DE REVOLUTIONIBUS ORBIUM COELESTIUM – ON THE REVOLUTIONS OF THE HEAVENLY SPHERES

Nicolaus Copernicus, 1543

" ….. the result which we hope to attain by the motion of the Earth. We shall assume this motion as a hypothesis and follow its consequence."

Nicolaus Copernicus, 1543

…. What if the Sun
Be Center to the World, and other Stars
By this attractive virtue and their own
Incited, dance about him various rounds?
Their wondering course now high, now low, then hid,
Progressive, retrograde, or standing still,
In six thou seest, and what if seventh to these
The planet Earth, so stedfast though she seems,
Insensibly three different motions move?

- John Milton, Paradise Lost, Book VIII, 1667

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The Almagest of Ptolemy

Ptolemy worked at the famous University of Alexandria in Egypt around 150 A.D. Alexandria at that time was the most important city in the Eastern part of the Mediterranean. Alexandra was built by Alexander the Great (356 – 323 B.C.) in the 3rd century B.C. The city included not only an excellent University, but the famous library of Alexandria which once held over a million folio and parchments.

Geocentric – Earth centered

The Earth centered, or geocentric, model of the solar system was developed by Aristotle around 350 B.C. and elaborated by Claudius Ptolemy of Alexandria around 150 A.D. There had been other mathematicians like the Pythagorean Philolaus who argued for a Sun centered, heliocentric, model of the solar system however the Aristotelians prevailed and Sun centered models of the solar system were forgotten for fifteen centuries.

Heliocentric- Sun centered

Ptolemy outlined his system in a treatise which has become known as the *Almagest*, meaning "the greatest". What Ptolemy established for the first time was a working mathematical model by which the positions of the planets could be predicted accurately.

Almagest – "The Greatest"

In the Ptolemaic system, each planet moved in a small circle known as an epicycle, whose centre was carried round the Earth in a larger orbit known as the deferens. For fourteen centuries astronomers computed planetary positions from tables based on this analysis.

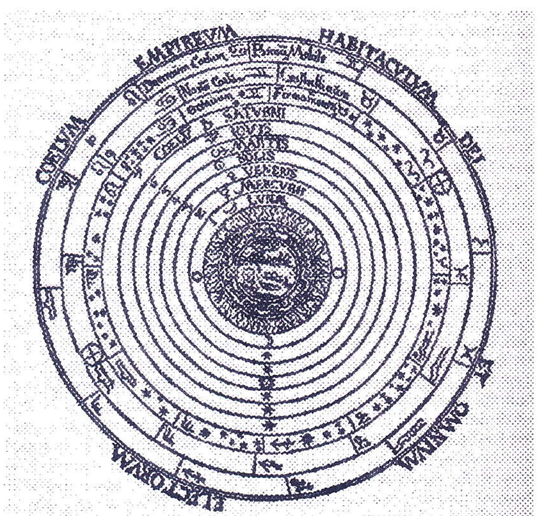

Figure 1. The Ptolemaic System – the Earth is at the Centre of the Universe

Ptolemy's *Almagest* was unknown in the early Middle Ages. Its first appearance in Western Europe is in a translation made direct from the Greek in Sicily in the year 1160. Translation direct from the Greek was very unusual in the 12th century.

About 1170 the Englishman Daniel of Morley was studying the Arabic text of Ptolemy at Toledo in Moorish Spain with the help of a native Arabic-speaking Christian, Ibn Ghalib. Daniel recounts how he listened in as Ibn Ghalib worked with the famous translator Gerard of Cremona (died 1187). Gerard's translation of the *Almagest* was completed about 1175 and used in the Middle Ages. Gerard's translation was from Arabic into Latin.

The *Almagest* was again translated from the Greek in the 15th century by George of Trezibond (1396-1486). Copies were made of the Trezibond translation in Venice in 1528 and were distributed to libraries across Italy, including the Medici Library in Florence. It is believed that Copernicus used a Trezibond copy of the Ptolemy's *Almagest*.

Nicolaus Copernicus (1473 – 1543)

Copernicus was born on February 19th, 1473, in Torun, Polish Prussia, the son of a merchant, youngest child of four. He lost his father at age ten and was adopted by his uncle.

Cracow was the ancient capital of Poland.

For his time Copernicus was exceptionally educated. He studied mathematics and geometry at Crakow, Greek at Bologna, medicine at Padua in Italy and became Doctor of Canon Law at Ferrara in 1503.

It is worth noting that when Christopher Columbus sailed to the new world in 1492 Copernicus was a student at the Jagiellonian University in Crakow; and during his lifetime Magellan's expedition rounded the world. Copernicus' new celestial investigations were part of this Age of Exploration.

When Copernicus was 19 Columbus sailed to the New World

As a student, Copernicus followed the standard medieval curriculum, inherited from Roman educational practice: the trivium – grammar, dialectic, rhetoric – and the quadrivium – arithmetic, music, geometry and astronomy. On completion of his university education he went on to lecture in mathematics at Rome.

Copernicus was proficient in Greek and Latin, using his linguistic skills to read, translate and in some cases transcribe several of the important Greek and Latin books. He was, however not a believer in Scholasticism. In his late twenties he returned home and was appointed a canon of Warmia, in Prussian Poland. He retained this position until his death in 1543; he never married.

Though today he is remembered as the father of modern astronomy, in his own time he made his livelihood not as an astronomer, but as an ecclesiastic. His position as canon of the cathedral of Fromback gave him both financial security and freedom to continue his studies in medicine, mathematics and astronomy. Copernicus used his medical skill to help the poor, and his mathematical skills to develop his astronomical theories.

It is evident that Copernicus was aware of the work of the ancient Greek mathematicians and astronomers, including Aristarchus and Philolaus. Shortly after 1508 Copernicus wrote a brief Commentary on astronomy which contained the sentence:

> "What appears to us as motion of the sun arises not from its motion but from the motion of the earth."

This important theme occupied his thoughts for the next thirty years. It was at Fromback in Prussia that Copernicus worked on his great book, the *De Revolutionibus Orbium Coelestium*.

Copernicus published his book *De Revolutionibus Orbium Coelestium* in 1543, the year he died

Although his mathematical and astronomical skills were quite admired he published his *De Revolutionibus* reluctantly and only saw the first printed copy on his deathbed on May 23rd, 1543.

The accepted model of the structure of the universe before Copernicus' time was earth-centred. The sun, the moon, the five known planets, and the stars were thought to revolve about the earth in endless, perfect circles.

Aristarchus of Samos had proposed a sun-centred model in ancient times

This earth-centred model was developed by Aristotle around 350 B.C. and elaborated by Claudius Ptolemy of Alexandria around 150 A.D. Ptolemy's earth-centred model, for a number of reasons, pushed Aristarchus of Samos' sun-centred model aside.

Ptolemy outlined his system in a treatise which has come to be known as the *Almagest*, meaning "the Greatest." What Ptolemy established for the first time was a working mathematical model by which the positions of the planets could be accurately predicted.

After Aristarchus, Aristotle had proposed an earth-centred model in 350 B.C.

While Aristarchus' sun-centred model is conceptually correct, neither Aristarchus nor his successors could build a predictive model based on the mathematics of the day.

Ultimately such a sun-centred predictive model relies on an in-depth understanding of projective geometry, of the mathematics of conic sections (circles, parabolas and ellipses) and of polynomial equations.

This earth-centred model was elaborated by Claudius Ptolemy of Alexandria around 150 A.D.

In the Ptolemaic system, each planet moved in a small circle (something called an epicycle) whose centre was carried round the earth in a larger orbit (or deferent). For fourteen centuries astronomers computed planetary positions from tables based on this analysis.

Copernicus described an unfamiliar universe, with the sun, not the earth, at its centre; he treated the earth as a planet amongst the other planets, with a yearly orbit around the sun, a daily rotation on its axis, and a conical precession.

Copernicus's great breakthrough is its recognition that the complex paths which we see traced out in the sky by the planets could be explained by a combination of their own motion and that of the earth from which we observe them.

Copernicus recognized that the paths of the planets could be explained by their own motion and that of the earth

It is worth noting, however, that he arrived at his innovation using some traditional assumptions, shared by Aristotle and Ptolemy, that the motion of the heavenly bodies must be a compound of circles, the major difference being in Copernicus' model the sun was at the centre of these compound circles.

Copernicus's new model not only gave astronomical inquiry the direction it still follows today, it also helped to define the beginning of modern scientific inquiry.

Following closely in his footsteps were other great scientists like Johannes Kepler (1571 –1630), Galileo Galilei (1564-1642) and Isaac Newton(1642 – 1727).

Galileo Galilei (1564-1642)

Johannes Kepler (1571 –1630)

Isaac Newton (1642 – 1727)

The Copernican model was not generally accepted until the seventeenth century. Johannes Kepler working with the finest of contemporary celestial measurements, found that the planets orbit the sun in ellipses, and that we could describe these orbits mathematically.

Galileo, outspoken supporter of the Copernican model, used his telescope to challenge the ancient earth-centered model. Building on the work of predecessors, Isaac Newton in the 1660's discovered his theory of Universal Gravitation, showing definitively the validity of the sun-centered model proposed by Copernicus.

The Concept of the Sphere

The concept of circles and spheres being perfect dates back to the time of Plato and his treatise *Timaeus*. The perfection of the sphere became a central principle of Aristotelian thought and was henceforth incorporated into the Ptolemaic system.

Aristotle's reasoning was the Heavens were perfect, as are circles and spheres are perfect, therefore they must govern the motion of the Heavenly Spheres. Aristotle's thoughts pervade the whole of astronomy in the Middle Ages until Kepler. The perfection of the sphere is accepted as a matter of course by Copernicus

Aristotle's reasoning was the Heavens were perfect, as are circles and spheres are perfect, therefore they must govern the motion of the Heavenly Spheres.

Nicolaus Copernicus and Modern Science

By Wilhelmina Iwanowska

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in hoc remotissimo loco terrae

It is hard to believe that one very modest man, living in a remote place of the Earth – "in hoc remotissimo loco terrae" as he defines his native country – working not professionally in astronomy, was able to change essentially the ways of human thought and living with his only book, which was issued the day of his death.

Born in Torun, Poland in 1473, as a son of a rich merchant who came to Torun from Cracow, he early lost his father and was educated by his mother and his uncle, the bishop of Warmia, a northern province of Poland at the time, and spent four years attending all available courses, including mathematics and astronomy, for which Cracow University was then renowned. Later he was sent by his uncle to Italy for almost seven years of further study in canonical law in Bologna and medical art in Padova. He obtained his doctoral degree in law at the University of Ferrara and returned to Poland in 1503.

Plato's Principle – only circular and uniform motion are appropriate for celestial bodies.

His main interest during his studies in Cracow, however, as well as in Italy, was astronomy, to which he devoted then and later all his free time. He considered astronomy the most important and attractive science but he was conscious that the state of this science was at that time unsatisfactory, needing some basic reform.

The most important astronomical work before Copernicus was *Almagest* written by Ptolemy of Alexandria in the second century A.D. This work stood at the high mathematical level for that time and explained the motions of all celestial bodies on the assumption that the Earth is motionless in the centre of the Universe with all other bodies revolving around it once a day. In addition, the Sun, the Moon, and the planets describe their orbits around the Earth.

deferens – the main circle of a Ptolemaic Orbit

These orbits were composed of circles: a main one called the *deferens* and a secondary one called *epicycle*, whose centre moved on the deferens with the planet circling the epicycle. The Earth was not strictly in the centre of the deferens and the motion was not strictly uniform.

epicycle – the smaller, secondary circle of the orbit

Thus Ptolemy disobeyed, to some extent, the principles expressed by Plato that only circular and uniform motions are appropriate to celestial bodies. Adjusting the sizes of circles and the periods of revolution for different planets, Ptolemy achieved with his model a relatively good agreement between the predicted and observed positions of celestial bodies and was able to predict their positions several centuries in advance. With time, however, the discrepancies between the tables and observations grew bigger and bigger. Astronomers of the Middle Ages modified the theory by adding new circles to the Ptolemaic model and changed the assumed values of the parameters.

