the sky, which had accumulated over centuries. He had at his disposal observations going back to Ptolemy, as well as more recent measurements of Arab astronomers embodied in the Toledo and Alfonsine tables, and updatings of these. However he himself made many of his own observations, and then used these to refine calculations of planetary and lunar motion. Such work is extremely painstaking when all calculations have to be done by hand, using methods of successive approximation. In choosing his measurements and calculations Copernicus was of course guided by the hypotheses he had made.

This approach is a large departure from the early pre-Alexandrian Greek fashion of doing theory, in its emphasis on comparison with data compiled by many workers over centuries, but of course Copernicus was here following a long line of previous astronomers. Ptolemy came to his elaborate theory using the same combination of empirical observation and a resort to certain principles, and the Ptolemaic methodology had been elaborated to great effect by Islamic astronomers, and then taken up by the late mediaeval astronomers. Some of the principles evoked by Copernicus were hardly different from those of Ptolemy - for example, the belief that motion had to be in circles, and that the universe and the earth had to be perfect spheres. In assuming this Copernicus was appealing partly to historical precedent, but also to a principle which he articulated in his missive to Pope Paul, viz., an appeal to the harmony and symmetry of such a world system. As we shall see in the discussion of the modern field theories of electromagnetism, particle physics, and general relativity, the appeal to principles of symmetry like these turns out to have enormous power if employed side by side with empirical observation- in this sense the approach of Copernicus not only harks back to ancient Greek ideas, but also has a very modern cast.

It is in the comparison with observation that the truly new ideas in Copernicus appear. In setting up his heliocentric system, Copernicus realised that he was able to explain a large number of observational facts in a very natural way. The first set of facts involved the observations of the positions of the planets over a very long period of time, going back to the data compiled by Ptolemy. The immense period of time over which the observations now extended, along with Copernicus's own lengthy calculations, allowed him to compile new tables describing the planetary motions, which were more accurate than previous tables. The second set of facts involved simple observations of the brightness of the planets and stars throughout the year- although well known, Copernicus argued that the only reasonable explanation of these lay in a heliocentric hypothesis, with the variable luminosity of the planets coming from their varying distance from the earth, and the almost fixed luminosity of the stars arising because they were so far away.

Thus Copernicus was led to his picture in which the sun was stationary, the earth and planets orbit in circles around in, and the moon orbits the earth; and that the earth itself turns on its axis once every day. Much farther away, the stars lay stationary on the 'celestial sphere'. For Copernicus the alternative, that the earth was stationary, not even rotating around its own axis, and that the sun, planets, and even the stars orbited round the earth at fantastic velocities, was simply too bizarre to countenance seriously. That he was able to find precedent in the arguments of some writers in antiquity was certainly of great help to him.

The details of the Copernican system were not trivial. The hypothesis that the Sun was at the centre of a set of circular planetary orbits led to consequences immediately at variance with observation, particularly if one insisted that the motion of each planet on its circle was uniform in velocity (as Copernicus did, in contrast to Ptolemy). Copernicus dealt with this difficulty in 2 ways. First, he displaced the centre of the earth's orbit from the sun- accordingly, for him the centre of the universe (ie., of the celestial sphere) could be considered to be at the centre of the earth's orbit. He then argued that the earth's motion could be described in terms of 2 motions, composed of the basic uniform motion around this displaced circle, plus another uniform motion around a smaller epicycle, having the same period as the basic circle. In this way Copernicus was able to derive the same basic motion as Ptolemy (although with somewhat different numerical values for the size of the different circles, and the displacement distance), but without dropping the requirement of uniform motion, as Ptolemy had done in his 'equant' theory. A good summary of Copernicus's theoretical framework for the motion of the earth was provided in his own writings:

"*33. In so many and such important ways, then, do the planets bear witness to the earth's mobility. I shall now give a summary of this motion, insofar as the phenomena are explained by it as a principle. As a whole, it must be admitted to be a threefold motion.*

The first motion, named 'nychthemeron' *by the Greeks, as I said, is the rotation which is the characteristic of a day plus a night. This turns around the earth's axis from west to east, just as the universe is deemed to be carried in the opposite direction. It describes the equator, which some people call the "circle of equal days", in imitation of the designation used by the Greeks, whose term for it is* 'isemerinos'.