There were, however, some aspects of the Ptolemaic system which contradicted the observed facts in an obvious way from the beginning. For example, the Moon should show its diameter at the quarters to be twice as great as at Full Moon, which was never observed. To prove this, while he was in Bolgna, Copernicus and his professor of astronomy, Maria Domenico Novara, observed the occultation of the star alpha Taura by the Moon. They did not find any considerable difference between the Moon's distance at different phases. This and some other contradictions were probably obvious to Ptolemy himself and surely to his successors. Nobody worried, however, very much about it.

In error, Ptolemy predicted that the Moon should show its diameter at the quarters to be twice as great as at Full Moon.

Although astronomy was one of the oldest sciences, for some twenty centuries from antiquity to the time of Copernicus it was nothing more than a practical tool for measuring time and assisting navigation. Moreover, astronomy was a domain of myths and legends and served to cast horoscopes. It was not a means to provide knowledge of the real world since nobody asked: how is it really? It was sufficient to have a formal scheme enabling one to predict the positions of celestial bodies.

After his return from Italy, Copernicus took a position as canon at the chapter in Frombork, Warmia, prepared for him by his uncle. Copernicus was soon involved in many administrative and medical duties in the unsettled environment of the day, since Warmia and other northern Polish provinces were under constant attack by the Teutonic Knights who held the neighbouring region. Copernicus had many conflicts with them and even organized the military defence of Olsztyn, asking the Polish King for help. Al these duties did not prevent him from continuing his astronomical work.

Before 1515 he wrote a booklet in Latin *Nicolai Copernici de hypothesibus motuum coelestium a se constitutes Commentariolus* – a Commentary on the hypothesis concerning celestial motion established by Nicolaus Copernicus. In this booklet he presented a first sketch of his heliocentric system, still as a hypothesis. This booklet was not printed, since printing was a newly discovered art, but was distributed in handwritten copies to some selected persons.

Nicolai Copernici de hypothesibus motuum coelestium a se constitutes *Commentariolus*

De Revolutionibus orbium coelestium - published in 1543

Copernicus needed thirty more years to prove his hypothesis and to turn it into a scientific theory. The results of these mathematical elaborations, supported by observations made by himself and by his predecessors were written in his major work *De Revolutionibus orbium coelestium* – On the Revolutions of Celestial Spheres.

Copernicus hesitated to publish his work because of a double fear: that it was not perfect and that it would be opposed by

> "those who basing on some places in the Holy Scriptures, interpreted badly and perversedly according to their intentions, will dare to condemn this my theory and myself. "
>
> (De rev., dedication letter).

George Joachim Rheticus arranged the publishing of De Revolutionibus in Nurnberg

Literally at the last moment, a few years before his death, Copernicus decided to deliver his work to be printed in Nuremberg, persuaded by his intellectual friends and his only student George Joachim Rheticus, a young professor of mathematics at the University of Wittemberg, who came to Frombork to learn the new theory from Copernicus himself. Rheticus helped his master to prepare the work for printing and took it to Nuremberg. The first copies of the printed book arrived in Frombork when Copernicus was on his deathbed.

Let us now review what this book contains. Precede by a remarkable letter dedicating the work to Pope Paul III and by a poetical introduction glorifying astronomy, the first chapter, called "book" presents the basic assumptions of the new theory: The Earth is not a motionless centre of the world, it is subject to a triple motion;

The Earth is not a motionless centre of the Universe, it is subject to a triple motion

- a daily motion around its axis,
- a yearly revolution around the Sun, and finally,
- the Earth's axis changes slowly its orientation in space (describing a cone in 26,000 years). The result of this last motion is a slow drift, called procession, of the position of the equinoxes relative to the stars.

The Sun, says Copernicus, stays in the centre of the system with the planets revolving around it in the order of their distances, following the lengths of their periods of revolution: Mercury, Venus, Earth, Mars, Jupiter and Saturn. The Earth, with the Moon revolving around it, is the third planet from the Sun. No planets beyond Saturn were known at that time.

The arguments for these assumptions were those of greater probability. It is more probable, says Copernicus, that the Earth rotates around its axis than that all remaining bodies, including stars, revolve around the Earth once a day – stars should then have enormous linear velocities. It is also more probable that the Earth revolves around the Sun in a year than vice versa, and that the other planets also revolve around the Sun.

Assumption of Greater Probability - This reasoning is a form of Bayesian reasoning

The observed motion of planets can then be interpreted much more simply, and the loops which they apparently describe reflect simply the yearly motion of the Earth. The big epicycles introduced by Ptolemy in order to take account of these loops are no longer necessary. Furthermore, the Sun is physically distinguished from the planets as the only shining body. Copernicus also considers it as more probable that the Earth's axis is swinging than the whole heavens suffer processional motion.

The loops the planets describe through the sky are caused by the yearly motion of the Earth around the Sun.

In addition to these assumptions, Copernicus says in the first book that the Earth is spherical and the Universe is spherical. He mentions gravity as a natural property keeping all celestial bodies in their spherical volumes. He argues that the distance to the stars are incomparably greater than the dimensions of the planetary system. This last statement was necessary in order to refute the most serious criticism raised against his theory; namely, if the Earth orbits the Sun, why then do not stars reflect this motion in their yearly oscillations similar to the loops described by planets?

Copernicus assumed the Earth is spherical, as is the Universe

Copernicus' answer was: stars do oscillate, reflecting Earth's yearly motion, but the amplitude of these oscillations are immeasurably small because of the enormous stellar distances. As we now know, these parallactic oscillations were discovered three hundred years later in the nineteenth century, but they were less than one second of arc. The fundamental method of determining stellar distances is based on measuring parallactic motions of stars. Whether the Universe is finite or infinite Copernicus considers to be an open question.

Parallax – small shift of the distant stars due to Earth's orbit around the Sun

After such a descriptive outline of his theory, presented in the first book of the Revolutions, the following five books contain a laborious mathematical development of the heliocentric model. Assuming the Earth's triple motion and the orbital revolutions of the planets around the Sun, Copernicus derives from these assumptions how an observer on the moving Earth should see the motions of all the other bodies. He then compares these predicted motions with those observed by his predecessors and by himself. There are records of about 60 observations made by Copernicus during his life up to the second to last year before his death. His instruments were very primitive, made

Planet means "wanderer" in Greek.

Planets appear to sometimes move forward across the sky, then stop and then move backwards (retrograde motion) by himself. They had no lenses, for these were not yet known. What he could do with these instruments was to measure the angular distances between planets and stars and the elevations of celestial bodies above the horizon. he also observed solar and lunar eclipses. He planned his observations in such a way as to get crucial tests for his theory, as far as possible. The mathematical tools of Copernicus were mainly Euclidean geometry and the elements of trigonometry.

Copernicus writes – a Commentary on the hypothesis concerning celestial motion, around 1515; de hypothesibus motuum coelestium a se constitutes Commentariolus

Copernicus tried to conform to the Platonic principle of uniform circular motions, and in *Commentariolus* he adheres to it strictly, placing the Sun in the common centre of circular orbits for all the planets. In order to take account of the non-uniformity of planetary motions, which Kepler later accomplished by introducing elliptical orbits, Copernicus introduced small double epicycles, thus keeping all motions uniform and circular. This resembles very much the development of a periodic function into a Fourier series, applied so often nowadays. In the Revolutions Copernicus changes this model, pushing the Sun slightly out of the centres of the planetary orbits and leaving a single small epicycle.

It is well known that the Copernican theory was received in a variety of ways. Some brilliant scientists, like the famous Italian physicist Galileo Galilei, who lived in both the sixteenth and seventeenth centuries, or his contemporary, the famous German astronomer, Johannes Kepler, accepted the new theory with enthusiasm. Galileo realized that it could not be otherwise, for with his lens telescope, which he was the first to turn on the sky, he had observed the succession of phases of the planets Venus, which indicated that it revolved around the Sun. not around the Earth.

Kepler analyzed long lists of observations of planetary positions made by his master, Tycho Brahe, and could find the relations, called Kepler's laws, only by placing the Sun in the centre of the planetary system. We know that Kepler improved the model of Copernicus by introducing elliptical orbits and placing the Sun in their common focus. The planets move with constant areal velocity and their distances to the Sun are proportional to some power (2/3) of their periods of revolution.

But the great majority of people, as well as official organizations such as the universities and the churches, rejected the theory of Copernicus. Why? Because it contradicted the common sense of immobility and of the importance of the Earth, and because it surpassed the limitations of human senses and of the human brain, which are anthropocentric in their nature. This opposition reached its peak at the beginning of the seventeenth century when the Holy

Inquisition forced Galileo to deny and to condemn the Copernican theory. The work of Copernicus, De Revolutionibus, was put on the list of prohibited books in 1616 and remained there for more than two hundred years.

These sad events hindered the acceptance of Copernican theory and the development of science, but they could not stop it. In the second half of the seventeenth century we find Isaac Newton, the founder of mechanics and a pioneer in other branches of physics. In 1687 he published his major work, *Philosophiae Naturalis Principia Mathematica*, in which he formulated the basic principles of dynamics, defining force as being connected with acceleration, not with velocity as his predecessors tried to do.

Isaac Newton – *Philosophiae Naturalis Principia Mathematica* 1687

In this same work Newton formulated the law of universal gravitation, stating that every two masses attract each other with a force proportional to the mass values and inversely proportional to the square of their distance. Newton discovered and proved this law, as well as his principle of dynamics, using planetary motions referred to the heliocentric system. Kepler's Laws appear as a direct consequence of Newton's dynamics.

Since the days of Newton it has frequently been found that the discovery and proof of new laws of nature have required a great laboratory than those which are available on Earth. In the case of Newton a laboratory at least as big as the planetary system was needed and it was Copernicus who brought this laboratory into order. It was by no means an accident, then, that the development of modern science began with astronomy. It could not be otherwise.

In order to use Newtonian mechanics for calculating celestial and terrestrial motions, more sophisticated mathematics than the elementary one available at the time was needed. It is known that Newton himself, invented the differential and integral calculus, which was also established independently by Leibnitz and Descartes, and had previously invented analytical geometry . Thus, astronomy, physics and mathematics, helping each other, began their progress which has continued as an ever-increasing rate up to the present time.

Newton's dynamics together with the law of universal gravitation served astronomers during the next several centuries as the key to the solution of all problems of celestial mechanics, especially for the calculations of the orbits of planets, comets, satellites, natural and artificial bodies. These orbits are not strictly Keplerian ellipses, parabolas or hyperbolas because the mutual attraction of all these bodies perturb the simple orbits. The same Newtonian laws enabled astronomers to calculate the orbits of double and multiple stars, stellar orbits in the Galaxy and the motions of the galaxies. The system worked well until astronomers encountered very large masses and very large velocities, when it was found that Newtonian mechanics was not sufficient.

At the beginning of the twentieth century Albert Einstein established the special and general theories of relativity which were generalizations of Newton's mechanics. These theories were tested and are still being proven using celestial observations. The successes attained in mechanics encouraged physicists to perform experiments in other branches of physics, and during the eighteenth and nineteenth centuries these other branches, such as optics, magnetism, electricity, thermodynamics and chemistry, made their appearance. In their turn, they were successfully applied to astronomy, opening a new field called astrophysics.

A common approach to problems, called "the scientific method", first introduced by Copernicus, was followed in all these investigations. The method begins with an idea called, "a working hypothesis," but then needs strict and thorough mathematical consideration of all its consequences and a confrontation of these consequences with experiment or observation.

Let us remember that science is still very young, being less than five hundred years old. It is on its ascending branch, progressing at an exponential rate. What its progress will be in the next five hundred years is difficult to predict. One might wish only that it serves to benefit all mankind.

From: Excerpt from a Copernicus Quincentennial Celebration presentation to the Royal Astronomical Society of Canada, 1973

A Commentary on the Hypothesis Concerning Celestial Motion

By Nicolaus Copernicus

Our ancestors assumed, I observe, a large number of celestial spheres for this reason especially, to explain the apparent motion of the planets by the principle of regularity. For they thought it altogether absurd that a heavenly body, which is a perfect sphere, should not always move uniformly. They saw that connecting and combining regular motions in various ways they could make any body appear to move to any position.

Callipps and Eudoxus, who endeavored to solve the problem by use of concentric spheres, were unable to account for all the planetary movements; they had to explain not merely the apparent revolutions of the planets but also the fact that these bodies appear to us sometimes to mount higher in the heavens, sometimes to descend; and this fact is incompatible with the principle of concentricity. Therefore it seemed better to employ eccentrics and epicycles, a system which most scholars finally accepted.

Yet the planetary theories of Ptolemy and most other astronomers, although consistent with the numerical data, seemed likewise to present no small difficulty. For these theories were not adequate unless certain equants were also conceived; it then appeared that a planet moved with uniform velocity neither on its deferent nor about the centre of its epicycle. Hence a system of this sort seemed neither sufficiently absolute nor sufficiently pleasing to the mind.

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

After I had addressed myself to this very difficult and almost insoluble problem, the suggestion at length came to me how it could be solved with fewer and much simpler constructions then were formerly used, if some assumptions (which are called axioms) were granted me.

They follow in this order:

Axioms

Copernicus' Seven Axioms

1. There is no one centre of all the celestial circles or spheres.

2. The centre of the Earth is not the centre of the Universe, but only of gravity and of the lunar sphere.

3. All the spheres revolve about the Sun as their mid-point, and therefore the Sun is the centre of the Universe.

4. The ratio of the Earth's distance from the Sun to the height of the firmament is so much smaller than the ratio of the Earth's radius to its distance from the Sun that the distance from the Earth to the Sun is imperceptible in comparison with the height of the firmament.

5. Whatever motion appears in the firmament arises not from any motion of the firmament, but from the Earth's motion. The Earth together with its circumjacent elements performs a complete rotation on its fixed poles in a daily motion, while the firmament and highest heaven abide unchanged.

6. What appear to us as motions of the Sun arise not from its motions but from the motion of the Earth and our sphere, with which we revolve about the Sun, like any other planet. The Earth has, then, more than one motion.

7. The apparent retrograde and direct motion of the planets arise not from their motion but from the Earth's motion. The motion of the Earth alone, therefore, suffices to explain so many inequalities in the heavens.

Having set forth these assumptions, I shall endeavour briefly to show how uniformity of the motions can be saved in a systematic way. However, I have thought it well, for the sake of brevity, to omit from this sketch mathematical demonstrations, reserving these for my larger work. But in the explanation of the circles I shall set down here the lengths of the radii; and from these the reader who is unacquainted with mathematics will readily perceive how closely this arrangement of circles agrees with numerical data and observations.

Accordingly, let no one suppose that I have gratuitously asserted, with the Pythagoreans, the motion of the Earth; strong proof will be found in my exposition of the circles. For the principal arguments by which the natural philosophers attempt to establish the immobility of the Earth rest for the most part on the appearances; it is particularly such arguments that collapse here, since I treat the Earth's immobility as due to an appearance.

from: *Nicolai Copernici de hypothesibus motuum coelestium a se constitutes Commentariolus* – a Commentary on the hypothesis concerning celestial motion established by Nicolaus Copernicus, circa 1515.

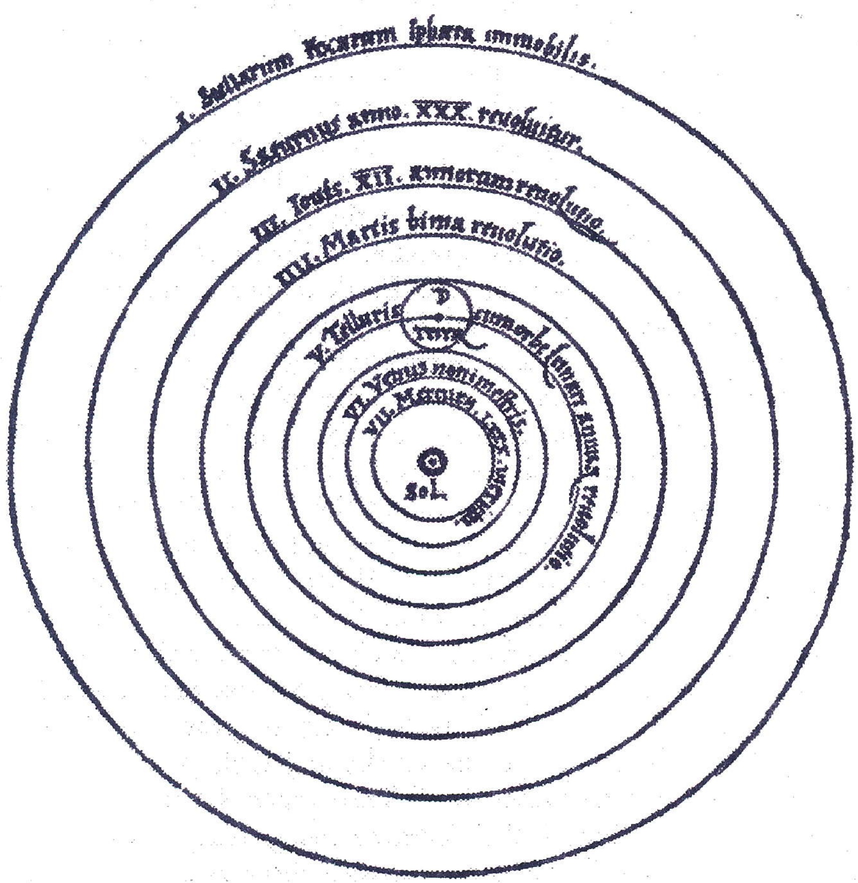


Figure 2. The Copernican System with the Sun at the Centre of the Universe

Preface to De Revolutionibus

By Nicolas Copernicus, 1543

To the Most Holy Lord, Pope Paul III

I may well presume, most Holy Father, that certain people, as soon as they hear that in this book On the Revolutions of the Spheres of the Universe I ascribe movement to the earthly globe, will cry out, that holding such views, I should at once be hissed off the stage. For I am not so pleased with my own work that I should fail duly to weight judgment which others may pass thereon: and though I know that the speculations of a philosopher are far removed from the judgment of the multitude – for his aim is to seek the truth in all things as far as God has permitted human reason so to do – yet I hold that opinions which are quite erroneous are to be avoided.

Thinking therefore within myself that to ascribe movement to the Earth must indeed seem an absurd performance on my part to those who know that many centuries have consented to the establishment of the contrary judgment, namely that the Earth is placed immovably at the central point in the middle of the Universe, I hesitated long whether, on the one hand, I should give light these my written Commentaries written to prove the Earth's motion, or whether, on the other hand, it were better to follow the example of the Pythagoreans and others who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth, as the letter of Lysis to Hipparchus witnesses.

In my judgment they did so not, as some would have it, through jealousy of sharing their doctrines, but as fearing lest these so noble and hardly won discoveries of the learned should be despised by such as either care not to study aught save for gain, or, - if by the encouragement and example of others they are stimulated to philosophical liberal pursuits – yet by reason of the dullness of their wits are in the company of philosophers as drones amongst bees. Reflecting thus, the thought of the scorn which I have to fear on account of the novelty and incongruity of my theory, well-nigh induced me to abandon my project.

These misgivings and actual protests have been overcome by my friends. First among these was Nicolaus Schönberg, Cardinal of Capua, a man renowned in every department of learning. Next was one who loved me well, Tiedemann Giese, Bishop of Kulm, a devoted student of sacred and all other good literature, who often urged and even importuned me to publish this work which I have kept in store not for nine years only, but to a fourth period of nine years. The same request was made to me by many other eminent and learned men. They urged that I should not, on account of my fears, refuse any longer to contribute the fruits of my labours to the common advantage of those interested in mathematics. They insisted that, though my theory of the Earth's movement might at first seem strange, yet it would appear admirable and acceptable when the publication of my elucidatory comments should dispel the mists of paradox. Yielding then to their persuasion I at last permitted my friends to publish that work which they have so long demanded.

That I allow the publication of these my studies may surprise your Holiness the less in that, having been at such travail to attain them, I had already not scrupled to commit to writing my thoughts about the motion of the Earth. How I came to dare to conceive such motion of the Earth, contrary to the received opinion of the Mathematicians and indeed contrary to the impression of the sense, is what your Holiness will rather expect to hear. So I should like your Holiness to know that I was induced to think of a method of computing the motions of the spheres by nothing else than the knowledge that the Mathematicians are inconsistent in their investigations.

For, first, the mathematicians are so unsure of the movements of the Sun and the Moon that they cannot even explain or observe the constant length of the seasonal year. Secondly, in determining the motions of these and of the other five planets, they do not even use the same principles and hypotheses as in their proofs of seeming revolutions and motions. So some use only concentric circles while others use eccentrics and epicycles. Yet even by these means they do completely attain their ends. Those who rely on concentrics, though they have proven the some different motions can be compounded therefrom, have not thereby been able fully to establish a system which agrees with the phenomena. Those again who devised eccentric systems, though they appear to have well-nigh established the seeming motions by calculations agreeable to their assumptions, have yet made any admissions which seem to violate the first principle of uniformity in motion. Nor have they been able thereby to discern or deduce the principal thing – namely the shape of the Universe and the unchangeable symmetry of its parts.

With them it is as though an artist were to gather the hands, feet, head and other members from his images from divers models, each part excellently drawn, but not related to a single body, and since they in no way match each other, the result would be monster rather than man. So in the course of their exposition, which the mathematicians cal their system we find that they have either omitted some indispensable detail or introduced something foreign and wholly irrelevant. This would of a surety not have been so had they followed fixed principles; for if their hypotheses were not misleading, all inferences based thereon might be surely verified. Though my present assertions are obscure, they will be made clear in due course.

I pondered long upon this uncertainty of mathematical tradition in establishing the motions of the systems of the spheres. At last I began to chafe that philosophers could by no means agree on any one certain theory of the mechanism of the Universe, wrought for us by the supremely good and orderly Creator, though in other respects they investigated with meticulous care the minutest points relating to its orbits. I therefore took pains to read again the works of all the philosophers on whom I could lay hand to seek out whether any of them had ever supposed that the motions of the spheres were other than those demanded by the mathematical schools.

I found first in Cicero that Hicetas had realized that the Earth moved. Afterwards I found in Plutarch that certain others had held the like opinion. I think fit here to add Plutarch's own words, to make them accessible to all:

> "The rest hold the Earth to be stationary, but Philolaus the Pythagorean says that she moves around the (central) fire on an oblique circle like the Sun and the Moon. Heraclides of Pontus and Ecphantus the Pythagorean also make the Earth to move, not indeed through space but by rotating round her own centre as a wheel on an axle from west to East."

Taking advantage of this I too began to think of the mobility of the Earth; and though the opinion seemed absurd, yet knowing now that others before me had been granted freedom to imagine such circles as they chose to explain the phenomena of the stars, I considered that I also might easily be allowed to try whether, by assuming some motion of the Earth, sounder explanations than theirs for the revolution of the celestial spheres might also be discovered.

Thus assuming motions, which in my work I ascribe to the Earth, by long and frequent observations I have at last discovered that, if the motions of the rest of the planets be brought into relation with the circulation of the Earth and be reckoned in proportion to the orbit of each planet, not only do their phenomena presently ensue, but the order and magnitudes of all stars and spheres, nay the Heavens themselves, become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all the other parts and of the Universe as a whole.

In the course of the work the order which I have pursued is as here follows: In the first book I describe the position of the spheres together with such movements as I ascribe to Earth; so that this book contains, as it were, the general system of the Universe. Afterwards, in the remaining books, I relate the motions of the other planets and all the spheres to the mobility of the Earth that we may gather thereby how far the motions and appearances of the rest of the planets and spheres may be preserved, if related to all the motions of the Earth.

I doubt not that gifted and learned mathematicians will agree with me if they are willing to comprehend and appreciate, not superficially but thoroughly, according to the demands of this science, such reasoning as I bring to bear in support of my judgment. But that learned and unlearned alike may see that I shrink not from any man's criticism, it is your Holiness rather than anyone else that I have chosen to dedicate these studies of mine, and since in this remote corner of Earth in which I live you are regarded as the most eminent by virtue alike of the dignity of your Office and of your love of letters and science.