34. The second is the yearly motion of the center, which traces the ecliptic around the sun. Its direction is likewise from west to east, that is, in the order of the zodiacal signs. It travels between Venus and Mars, as I mentioned, together with its associates. Because of it, the sun seems to move through the zodiac in a similar motion. Thus, for example, when the earth's center is passing through the Goat, the sun appears to be traversing the Crab; with the earth in the Water Bearer, the sun seems to be in the Lion, and so on, as I remarked.

35. To this circle, which goes through the middle of the signs, and to its plane, the equator and the earth's axis must be understood to have a variable inclination. For if they stayed at a constant angle, and were affected exclusively *by the motion of the center, no inequality of days and nights would be observed. On the contrary, it would always be either the longest or shortest day or the day of equal daylight and darkness, or summer or winter, or whatever the character of the season, it would remain identical and unchanged.*

The third motion in inclination is consequently required. This also is a yearly revolution, but it occurs in the reverse order of the signs, that is, in the direction opposite to that of the motion of the center. These two motions are opposite in direction and nearly equal in period. The result is that the earth's axis and equator, the largest of the parallels of latitude on it, face almost the same portion of the heavens, just as if they remained motionless. Meanwhile the sun seems to move through the obliquity of the ecliptic with the motion of the earth's center, as though this were the center of the universe. Only remember that, in relation to the sphere of the fixed stars, the distance between the sun and the earth vanishes from our sight forthwith.

In dealing with the other planets Copernicus gave the order of the orbits correctly, and did succeed in obtaining a reasonable agreement with observation, although he did complicate his theory considerably by insisting that the centre of the universe lay at the centre of the earth's orbit - this made the orbits of the other planets implicitly dependent on that of the earth. His theory of the moon's orbit around the earth was far simpler and more plausible than that of Ptolemy, who required the moon's distance from the earth to vary by a factor of two.

Copernicus was in no doubt that the great advantage of his system was its simplicity and elegance, and this for him was an overwhelming philosophical advantage. A number of quotes from his letter to the Pope illustrate this:

"*28. All these facts are disclosed to us by the principle governing the order in which the planets follow one another, and by the harmony of the entire universe, if only we look at the matter, as the saying goes, with both eyes.*

29. Hence I feel no shame in asserting that this whole region engirdled by the moon, and the center of the earth, traverse this grand circle amid the rest of the planets in an annual revolution around the sun. Near the sun is the center of the universe. Moreover, since the sun remains stationary, whatever appears as a motion of the sun is really due rather to the motion of the earth. In comparison with any other spheres of the planets, the distance from the earth to the sun has a magnitude which is quite appreciable in proportion to those dimensions. But the size of the universe is so great that the distance earth-sun is imperceptible in relation to the sphere of the fixed stars. This should be admitted, I believe, in preference to perplexing the mind with an almost infinite multitude of spheres, as must be done by those who kept the earth in the middle of the universe. On the contrary, we should rather heed the wisdom of nature. Just as it especially avoids producing anything superfluous or useless, so it frequently prefers to endow a single thing with many effects."

or, later on, as he discusses the advantages of his system both in terms of its simplicity and internal harmony, and its more natural explanation of various observational facts, he remarks that:

"*32. In this arrangement, therefore, we discover a marvelous symmetry of the universe, and an established harmonious linkage between the motion of the spheres and their size, such as can be found in no other way. For this permits a not inattentive student to perceive why the forward and backward arcs appear greater in Jupiter than in Saturn and smaller than in Mars, and on the other hand greater in Venus than in Mercury. This reversal in direction appears more frequently in Saturn than in Jupiter, and also more rarely in Mars and Venus than in Mercury. Moreover, when Saturn, Jupiter, and Mars rise at sunset, they are nearer to the earth than when they set in the evening or appear at a later hour. But Mars in particular, when it shines all night, seems to equal Jupiter in size, being distinguished only by its reddish color. Yet in the other configurations it is found barely among the stars of the second magnitude, being recognized by those who track it with assiduous observations. All these phenomena proceed from the same cause, which is in the earth's motion.*

Yet none of these phenomena appears in the fixed stars. This proves their immense height, which makes even the sphere of the annual motion, or its reflection, vanish from before our eyes."