You by your influence and judgment can readily hold the slanderers from biting, though the proverb hath it that there is no remedy against the sycophant's tooth. It may fall out, too, that idle babblers, ignorant of mathematics, may claim a right to pronounce a judgment on my work, by reason of a certain passage of Scripture basely twisted to suit their purpose. Should any such venture to criticize and carp at my project, I make no account of them; I consider their judgment rash, and utterly despise it. I well know that even Lactantius, a writer in other ways distinguished but in no sense a mathematician, discourses in a most childish fashion touching the shape of the Earth, ridiculing even those who have stated the Earth to be a sphere. Thus my supporters need not be amazed if some people of like sort ridicule me too.

Mathematics is for mathematicians, and they, if I be not wholly deceived, will hold that these my labours contribute somewhat even to the Commonwealth of the Church, of which your Holiness is now Prince. For not long since, under Leo X, the question of correcting the ecclesiastical calendar was debated at the Council of the Lateran. It was left undecided for the sole cause that the lengths of the years and months and motions of the Sun and Moon were not held to have been yet determined with sufficient exactness.

From that time on I have given thought to their more accurate observation, by the advice of the eminent Paul, Lord Bishop of Sempronia, sometime in charge of that business of the calendar. What results I have achieved therein, I leave to the judgment of learned mathematicians and of your Holiness in particular. And now, not to seem to promise your Holiness more than I can perform with regard to usefulness of the work, I pass to my appointed task.

First Book, De Revolutionibus

By Nicolas Copernicus 1543

The titles to several of the chapters in Copernicus' book are borrowed from Ptolemy's Almagest

1. That the Universe is Spherical

In the first place we must observe that the Universe is spherical. This is either because that figure is the most perfect, as not being articulated but whole and complete in itself; or because it is most capacious and therefore best suited for that which is to contain and preserve all things; or again because all the perfect parts of it, namely, Sun, Moon and Stars, are so formed; or because all things tend to assume this shape, as is seen in the case of drops of water and liquid bodies in general if freely formed. No one doubts that such a shape has been assigned to Heavenly bodies.

2. That the Earth also is Spherical

The Earth also is spherical, since on all sides it inclines towards the centre. At first sight, the Earth does not appear absolutely spherical, because of the mountains and valleys; yet these make but little variation in its general roundness, as appears with what follows. As we pass from any point northward, the North Pole of the daily rotation gradually rises, while the other pole sinks correspondingly and more stars near the North Pole cease to set, while certain stars in the South do not rise. Thus, Canopus, invisible in Italy, is visible in Egypt, while the last star of Eradinus, seen in Italy, is unknown in our colder zone. On the other hand, as we go southward, these stars appear higher, while those which are high for us appear lower. Further, the change in altitude of the pole is always proportional to the distance traversed on the Earth, which could not be save on a spherical figure. Hence the Earth must be finite and spherical.

Furthermore, dwellers in the East do not see eclipses of the Sun and Moon which occur in the evening here, nor do they in the West see those which occur here in the morning. Yet mid-day eclipses here are seen later in the day by the eastward dwellers, earlier by the westerners. Sailors too have noted that the sea also assumes the same shape, since land invisible from the ship is often sighted at the mast-head. On the other hand, if some shining object at the mast-head be observed from the shore, it seems gradually to sink as the vessel leaves the land. It is also a sure fact that water free to flow always seeks a lower level, just as the Earth does, nor does the sea come higher up the shore than the convexity of the Earth allows. It therefore follows the land, rising above the level of Ocean, is by so much further removed from the centre.

3. How Earth, with the Water on it, Forms one Sphere

The waters spread around the Earth form the sea and fill the lower declivities. The volume of the waters must be less than that of the Earth, else they would swallow up the land (since both, by their weight, press towards the same centre). Thus, for the safety of living things, stretches of the Earth are left uncovered, and also numerous islands widely scattered. Nay, what is a continent, and indeed the whole of the Mainland, but a vast island?

We must pass by certain Peripatetics who claim the volume of the waters to be ten times that of the Earth. They base themselves on a mere guess that in the transmutation of the elements, one part of Earth is resolved into ten parts of water. They say, in fact, that the Earth rises to a certain height above the water because, full of cavities, it is not symmetrical as regards weight and therefore the centre of weight does not accord with the geometrical centre. Ignorance of geometry prevents them from seeing that the waters cannot be even seven times as great if some parts of the Earth is to be left dry, unless the Earth, as being heavier, be quite removed from the centre of gravity to make room for the waters. For spheres are to each other as the cubes of their diameters. If, therefore, there have been seven parts of water to one of Earth, the Earth's diameter could not be greater than the radius of the waters. Even less is it possible that the waters could be ten times as great as the Earth.

There is, in fact, no difference between the Earth's centre of gravity and its geometric centre, since the height of the land above the ocean does not increase continuously – for so it would utterly exclude the waters and there would be no great gulfs of seas between parts of the Mainland. Further, the depth of the ocean would constantly increase from the shore outwards, and so neither island or rock nor anything of the nature of land would be met by sailors, how far soever they ventured. Yet, we know that between the Egyptian Sea and the Arabian Gulf, well-nigh in the middle of the great land-mass, is a passage barely 15 stades wide. On the other hand, in his Cosmography Ptolemy would have it that the habitable land extends to the middle circle with a terra incognita beyond where discovery has added Cathay and a very extensive region as far as 60° of longitude. Thus we know now that the Earth is inhabited to a greater longitude than is left for Ocean.

This will more evidently appear if we add the islands found in our own time under the Princes of Spain and Portugal, particularly America, a land named after the Captain who discovered it and, on account of its unexplored size, reckoned as another Mainland – besides many other islands hitherto unknown. We thus wonder the less at the so-called Antipodes or Antichthones. For geometrical arguments demands that the Mainland of America on account of its postion be diametrically opposite to the Ganges basin in India.

From such considerations then, it is clear that Land and Water have the same centre of gravity, which coincides with the centre of Earth's volume. yet since Earth is heavier, and its chasms filled with water, therefore the quantity of water is moderate as against Earth, though, as to the surface, there may perhaps be more water. Moreover, the Earth, with the waters around it, must have a shape conformable with its shadow. Now at the Moon's eclipse we see a perfect arc of a circle; the Earth therefore is not flat as Empedocles and Anaxagoras would have it, nor drum shape as Leucippus held, nor bowl shape as Heraclitus said, nor yet concave in some other way as Democritus believed; nor again cylindrical as Anaximander maintained, nor yet infinitely thick with roots extending below as Xenophanes represented; but perfectly round, as the Philosophers rightly held.

4. That the Motion of the Heavenly Bodies is Uniform, Circular, and Perpetual, or Composed of Circular Motion

We now note that the motion of the heavenly bodies is circular. Rotation is natural to a sphere and by that very act is its shape expressed. For here we deal with the simplest kind of body, wherein neither beginning nor end may be discerned nor, if it rotate ever in the same place, may the one de distinguished from the other.

Now in the multitude of heavenly bodies various motions occur. Most evident to sense is the diurnal rotation, marking day and night. By this motion the whole Universe, save Earth alone, is thought to glide from East to West. This is the common measure of all motions, since time itself is measured in days. Next we see other revolutions in contest, as it were, with this daily motion and opposing it from West to East. Such opposing motions are those of Sun and Moon and the five planets. Of these the Sun portions out the year, the Moon the month, the common measures of time. In like manner the five planets define each of his own independent period.

But these bodies exhibit various differences in their motion. First their axes are not that of diurnal rotation, but of the Zodiac, which is oblique thereto. Secondly, they do not move uniformly even in their own orbits;

for are not Sun and Moon found now slower, now swifter in their courses? Further, at times the five planets become stationary at one point and another even go backward. While the Sun ever goes forward unswerving on his own course, they wander in divers ways, straying southward, now northward. For this reason they are named *Planets*. Furthermore, sometimes they approach Earth, being there in *Perigee*, while at other times receding they are in *Apogee*.

Nevertheless, despite these irregularities, we must conclude that the motions of these bodies are ever circular or compounded of circles. For the irregularities themselves are subject to a definite law and recur at stated times, and this could not happen if the motions were not circular, for a circle alone can thus restore the place of a body as it was. So with the Sun which, by a compounding of circular motions, brings ever again the changing days and nights and the four seasons of the year. Now therein it must be that divers motions are conjoined, since a simple celestial body cannot move irregularly in a single orbit. For such irregularity must come of unevenness either in the moving force (whether inherent or acquired) or in the form of the revolving body. Both these alike the mind abhors regarding the most perfectly disposed bodies.

It is then generally agreed that the motions of the Sun, Moon and Planets do but seem irregular either by reason of the divers directions of their axes of revolution, or else by reason that Earth is not the centre of the circles in which they revolve, so that to us on Earth the displacements of these bodies when they seem greater than when they are more remote, as is shown in the Optics. If then we consider equal arcs in the paths of the planets we find that they seem to describe differing distances in equal period of time. It is therefore above all needful to observe carefully the relation of the Earth toward the Heavens, lest, searching out the things on high, we should pass by those nearer at hand, and mistakenly ascribe earthly qualities to heavenly bodies.

5. Whether Circular Motion Belongs to the Earth; and Concerning its Position

Since it has been shown that Earth is spherical, we now consider whether her motion is conformable to her shape and her position in the Universe. Without these we cannot construct a proper theory of the heavenly phenomena. Now authorities agree that Earth holds firm her place at the centre of the Universe, and they regard the contrary as unthinkable, nay as absurd. Yet if we examine more closely it will be seen that this question is not so settled, and needs wider consideration.

A seeming change of place may come of movement either of object or of observer, or again of unequal movements of the two (for between equal and parallel motions no movement is perceptible). Now it is Earth from which the rotation of the Heavens is seen. If then some motion of Earth is assumed it will be reproduced in external bodies, which will seem to move in the opposite direction.

Consider first the diurnal rotation. By it the whole Universe, save Earth alone and its contents, appears to move very swiftly. Yet grant that Earth revolves from West to East, and you will find, if you ponder it, that my conclusion is right. It is the vault of Heavens that contains all things, and why should not mention be attributed rather the contained than to the container, to the located than the locater? The later view was certainly that of Heraclides and Ecphantus the Pythogorean and Hicetas of Syracuse (according to Cicero). All of them made the Earth rotate in the midst of the Universe, believing that the Stars set owing to the Earth coming in the way, and rise again when it has passed on.

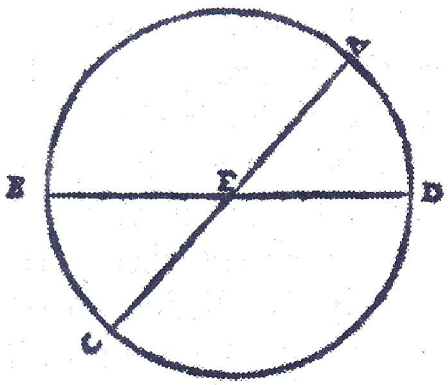
There is another difficulty, namely, the position of the Earth. Nearly all have hitherto held that Earth is at the centre of the Universe. Now, grant that Earth is not at the exact centre but at a distance from it which, while small compared to the starry sphere, is yet considerable compared to the orbits of Sun and the other planets. Then calculate the consequent variations in their seeming motions, assuming these to be really uniform and about the some centre other than the Earth's. One may then perhaps adduce a reasonable cause for these variable motions. And indeed since the Planets are seen at varying distances from the Earth, the centre of the Earth is surely not the centre of their orbits. Nor as it certain whether the Planets move toward and away from Earth, or Earth toward or away from them. It is therefore justifiable to hold that the Earth has another motion in addition to diurnal rotation. That the Earth, besides rotating, wanders with several motions and is indeed a Planet, is a view attributed to Philolaus the Pythagorean, no mean mathematician, and one whom Plato is said to have eagerly sought out in Italy.

Many, however, have thought that Earth could be shown by geometry to be at the centre and like a mere point in the vast Heavens. They have thought too that Earth, as centre, remains unmoved, since if the whole system move the centre must remain at rest, and the parts nearest the centre must move slowly.

6. Of the Vastness of the Heavens Compared to the Size of the Earth

That the size of the Earth is insignificant in comparison with the Heavens, may be inferred thus.

The bounding Circles (interpreting the Greek word horizons) bisect the Celestial Sphere. This could not be if the size of the Earth or its distance from the centre were considerable compared with the Heavens – for a circle to bisect a sphere must pass through its centre and be in fact a "great circle."



Let the circle ABCD represent the celestial horizon, and E the point of the Earth from which we observe. The "horizon" or boundary line between bodies visible and bodies invisible has its centre at this point. Suppose that from point E we observe with Dioptra or Astrolabe or Chorobates the first point of the sign Cancer rising at C and at the same moment the first point of Capricorn setting at A. AEC, since it is observed as a straight line through Dioptra, is a diameter of the Ecliptic, for six Zodiacal Signs from a semicircle and its centre E coincides with that of the horizon. Next, suppose that after some time the first point of Capricorn rises at B; then Cancer will be seen setting at D, and BED will be a stright line, again a diameter of the ecliptic. Hence, it is clear that E, the point of intersection of the two lines, is the centre of the horizon. Therefore the horizon always bisects the ecliptic, which is a great circle on the sphere. But a circle that bisects a great circle must itself be a great circle. Therefore the horizon is a great circle and its centre is that of the ecliptic.

It is true that a line from the surface of Earth cannot coincide with the one from its centre. Yet owing to their immense length compared to the size of the Earth these lines are practically parallel. Moreover, owing to the great distance of their meeting point they are practically one line – for the distance between them is immeasurably small in comparison with their length – as is shown in Optics. It therefore follows that the Heavens are immeasurable in comparison with the Earth. Thus the Earth appears as a mere point compared to the Heavens, as a finite thing to the infinite.

Yet it does not follow that the Earth must be at rest at the centre of the Universe. Should we not be more surprised if the vast Universe revolved in twenty-four hours, then the little Earth should do so? For the idea that the centre is at rest and the parts nearest it moves least does not imply that Earth remains still. It is merely as one should say that the Heavens revolve, but the poles are still, and the parts nearest them move the least (as *Cynosura* moves slower than *Aquila* or *Procyon* because, being near the pole, it describes a smaller circle). These all belong to the same sphere, whose motion becomes zero at the axis. Such motion does not admit that all the parts have the same rate of motion, since the revolution of the whole brings back each point to the original position in the same time, though the distances moved are unequal.

So too, it may be said, Earth, as part of the celestial sphere, shares in the motion thereof, though being at the centre she moves but little. Being herself a body and not a mere point, she will therefore move through the same angle as the Heavens but with a smaller radius in any given period of time. The falsity of this is clear, for if true it would always be mid-day in one place and mid-night in another, and the daily phenomena of rising and setting could not occur, for the motion as a whole and the part are one and inseparable. A quite different theory is required to explain the various motions observed, namely the bodies moving in smaller paths revolve more quickly than those moving in larger paths. Thus Saturn, most distant of the Planets, revolves in 30 years, and Moon, nearest Earth, compasses her circuit in a month. Lastly, then, the Earth must be taken to go round in the course of a day and a night, and so doubt is again cast on the diurnal rotation of the Heavens.

Besides we have not yet fixed the exact position of the Earth, which as shown above, is quite uncertain. For what was proved is only the vast size of the Heavens compared with the Earth, but how far this immensity extends is quite unknown.

7. Why the Ancients Believed that the Earth is at Rest, like a Centre, in the Middle of the Universe.

The ancient Philosophers tried by divers other methods to prove Earth fixed in the midst of the Universe. The most powerful argument was drawn by the doctrine of the heavy and the light. For, they arguer, Earth is the heaviest element, and all things of weight move towards it, tending to its centre. Hence, since the Earth is spherical, and heavy things more vertically to it, they would all rush together to the centre if not stopped at the surface. Now these things which move towards the centre must, on reaching it, remain at rest. Much more then will the whole Earth remain at rest at the centre of the Universe. Receiving all falling bodies, it will remain immovable by its won weight.

Another argument is based on the supposed nature of motion. Aristotle says that the motion of a single and simple body is simple. A simple motion may be either straight, or circular. Again a straight motion may be either up or down. So every simple motion must be either toward the centre, namely downward, or away from the centre, namely upward, or round the centre, namely circular. Now it is a property only of the heavy elements earth and water to move downward, that is to seek the centre. But the light elements air and fire move upward away from the centre. Therefore we must ascribe rectilinear motion to these four elements. The celestial bodies however have circular motion. So far Aristotle.

If then, says Ptolemy, Earth moves at least with a diurnal rotation, the result must be reverse of that described above. For the motion must be of excessive rapidity, since in 24 hours it must impart a complete rotation to the Earth. Now things rotating very rapidly resist cohesion or, if united, are apt to disperse, unless firmly held together. Ptolemy therefore says that Earth should have been dissipated long ago, and (which is the height of absurdity) would have destroyed the Heavens themselves; and certainly all living creatures and other heavy bodies free to move could not have remained on its surface, but must be shaken off. Neither could falling objects reach their appointed place vertically beneath, since in the meantime the Earth would have moved swiftly from under them. Moreover clouds and everything in the air would continually move westward.

8. The Insufficiency of these Arguments and Their Refutation

For these and like reasons, they say that Earth surely rests at the centre of the Universe. Now if one should say that the Earth moves, that is as much as to say that the motion is natural, not forced; and things which happen according to nature produce the opposite effects to those due to force. Things subjected to any force, gradual or sudden, must be disintegrated, and cannot long exit. But natural processes being adapted to their purpose work smoothly.

Idle therefore is the fear of Ptolemy that Earth and all thereon would be disintegrated by natural rotation, a thing far different from an artificial act. Should he not fear even more for the Universe, whose motion must be as much more rapid as the Heavens are greater than the Earth? Have the Heavens become so vast because of the centrifugal force of their violent motion, and would they collapse if they stood still?

If this were so the Heavens must be of finite size. For the more they expand by centrifugal force of their motion, the more rapid will become the motion because of the ever increasing distance to be traversed in 24 hours. And in turn, as the motion waxes, must the immensity of the Heavens wax. Thus velocity and size would increase each the other to infinity – and as the infinite neither be traversed nor moved, the Heavens must stand still!

They say too that outside the Heavens is no body, no space nay not even void, in fact absolutely nothing, and therefore no room for the Heavens to expand. Yet surely it is strange that something can be held by nothing. Perhaps indeed it will be easier to understand this nothingness outside the Heavens if we assume them to be infinite, and bounded internally only by their concavity, so that everything, however great, is contained in them, while the Heavens remains immovable. For the fact that it moves is the principal argument by which men inferred that the Universe is finite.

Let us then leave to Physicists the question whether the Universe be finite or no, holding only to this that Earth is finite and spherical. Why then hesitate to grant Earth that power of motion natural to its shape, rather than suppose a gliding round of the whole Universe, whose limits are unknown and unknowable? And why not grant that the diurnal rotation is only apparent in the Heavens but real in the Earth? It is but as the saying of Aeneas in Virgil – "We sail forth from the harbour, and lands and cities retire." As the ship floats along in the calm, all external things seem to have the motion that is really that of the ship, while those within the ship feel that they and all its contents are at rest.

It may be asked what of the clouds and other objects suspended in the air, or sinking and rising in it? Surely not only the Earth, with the water on it, moves thus, but also a quantity of air and all things associated with the Earth. Perhaps the contiguous air contains an admixture of earthy and watery matter and so follows the same natural law as the Earth, or perhaps the air acquires motion from the perpetually rotating Earth by propinquity and absence of resistance. So the Greeks thought that the higher regions of the air follow the celestial motion, as suggested by those swiftly moving bodies, the "Comets," or "Pogoniae" as they called them, for whose origin they assign this region, for these bodies rise and set like other stars. We observe that because of the great distance from the Earth that part of the air is deprived of terrestrial motion, while the air nearest the Earth, with objects suspended in it, will be stationary, unless disturbed by the wind or other impulse which moves with them this way or that – for a wind in the air is as a current in the sea.

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. So also there are objects which by their fiery force can carry into the higher regions. This terrestrial fire is nourished particularly by earthy matter, and flame is simply burning smoke. Now it is the property of fire to expand that which it attacks, and this so violently that it cannot in any wise be restrained from breaking its prison and fulfilling its end. The motion is one of extension from the centre outward, and consequently any earthy parts set on fire are carried to the upper region.

That the motion of a simple body must be simple is true then primarily of circular motion, and only so long as the simple body rests on its own place and state. In that state no motion save circular is possible, for such motion is wholly self-contained and similar to being at rest. But if objects move or are moved from their natural place rectilinear motion supervenes. Now it is inconsistent with the whole order and form of the Universe that it should be outside its own place. Therefore there is no rectilinear motion save of objects out of their right place, nor is such motion natural to perfect objects, since they would be separated from the whole to which they belong and thus would destroy its unity. Moreover, even apart from circular motion, things moving up and down do not move simply or uniformly; for they cannot avoid the influence of their lightness or weight. Thus all things which fall begin by moving slowly, but their speed is accelerated as they go. On the other hand earthly fire (the only kind we can observe) when carried aloft loses energy, owing to the influence of the earthy matter.

A circular motion must be uniform for it has a never falling cause of motion; but other motions have always a retarding factor, so that bodies having reached their natural place cease to be either heavy or light, and their motion too ceases.

Circular motion then is of things as a whole, parts may possess rectilinear motion as well. Circular motion, therefore may be combined with rectilinear – just as a creature may be at once animal and horse. Aristotle's method of dividing simple motion into three classes, from the centre, to the centre, and round the centre, is thus merely abstract reasoning; just as we form separate conceptions of a line, a point, and a surface, thought they cannot exist without another, and none can exist without substance.

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 the contained and located, namely the Earth?

Lastly, since the planets approach and recede from the Earth, both their motion around the centre, which is held to be the Earth, and also their motion outward and inward are the motion of one body. Therefore we must accept this motion around the centre in a more general sense, and must be satisfied that every motion has a proper centre. From all these considerations it is more probable that the Earth moves that that it remains at rest. This is especially the case with the diurnal rotation, as being particularly a property of the Earth,

9. Whether More than one Motion can be Attributed to the Earth, and of the Centre of the Universe.

Since then there is no reason why the Earth should not possess the power of motion, we must consider whether in fact it has more motions than one, so as to be reckoned as a Planet.

That Earth is not the centre of all revolutions is proved by the apparently irregular motions of the planets, and the variations in their distances from the Earth. These would be unintelligible if they moved in circles concentric with Earth. Since, therefore, there are more centres than one, we may discuss whether the centre of the Universe is or is not the Earth's centre of gravity.

Now it seems to me gravity is but a natural inclination, bestowed on the parts of bodies by the Creator so as to combine the parts in the form of a sphere and thus contribute to their unity and integrity. And we may believe this property present even in the Sun, Moon and Planets, so that thereby they retain their spherical form notwithstanding their various paths. If, therefore, the Earth also has other motions, these must necessarily resemble the many outside motions having a yearly period. For if we transfer the motion of the Sun to the Earth, taking the Sun to be at rest, then morning and evening settings of Stars will be unaffected, while the stationary points, retrogressions, and progressions of the Planets are due not to their own proper motions, but to that of the Earth, which they reflect. Finally we shall place the Sun himself at the centre of the Universe. All this is suggested by the systematic procession of events and harmony of the whole Universe, if only we face the facts, as they say, "with both eyes open."

10. Of the Order of the Heavenly Bodies

No one doubts that the Sphere of the Fixed Stars is the most distant of visible things. As for the planets, the early Philosophers were inclined to believe that they form a series in order of magnitude of their orbits. They adduce the fact that of objects moving with equal speed, those further distant seem to move more slowly (as is proved in Euclid's Optics). They think that the Moon describes her path in the shortest time, because, being nearest to the Earth, she revolves in the smallest circle. Furthest they place Saturn, who in the longest time describes the greatest orbit. Nearer than this is Jupiter, and then Mars.

Opinions differ as to Venus and Mercury which, unlike the others, do not altogether leave the Sun. Some place them beyond the Sun, as Plato in his Timaeus, others nearer the Sun, as Ptolemy and many of the moderns. Alpetragius makes Venus nearer and Mercury further than the Sun. If we agree with Plato in thinking that the planets are themselves dark bodies that do but reflect the light from the Sun, it must follow, that if nearer than the Sun, on account of their proximity to him they would appear as half or partial circles; for they would generally reflect such light as they receive, upwards, that is toward the Sun, as with the waxing and waning Moon. Some think that since no eclipse even proportional to their size is ever caused by these planets they can never be beween us and the Sun.