Copernicus was also well aware that the most important difference between his heliocentric picture and the standard earth-centred picture of Ptolemy was based on a different choice for the frame of reference, and that the *relative* motion of the planets and sun to each other was not necessarily different in these 2 pictures (although there were some differences of detail with Ptolemy). Likewise, one can, if only interested in *relative* rotations, describe the daily movement of the stars, planets, and sun around the sky, either in terms of a rotation of the earth, or of a rotation of the firmament around a non-rotating earth- and Copernicus was equally aware of this. Indeed he makes it very clear that the crucial difference between the 2 pictures does not lie in the relative motion, but in the different underlying physical structure:

"*25. We regard it as a certainty that the earth, enclosed between poles, is bounded by a spherical surface. Why then do we still hesitate to grant it the motion appropriate by nature to its form rather than attribute a movement to the entire universe, whose limit is unknown and unknowable? Why should we not admit, with regard to the daily rotation, that the appearance is in the heavens and the reality in the earth? This situation closely resembles what*

Vergil's Aeneas says: 'Forth from the harbor we sail, and the land and the cities slip backward [Aeneid, III, 72]'.

26. For when a ship is floating calmly along, the sailors see its motion mirrored in everything outside, while on the other hand they suppose that they are stationary, together with everything on board. In the same way, the motion of the earth can unquestionably produce the impression that the entire universe is rotating......."

Copernicus was of course not the first to address this question of relative motion, and the physical difference between the 2 pictures just discussed. The discussion of Nicolas Oresme was presumably known to him, as were the earlier deliberations of some of the Greeks. However, unlike Oresme, he came down boldly and firmly in favour of a heliocentric picture, making the physical choice between the two theories.

In recent years it has been common to see some philosophers and historians of science argue that the *only* important difference between the theories of Ptolemy and Copernicus, apart from questions of detail, is in the assumption of different frames of reference - and that because only relative motion is meaningful in both the Copernican theory and later planetary theories like the Newtonian one, there is fundamentally no difference between the Ptolemaic theory and later theories like the Copernican or Newtonian theories. From one rather narrow point of view, which takes into account only the observations of the planetary motions, this argument is trivially correct. In fact one can argue more generally that *any* theory can be rewritten in a a different way, usually far more complex, that nevertheless has the same observational consequences (such an argument was given most convincingly by Poincaré at the beginning of the 20th century, in his philosophical work "*Science et Hypothèse*".

However from a broader perspective this argument is sheer baloney. The reason is that any theory of Nature contains its own internal logic, and by application to the real world, also gives a logic and a structure describing how the world works. This is quite unavoidable, if the theory makes any claim to give a general picture of the world. The only way that one can avoid this, and only discuss the observational consequences of the theory, is by artificially restricting the theory so that (i) it only is supposed to describe some limited set of phenomena (in the present case, the observed motion of the planets); and (ii) it is not required to be consistent with any other theory of Nature which overlaps with it in the phenomena that they both describe. The importance of these remarks becomes much clearer once one assumes that a proper theory has to be *predictive*, ie., that it has to be able to discuss quantitatively hitherto unobserved phenomena. The problem with a theory like that of Ptolemy is that it is quite unable to do so - indeed, any increase in the number of phenomena it is asked to describe lead to ever more fantastic constructions, which have no justification in any internal logic of the theory, but only in that with sufficient ingenuity they can be forced into agreement with the new phenomena. In this respect, one cannot consider the theory of Copernicus to be the same as that of Ptolemy at all - the picture of the universe that it offers has a quite different internal logic, and indeed it immediately suggests all sorts of possibilities which were unknown to astronomers living before the invention of the telescope (including further planets, or other smaller objects orbiting the sun, and the existence of some medium or dust through which the earth moved in its orbit). Such possibilities are of course explicable after their observation, in a very contrived way; but nothing in the Ptolemaic world-picture suggests them in any natural way, consistent with the internal logic of the theory, or the general picture of the world's structure that it offers.

Such a point of view now seems natural to us, but at the time Copernicus lived it was not - scientists, philosophers, and religious thinkers were still wedded to ancient ways of thinking, and the modern ideas of science were still to come. From this point of view we can see that the ideas of Copernicus were in some respects very daring indeed, in an interesting contrast to his apparently rather conventional life. We will return to this essentially epistemological point at several occasions in the later notes.