On the other hand, those who place Venus and Mercury nearer the Sun adduce in support the great distance which they posit between Sun and Moon. For the maximum distance of Moon from Earth, namely 64 1/6 times Earth's radius, they calculate is about 1/18 of the minimum distance from the Sun to Earth, which is 1160 times Earth's radius. So the distance between the Sun and the Moon is 1096 such units. So vast a space must not remain empty. By calculating the widths of the paths of these planets from their greatest and least distances from the Earth they find that the sum of the widths is approximately the same as the whole distance. Thus the perigee of Mercury comes immediately beyond the apogee of the Moon and the apogee of the Mercury is followed by the perigee of Venus, who finally, at her apogee practically reaches the perigee of the Sun. For they estimate that the difference between the greatest and least distances of Mercury is nearly 177 ½ of the aforesaid units, and the remaining space is very nearly filled up by the difference between the maximum and minimum distances of Venus, reckoned at 910 units.

They therefore deny that the planets are opaque like the Moon, but think that they either shine by their own light or that their bodies are completely pervaded by the light of the Sun. They also claim that the

Sun is not obstructed by them for they are very rarely interposed between our eyes and the Sun since they usually differ from him in latitude. They are small, too, compared with the Sun. According to Albategni Aratenis even Venus, which is greater than Mercury, can scarcely cover a hundredth part of the Sun. He estimates the Sun's diameter to be ten times that of Venus; and, therefore, so small a spot to be almost invisible in so powerful a light. Averroes indeed, in his Paraphrases of Ptolemy, records that he saw a kind of black spot when investigating the numerical relations between the Sun and Mercury. This is the evidence that these two planets are nearer than the Sun.

But this reasoning is weak an uncertain. Whereas the least distance of the Moon is 38 times Earth's radius, according to Ptolemy, but according to a truer estimate, more than 52 yet we are not aware of anything in all that space except air, and, if you will, the so called "fiery" element." Besides, the diameter of the orbit of Venus, but which she passes to a distance of 45 degrees more or less on either side of the Sun, must be six times the distance from the Earth's centre to her perigee. What then will they say is contained in the whole of that space, which is so much bigger than that which could contain the Earth, the Air, the Aether, the Moon and Mercury, in addition to the space that the huge epicycle of Venus would occupy if it revolved round the resting Earth?

Unconvincingly too is Ptolemy's proof that the Sun moves between the bodies that do and those that do not recede from him completely. Consideration of the case of the Moon, which does so recede, exposes his falseness. Again, what cause can be alleged, by those who place Venus nearer than the Sun, and Mercury nest, or in some other order? Why should not these planets also follow separate paths, distinct from that of the Sun, as do the other planets? and this might be said even if their relative swiftness and slowness does not belie their alleged order. Either then the Earth cannot be the centre to which the order of the planets and their orbits are related, or certainly their relative order is not observed, nor does it appear why a higher position should be assigned Saturn than Jupiter, or any other planet.

Therefore I think we must seriously consider the ingenious view held by Martianus Capella the author of the Encyclopedia and certain other Latins that Venus and Mercury do not go round the Earth like the other planets but run their courses with the Sun as centre, and so do not depart from him further than the size of their orbits allows. What else can they mean than that the centre of these orbits is near the Sun? So certainly the orbit of Mercury must be within that of Venus, which, it is agreed, is more than twice as great.

We may now extend this hypothesis to bring Saturn, Jupiter and Mars also into relation with this centre, making their orbits great enough to contain those of Venus and Mercury and Earth; and their proportional motions according to the Table demonstrate this. These outer planets are always nearer to the Earth about the time of their evening rising, that is, when they are in opposition to the Sun, and the Earth between them and the Sun. They are more distant from the Earth at the time of their evening setting, when they are in conjunction with the Sun and the Sun between them and the Earth. These indications prove that their centre pertains rather to the Sun than to the Earth, and that this is the same centre as that to which the revolutions of Venus and Mercury are related.

But since all these have one centre it is necessary that the space between the orbit Venus and the orbit of Mars must be viewed as a Sphere concentric with the others, capable of receiving the Earth with her satellite the Moon and whatever is contained within the Sphere of the Moon – for we must not separate the Moon from the Earth, the former being beyond all doubt nearer to the latter, especially as in that space we find suitable and ample room for the Moon.

We therefore assert that the centre of the Earth, carrying the Moon's path, passes in a great orbit among the other planets in an annual revolution round the Sun; that near the Sun is the centre of the Universe; and that whereas the Sun is at rest, any apparent motion of the Sun can be explained by motion of the Earth. Yet so great is the Universe that though the distance of the Earth from the Sun is not insignificant compared with the size of any other planetary path, in accordance with the ratios of their sizes, it is insignificant compared with the distance of the Sphere of Fixed Stars.

I think it is easier to believe this than to confuse the issue by assuming a vast number of Spheres, which those who keep Earth at the centre must do. We thus rather follow Nature, who producing nothing vain or superfluous often prefers to endow one cause with many effects. Though these views are difficult, contrary to expectation, and certainly unusual, yet in the sequel we shall, God willing, make them abundantly clear at least to mathematicians.

Given the above view – and there is none more reasonable – that the periodic times are proportional to the sizes of their orbits, then the order of the Spheres, beginning from the most distant, is as follows. Most distant of all is the Sphere of the Fixed Stars, containing all things, and being therefore immovable. It represents that to which the motion and position of all the other bodies must be referred. Some hold that it too changes in some way, but we shall assign another reason for this apparent change, as will appear in the account of the Earth's motion. Next is the planet Saturn, revolving in 30 years. Next comes Jupiter, moving in a 12 year circuit; then Mars, who goes around in 2 years. the fourth place is held by the annual revolution in which the Earth is contained, together with the orbit of the Moon as on an epicycle. Venus, whose period is 9 months, is in the fifth place, and sixth is Mercury, who goes around in the space of 80 days.

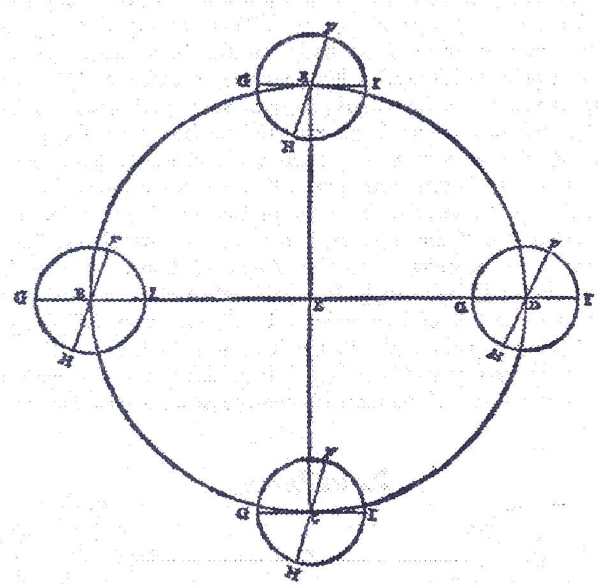
In the middle of all sits Sun enthroned. In this most beautiful temple could we place this luminary in any better position from which he can illuminate the whole at once? He is rightly called the Lamp, the Mind, the Ruler of the Universe; Hermes Trismegistus named him the Visible God, Sophocles' Electra calls him the All-seeing. So the Sun sits as upon a royal throne ruling his children the planets which circle round him. The Earth has the Moon at her service. As Aristotle says, in his *de Animalibus*, the Moon has its closest relationship with the Earth. Meanwhile the Earth conceives by the Sun, and becomes pregnant with an annual rebirth.

So we find underlying this ordination an admirable symmetry in the Universe, and a clear bond of harmony in their motion and magnitude of the orbits such as can be discovered in no other wise. For here we may observe why the progression and retrogression appear greater for Jupiter than for Saturn, and less for Mars, but again greater for Venus than in Mercury; moreover why Saturn, Jupiter and Mars are nearer to the Earth at opposition to the Sun than when they are lost in or emerge from the Sun's rays. Particularly Mars, when he shines all night, appears to rival Jupiter in Magnitude, being only distinguishable by his ruddy colour; otherwise he is scarce equal to a star of second magnitude, and can be recognized only when his movements are carefully followed. All these phenomena proceed from the same cause, namely Earth's motion.

That there are no such phenomena for the Fixed Stars proves their immeasurable distance, compared to which even the size of the Earth's orbit is negligible and the parallactic effect unnoticeable. For every visible object has a certain distance beyond which it can no longer be seen (as is proved in the Optics). The twinkling of the stars, also, shows that there is still a vast distance between the furthest of the planets, Saturn, and the Sphere of the Fixed Stars, and it is chiefly by this indication that they are distinguished from the planets. Further, there must necessarily be a great difference between moving and non-moving bodies. So great is the divine work of the Great and Noble Creator!

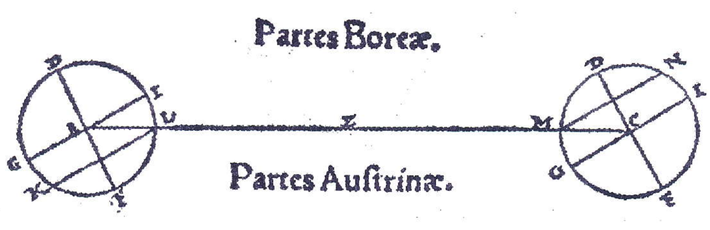
11. Explanation of the Threefold Motion of the Earth

Since then planets agree in witnessing to the possibility that Earth moves, we shall now briefly discuss the motion itself, in so far as the phenomena can be explained by this hypothesis. This motion was must take to be threefold. The first defines the cycle of night and day. It is produced by the rotation of the Earth on its axis from West to East, corresponding to the opposite motion by which the Universe appears to move round the equinoctial circle, that is the equator, which some call the "equidial" circle. The second is the annual revolution of the centre of the Earth, together with all things on the Earth. This describes the ecliptic round the Sun, also from West to East, that is, backwards, between the orbits of Venus and Mars. So it comes about that the Sun himself seems to traverse the ecliptic with a similar motion. For instance, when the centre of the Earth passes over Capricorn, as seen from the Sun, the Sun appears to pass over Cancer as seen from Earth; but seen from Aquarius, he would seem to pass over Leo, and so on. The equator and Earth's axis are variably inclined to this circle, which passes through the middle of the Zodiac, and to its plane, since if they were fixed and followed simply the motion of the Earth's centre there would be no inequality of days and nights. Then there is a third motion, of declination, which is also an annual revolution, but forwards, that is, tending in opposition to the motion of the Earth's centre; and thus, as they are nearly equal and opposite, it comes about that the axis of the Earth, and its greatest parallel, the equator, point in an almost constant direction, as if they are fixed. But meantime the Sun is seen to move along the oblique direction of the Ecliptic with that motion which is really due to the centre of the Earth (just as if the Earth were the centre of the Universe, remembering that we see the line joining the Sun and Earth projected on the Sphere of the fixed Stars).



To express it graphically, draw a circle ABCD to represent the annual path of the Earth's centre in the plane of the Ecliptic. Let E near its centre be the Sun. Divide this circle into four equal parts by the diameters AEC and BED. Let the first point of Cancer be at A, of Libra at B, of Capricorn at C and of Aries at D. Now let the centre of the Earth be first at A and round it draw the terrestrial equator FGHI. This circle FGHI however is not in the same plane as the Ecliptic but its diameter GAI is the line of intersection with the ecliptic. Draw the diameter FAH, at right angles to GAI, and let F be the point of the greatest declination to the South, H to the north. This being so the inhabitants of the Earth will see the Sun near the centre E at its winter solstice in Capricorn, owing to the turning towards the Sun of the point of greatest Northern declination H. Hence in the diurnal rotation the inclination of the equator to AE makes the Sun move along the Tropic of Capricorn, which is distant from the Equator by an angle equal to EAH.

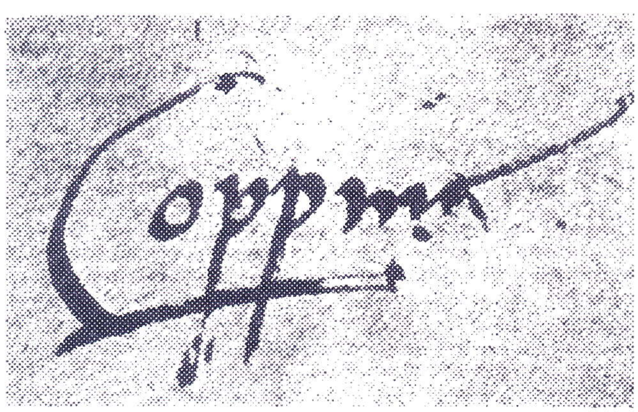
Now let the centre of the Earth travel forwards and let F, the point of greatest declination, move to the same extent backwards until both have completed quadrants of their circles at B. During this time the angle EAI remains always equal to the angle AEB, on account of the equality of the motions. The diameters FAH, FBH, and GAI, GBI are also always parallel each to each, and the Equator remains parallel to itself. These parallel lines appear coincident in the immensity of the Heavens as has often been mentioned. Therefore, from the first point of Libra, E will appear to be in Aires, and the intersection of the planes will be the line GBIE, so that the diurnal rotation will give no declination, and all the motion of the Sun will be lateral (in the plane of the Ecliptic). The Sun is now at the vernal equinox. Further, suppose that the centre of the Earth continues its course. When it has completed a semi-circle at C, the Sun will appear to be entering Cancer. F, the point of greatest southern declination of the Equator, is now turned towards the Sun, and he will appear to be running along the Tropic of Cancer, distant from the Equator by an angle equal to ECF. Again, when F has turned through it third quadrant, the line of intersection GI will once more fall along the line ED, and from this position the Sun will be seen in Libra at the autumnal equinox. As the process continues and HF gradually turns towards the Sun, it will produce a return of the same phenomena as we observed at the starting point.



We can explain it otherwise as follows. Take the diameter AEC in the plane of the page. AEC is the line of intersection by this plane of a circle perpendicular to it. At points A and C, that is at Cancer and

Capricorn respectively, describe in this plane a circle of longitude of the Earth DFGI. Let DF be the axis of the Earth, D the north pole, F the south, and GI a diameter of the equator. Since then F turns towards the Sun at E, and the northern inclination of the equator is the angle IAE, the rotation round the axis will describe a parallel south of the equator with diameter KL and at a distance from the equator equal to LI, the apparent distance from the equator of the Sun in Capricorn. Or better, by this rotation round the axis the line of sight AE describes a conical surface, with vertex at Earth's centre and as base a circle parallel to the equator. At the opposite point C the same phenomena occur, but conversely. Thus the contrary effects of the two motions, that of centre and that of declination, constrain the axis of the Earth to remain in a constant direction, and produce all the phenomena of solar motions.

We were saying that the annual revolution of the centre and of declination were almost equal. If they tallied exactly the equinoctial and solstitial points and the whole obliquity of the Ecliptic with reference to the Sphere of the Fixed Stars would be unchangeable. There is, however, a slight discrepancy, which has only become apparent as it accumulated in the course of the ages. Between Ptolemy's time and ours it has reached nearly 21°, the amount at which the equinoxes have precessed. For this reason some thought that the Sphere of the Fixed Stars also moves, and they have therefore postulated a ninth sphere. This being found insufficient, modern authorities now add a tenth. Yet they have still not attained the result which we hope to attain by the motion of the Earth. We shall assume this motion as a hypothesis and follow its consequence.



The Study of Astronomy

Sir James Jeans

On the evening of January 7, 1610, a fateful day for the human race, Galileo Galilei, Professor of Mathematics in the University of Padua, sat in front of a telescope he had made with his own hands.

More than three centuries previously, Roger Bacon, the inventor of spectacles, had explained how a telescope could be constructed so as "to make the stars appear as near as we please." He had shown how a lens could be so shaped that it would collect all the rays of light falling on it from a distant object, bend them until they met in a focus, and then pass them on through the pupil of the eye and on to the retina.

Such an instrument would increase the power of the human eye just as an ear trumpet increases the power of the human ear by collecting all the waves of sound which falls on a large aperture, bending them, and passing them through the orifice of the ear on to the ear drum.

Yet it was not until 1608 that the first telescope had been constructed by Lippershey, a Flemish spectacle-maker. On hearing of this instrument, Galileo had set to work to discover the principles of its construction and had soon made himself a telescope far better than the original. His instrument had created no small sensation in Italy. Such extraordinary stories had been told of its powers that he had been commanded to take it to Venice and exhibit it to the Doge and Senate. The citizens of Venice had then seen the most aged of their Senators climbing the highest bell-towers to spy through the telescope at ships which were too far out to sea to be seen at all without its help.

The telescope admitted about a hundred times as much light as the unaided eye, and Galileo claimed that it showed objects fifty miles distant as clearly as though they were only five miles away. The absorbing interest of his new instrument had almost driven from Galileo's mind a problem to which he had once given much thought.

Over two thousand years previously, Pythagorus and Philolaus had taught that the earth is not fixed in space but rotates on its axis every twenty-four hours, thus causing the alternation of day and night. Aristarchus of Samos, perhaps the greatest of all Greek mathematicians, had further maintained that the earth not only turned on its axis, but it also described a yearly journey round the sun, this being the cause of the cycle of the seasons.

Then these doctrines had fallen in disfavour. Aristotle had pronounced against them, asserting that the earth formed a fixed centre of the universe. At a later date Ptolemy had explained the tracks of the planets across the sky in terms of a complicated system of cycles and epicycles; this explanation had again supposed the planets moved around an immoveable earth. The Church had given its sanction and active support to these doctrines.

Yet, even in the Church, the doctrine had not gained universal acceptance. Oresme, Bishop of Lisieux, and Cardinal Nicholas of Cusa had both declared against it, the latter writing in 1440:

> "I have long considered that this earth is not fixed, but moves as do the other stars. To my mind the earth turns upon its axis once every day and night."

At a later date such views incurred the active hostility of the Church, and in 1600 Giordano Bruno was burned at the stake, one of the counts against him being his insistence on the doctrine of the plurality of worlds. He had written:

> "It has seemed to me unworthy of the divine goodness and power to create a finite world, when able to produce beside it another and others infinite; so that I have declared that there are endless particular worlds similar to this of the earth; with Pythagoras I regard it as a star, and similar to it are the moon, the planets and other stars, which are infinite in number, and all these bodies are worlds."

The most weighty attack on orthodox doctrine had, however, been delivered by the Polish ecclesiastic and astronomer, Nicolaus Copernicus (1473 – 1543). In his great work *De Revolutionibus Orbium Coelestium* Copernicus had shown most of Ptolemy's elaborate structure of cycles and epicycles to be unnecessary, because the tracks of the planets across the sky could be explained in a much simpler manner by supposing that the earth and the planets all moved round a fixed central sun.

The sixty-six years which had elapsed since this book was published had seen these theories hotly debated, but they were still neither proved nor disproved. And although Galileo found himself powerfully attracted to them, he had hitherto though it the more prudent course to keep his opinions to himself. Galileo had already found that his new telescope provided a means of testing astronomical theories. As soon as he had turned it on to the Milky Way, a whole crowd of legends and fables as to their nature and structure of this object had vanished into thin air; it proved to be nothing more that a swarm of faint stars scattered like golden dust on the black background of the sky.

Another glance through the telescope had disclosed the true nature of the moon. On it were mountains which cast shadows, so that it proved to be a world like our own, as Giordano Bruno had maintained. What if the telescope should now in some way prove able to decide between the orthodox doctrine that the earth formed the hub of the universe, and the revolutionary new doctrine that the earth was only one of a number of bodies, all circling round the sun like moths round a candle-flame?

And now Galileo catches Jupiter in the field of his telescope and sees four small bodies circling around the great mass of the planet – like moths round a candle-flame. What he sees is an exact replica of the solar system, as imagined by Copernicus, and it provides direct visual proof that such systems are at least not alien to the architectural plan of the universe.

On January 30th he writes to Belisario Vinta that these small bodies move round the far greater mass of Jupiter "just as Venus and Mercury, and perhaps the other planets, move round the sun."

Any lingering doubts that Galileo may have felt as to the significance of his discovery were removed nine months later when he observed the phases of Venus; the shining surface of the planet was seen to pass through the same cycle of shapes as the moon – from crescent through semicircle to a full circle, and then, reversing the paths, back through semicircle to crescent. This of course showed at once that the planet was not self-luminous, since had it been so, its surface would always have appeared as a full circle of light. But even when it was known that the planet was not self-luminous, two distinct alternatives remained.

If Venus moved round the earth in a Ptolemaic epicycle, then, as Ptolemy had himself pointed out, should never show more than half her surface illuminated. If, on the other hand, she moved round the sun in a large circle, as the new Copernican view required, then the shining surface of Venus ought to exhibit the complete sequence of phases shown by the moon, the surface of the planet appearing completely dark at the moment when it passed between the earth and the sun. And the same ought to be true also of Mercury. It had indeed urged as an objection to the Copernican theory that neither Venus nor Mercury exhibited this full cycle of phases.

Galileo's telescope now showed that, precisely as Copernicus had foretold, Venus passed through the full cycle of phases, so that, in Galileo's own words:

"we are now supplied with a determination most conclusive, and appealing to the evidence of our senses, of two very important problems, which up until this day have been discussed by the greatest of intellects with different conclusions. One is that the planets are not self-luminous. The other is that we are absolutely compelled to say that Venus, and Mercury also, revolve around the sun, as do also all the rest of the planets, a truth believed indeed by the Pythagorean school, by Copernicus and by Kepler, but never proved by the evidence of our sense, as is now proved in the case of Venus and Mercury."

These discoveries of Galileo made it clear that Aristotle, Ptolemy and the majority of those who had thought about these things in the past 2000 years had been utterly and hopelessly wrong.

In estimating his position in the universe, man had up to now been guided mainly by his own desires, and his self-esteem; long fed on boundless hope, he had spurned the simpler fare offered by patient scientific thought. Inexorable facts now dethroned him from his self-arrogated station at the centre of the universe; henceforth he must reconcile himself to the humble position of the inhabitant of a speck of dust, and adjust his views as to the significance and importance of human life accordingly.

The adjustment was not made at once. Human vanity, reinforced by the authority of the Church, contrived to make a rough road for those who dared draw attention to the earth's insignificant position in the universe. Galileo was forced to abjure his beliefs.

Well on into the eighteenth century the ancient University of Paris was teaching that the motion of the earth round the sun was a convenient *but false* hypothesis, while the newer American Universities of Harvard and Yale taught the Ptolemaic and Copernican systems of astronomy side by side as if they were equally tenable.

Yet men could not keep their heads buried in the sand for ever, and when at last its full implications were accepted, the revolution of thought initiated by Galileo's observation of January 7, 1610, proved to be the most catastrophic in the history of the race.

The cataclysm was not confined to the realms of abstract thought; henceforth human existence itself was to appear in a new light, and human aims and aspirations would be judged from a different standpoint.

This oft-told story has been told once again, in the hope it might explain some of the interest taken in astronomy today. The more mundane sciences prove their worth by adding to the amenities and pleasures of life, or by alleviating pain or distress, but it may well be asked what reward astronomy has to offer. Why does the astronomer devote arduous nights, and even more arduous days, to studying the structure, motions and changes of bodies so remote that they can have no conceivable influence on human life?

In part at least the answer would seem to be that many have begun to suspect that the astronomy of today, like that of Galileo, may have something to say on the enthralling question of human life in the universe in which it is placed, and on the beginnings, meaning and destiny of the human race.

Bede records how, some twelve centuries ago, human life was compared in poetic simile to the flight of a bird through a warm hall in which men sit feasting, while the winter storms rage without:

> "The bird is safe from the tempest for a brief moment, but immediately passes from winter to winter again. So man's life appears for a little while, but of what is it to follow, or of what went before, we know nothing. If, therefore, a new doctrine tells us something certain, it seems to deserve to be followed."

Man wishes to probe farther into the past and the future than his brief span of life permits. He wishes to see the universe as it existed before man was, as it will be after the last man has passed again into the darkness from which he came.

The wish does not originate solely in mere intellectual curiosity, in the desire to see the next range of mountains, the desire to attain a summit commanding a wide view, even if it be only of a promised land which he may never hope himself to enter; it has deeper roots and a more personal interest. Before he can understand himself, man must first understand the universe from the dust of which his body has been formed, and from the events of which all his sense perceptions are drawn. He wishes to explore the universe, both in space and time, because he himself forms part of it, and it forms part of him.

Except from: The Universe Around Us, Cambridge University Press, 1938, Sir James Jeans

Copernicus Discovered Nothing

Max Planck

Suppose we say, with Ptolemy, that the earth is the fixed centre of the universe and that the sun and all the stars move around it; or supposing we say, with Copernicus, that the earth is a small particle of matter which is relatively insignificant in relation to the whole universe, turning on its axis once every 24 hours and revolving around the sun once every twelve months on the positivist principle the one theory is as good as the other, when considered from the scientific viewpoint.

They are merely two different ways of making a mental construction out of sensory reactions to some outer phenomena; but they have no more right to be looked upon as scientifically significant than the mental construction which the mystic or poet may make out of his sensory impressions when face to face with nature.

It is true that the Copernican theory of astronomy is more widely accepted; but that is because it is a simpler way of formulating a synthesis of sensory observations and it does not give rise to so many difficulties about astronomical laws as would arise from the acceptance of the Ptolemaic theory. Therefore Copernicus is not to be judged as a pioneer discoverer in the realms of science, no more than a poet is to be judged as a pioneer discoverer when he gives fanciful and attractive expression to sentiments that are known to every human breast. Copernicus *discovered* nothing. He only formulated, in the shape of a fanciful mental construction, a mass of facts that were already known. He did not add anything to the store of scientific knowledge already in existence.

A tremendous mental revolution was caused by this theory and bitter battles were waged around it. For the logical consequence of it was to give an entirely different account of man's place in the universe from that generally held at the time by religion and philosophy of Europe.

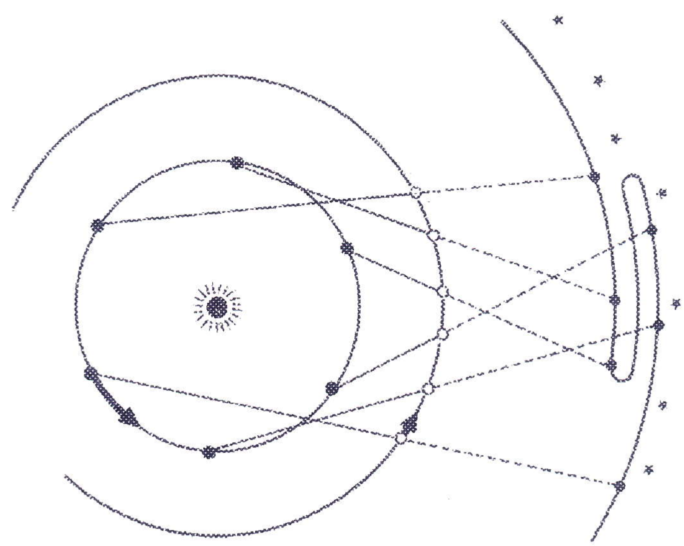
But for the positivist scientist all the fuss and trouble made over the Copernican theory were quite as senseless, from the scientific point of view, as if one were to quarrel with the rapture of a contemplative poet who gazes at the Milky Way and ponders over the fact that each star in the Milky Way is a sun somewhat like ours and that each spiral nebula is again a Milky Way from which the light has taken many millions of years to reach our earth, while the earth itself, with its human race on it, sinks away into an insignificant speck which is hardly discernible in the boundless space.

From: Where is Science Going? George Allen & UnWin, London, 1933,

Apparent Motion and the Orbits of the Planets

The planets all orbit the sun in the same direction, but orbit at different speeds. As a result planets seen from earth will display apparent motion. Apparent motion is when a planet viewed against the background of "fixed stars" (stars very far in the distance), accelerates, decelerates and changes direction.

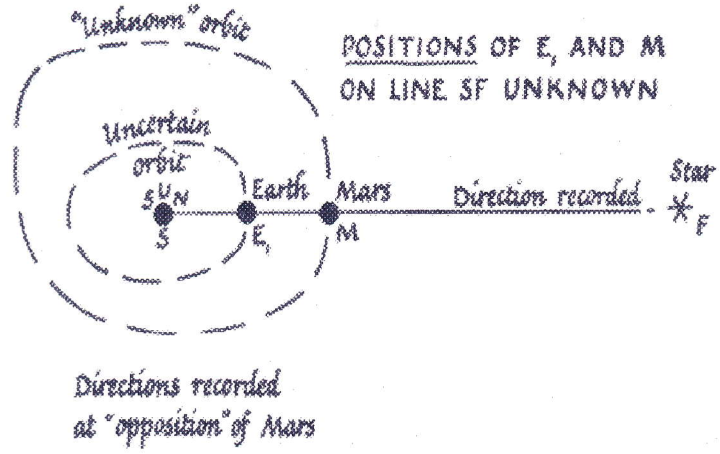
For instance Mars as seen from Earth displays apparent motion:



Against the distance stars planets like Mars trace out a strange motion, sometimes moving forward and sometime moving backwards (retrograde motion).

Mapping a planet's orbit is very difficult and involves complicated mathematics and trigonometry. To map a planet's orbit, for instance the Earth's orbit, around the sun we need many sets of measurements, each giving the Earth's bearing from two fixed points.

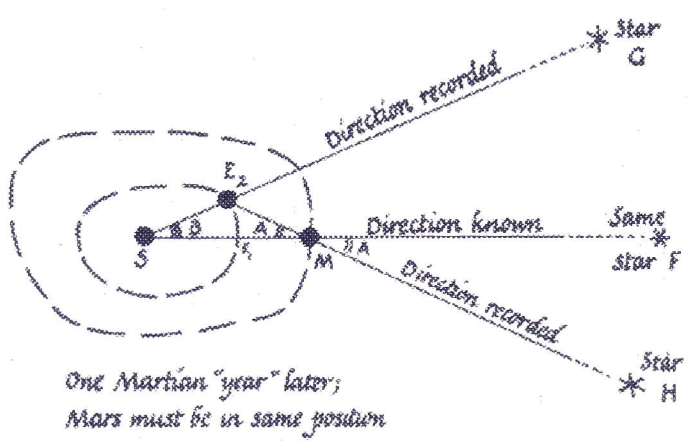
Johannes Kepler (1571-1630) took the fixed Sun for one of these points, and for the other he took Mars at a series of times when it was in the same position in its orbit. He started by marking the "position" of Mars in the star pattern at one opposition (opposite the Sun, overhead at midnight).



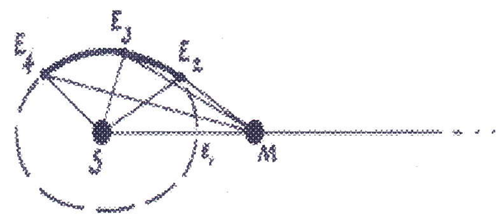
That gave him the direction of a base line Sun – (Earth) – Mars, SE_1M. Then he turned the pages of Tycho Brahe's records to a time exactly one Martian year later (the time of Mar's motion around its orbit was known accurately, from records over centuries). Then he knew that Mars was in the same position, M so that SM had the same direction. By now Earth had moved on to E_2 in its orbit.

Tycho's record of the position of Mars in the star pattern gave him the new apparent direction of Mars, E_2M; and the Sun's position gave him the direction E_2S. Then he could calculate the angles of the triangle SE_2M from the record thus; since he knew the direction E_1M and E_2M (marked on the celestial sphere of stars) he could calculate the angle A between them.

Since he knew the direction E_1S and E_2S he could calculate the angle B, between them. Then on a scale diagram he could choose two points to represent S and M and locate the Earth's position, E_2, as follows: at the ends of the fixed baseline SM, draw lines making angles A and B and mark their intersection E_2.



One Mars year later, you find the directions E_3M and E_3S from the records and mark E_3 on this diagram. Thus Kepler could start with the points S and M and locate E_2, E_3, E_4,… and enough points to show the orbit's shape.

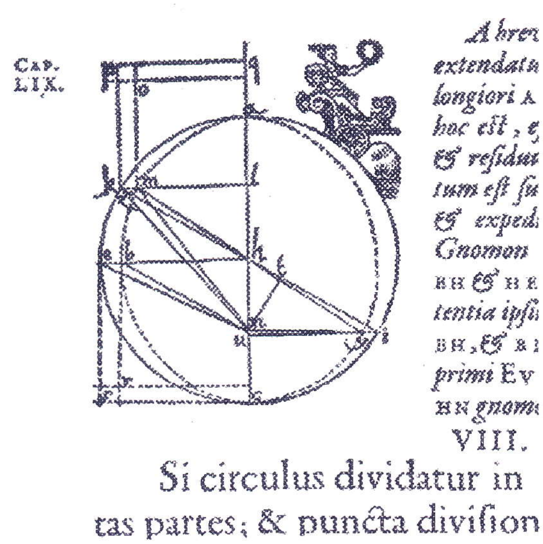


Construction of Earth's orbit

Then, knowing the Earth's true orbit, he could invert the investigation and plot the shape of Mars' orbit. He found he could treat the Earth's orbit either as an eccentric circle or as slightly oval; but Mars' orbit was far from circular.

By plotting the orbits or the Earth and Mars Kepler was able to show that these two planets orbit the Sun in ellipses with the Sun in one focus. This proof was the basis of his First Law.

By plotting the location and dates of the Earth and Mars in their orbits he discovered his Second law (Equal Areas in Equal Times).



Kepler was so proud of his achievements that he added a sketch of a victorious astronomer to his diagram of elliptic orbits in his book on the orbit of planets.

Today we know the distances from the sun of the different planets and the time it takes the planets to orbit the sun (in earth years) very accurately:

Planet	Distance from Sun (R) (10^6 km)	Period (T) Earth Years
Mercury	57.9	0.241
Venus	108.2	0.615
Earth	149.6	1.00
Mars	227.9	1.88
Jupiter	778.3	11.86
Saturn	1427	29.5
Uranus	2870	84.0
Neptune	4497	165
Pluto	5900	248

From: "Physics for the Inquiring Mind" by E. Rogers, Princeton University Press, 1960.

Glossary

Almagest – astronomy book by Claudius Ptolemy of Alexandria published around 150 A.D.

Assumption of Greater Probability – reasoning used by Copernicus … "given the evidence it is more likely that …". This reasoning is a form of Bayesian reasoning.

Concept of the Sphere – Aristotle's reasoning was the Heavens were perfect, as are circles and spheres are perfect, therefore they must govern the motion of the Heavenly Spheres

Deferens – the main circle of a Ptolemaic Orbit.

Epicycle – the smaller, secondary circle of the orbit.

Geocentric – Earth centered model of the Universe (geo : Earth).

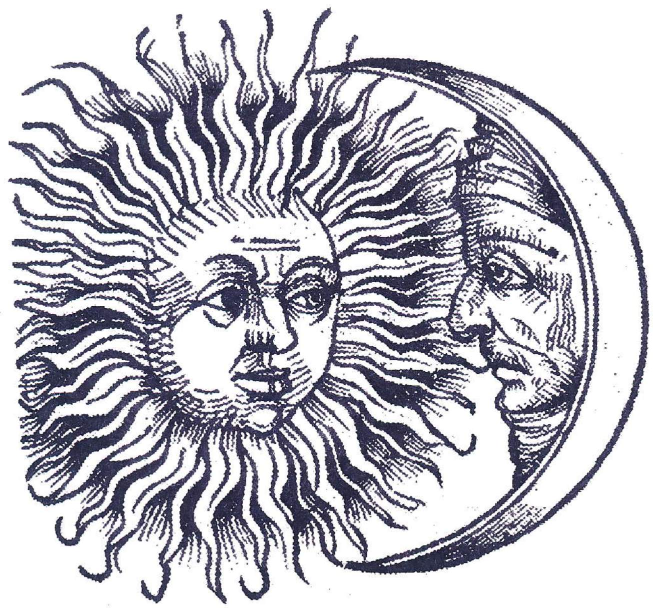
Heliocentric – Sun centered model of the Universe (Helios: Sun).

Plato's Principle – only circular and uniform motion are appropriate for celestial bodies.

Ptolemaic System – a model of the Universe with the Earth at its Centre.

Retrograde motion – reverse motion of a planet through the heavens

Timaeus – Plato's most important dialogue about physics and cosmology.



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