Chapter 2

HEAVENLY MOTIONS

Modern physics - as the systematic study of nature based on observation, experimentation, reason and mathematical analysis - had its beginnings in the 1600's with the work of Galileo Galilei and Isaac Newton. Their accomplishments, however, owed much to earlier discoveries. In fact, mankind's efforts to understand nature can be traced back thousands of years.

EARLY ASTRONOMY

Astronomy was the first science to emerge; for thousands of years, it was the "Queen of sciences." Since ancient times, mankind has been awed and intrigued by the grand canvass of the sky with its myriad stars, planets and comets, and by the motions of these heavenly bodies.

The ancients believed that the heavens were inhabited by gods, and that heavenly phenomena could influence earthly events. Thus, religion, astrology and astronomy were intimately linked: a combination of the three can be found in the early history of places as diverse as ancient Mesopotamia (present-day Iraq), Egypt, China, India and Central America.

The heavens, which presented an irresistible puzzle to the curiosity of early humankind, eventually became the source of very useful knowledge. Early on, it was observed that the stars in the night sky did not seem to move with respect to one another, but appeared fixed in a pattern that rotated daily about the Earth. Later, nomads discovered that they could be guided in their travels by their familiarity with certain clusters of stars, or constellations. Later still, when nomads settled down and became farmers, knowledge of the constellations helped them keep track of the seasons.

Very early, it was noticed that, beside the Sun and the Moon, a few heavenly bodies moved against the background of the fixed stars in the course of a year. Only seven such wandering bodies were known to the ancients: the Sun, the Moon, Mercury, Venus, Mars, Jupiter and Saturn. Later, they were all called "planets", from the Greek word for "wanderers."

In the familiar seven-day week, which was first introduced by the ancient Babylonians in Mesopotamia, the names of the days can be traced in various languages to the seven planet-gods. In English, Saturday, Sunday and Monday are associated with Saturn, the Sun and the Moon, respectively. In Romance languages, such as French or Italian, the names of the days from Monday through Friday are associated with the Moon, Mars, Mercury, Jupiter and Venus, respectively.

Foremost among the "wanderers" was the Sun. Its rising and setting defined the cycle of day and night. Its yearly motion through various constellations defined the time to seed and the time to harvest. Next in importance was the Moon, whose shape could be seen to change through four regularly repeated phases.

By observing the motions of the Sun and the Moon, the ancients were able to develop various calendars based on solar or lunar cycles. These calendars made it possible to set the times for religious ceremonies, farming and other events. Together with the Sun and the Moon, the other five planets played an important role in astrology.

Western astronomy had its origins in ancient Egypt and Mesopotamia. In Egypt, astronomy was concerned primarily with predicting the time of the annual flooding of the river Nile, which played a crucial role in the life of that country by fertilizing its land. Egyptian astronomy's main lasting contribution was a calendar of 365 days, divided into 12 months of 30 days each, with five feast days at the end of the year.

In Mesopotamia, powerful and capricious gods were believed to inhabit the skies. Since heavenly phenomena were deemed to foretell earthly disasters[2], they were carefully observed and recorded. These practices led to a highly developed mathematics and the most sophisticated astronomy in the ancient world until the Greeks. It was the Greeks who first attempted to explain natural phenomena on the basis of reason, rather than the arbitrary will of gods. They were also the first to apply geometry to astronomy.

GREEK CIVILIZATION

The classical period of Greek civilization started in the 5th century BC. With their prodigious creativity in art, architecture, literature, philosophy and science, the Greeks laid the foundations of Western culture.

The area in which this civilization flourished extended beyond mainland Greece and the islands of the Aegean Sea. It included also the many colonies the Greeks had established all along the western coast of present-day Turkey, and in parts of southern Italy and Sicily. These lands were collectively referred to as "Hellas", and the Greeks as "Hellenes".

From Macedonia, which bordered on northern Greece, in the 4th century BC, the Greek-educated Alexander the Great (356-323 BC) conquered a vast empire, which included Greece and Egypt, and extended from Turkey and the Middle East to western India. The three centuries after Alexander's death - known as the Hellenistic period - were among the most creative in all of Greek history. In Egypt, the city of Alexandria became a

[2] The word *disaster* derives from *dis-* (opposite) and *aster* (star).

leading center of Greek scholarship: its famous library held more than 500,000 scrolls, before it was destroyed by fire.

The systematic application of reason to the explanation of natural phenomena represents the most enduring legacy of Greek culture to modern science. It led to major accomplishments in philosophy, geometry and astronomy, and reached its peak with the philosopher Aristotle (384-322 BC).

Early Greek Philosophy

In its very beginnings, Greek philosophy was concerned with nature. This early "natural philosophy" was the forerunner of modern physics (which was still called natural philosophy well into 1800's). Starting in the 6th century BC, the earliest Greek philosophers theorized that, beneath the great variety of nature, all things were made of only a few fundamental substances, or "elements". By the 4th century BC, most philosophers supported a theory of only four elements: earth (soil), water, air and fire.

A totally different conception of reality was held by the "Atomists" (5th century BC). They believed that the physical world consisted of countless, unchangeable, indivisible particles, which differed in size and shape and moved in a "void", or vacuum (empty space). These fundamental particles were called "atoms" from the Greek word for indivisible. By combining in various ways, they formed all the matter in the universe. All natural phenomena resulted from the variety of motions and configurations of atoms in empty space.

Greek Geometry

Geometry developed in Egypt and Mesopotamia as an empirical art based on practical experience. Later, Greek geometers gradually transformed it into a logical system.

The most famous book on Greek geometry is "The Elements" by Euclid, who taught in Alexandria about 300 BC. It has been said that, next to the Bible, Euclid's Elements may have been the most translated and studied book in the Western world. Euclid presented his subject using the so-called axiomatic-deductive method, which has since served as the model for the development of many other mathematical subjects.

In the Elements, after some basic definitions, Euclid introduces ten statements offered as "axioms" or "postulates", i.e., to be accepted as true without proof, because they are deemed self-evident. Step by step, he proceeds then to prove a number of "theorems", each built on postulates and previous theorems. Thus, starting from statements that are accepted as immediately evident, the reader is led, by a long series of logical steps, to accept the truth of much more complex statements, which would not have been accepted at the start.

In the Elements, Euclid gave a compilation of all the geometry that had been developed during the preceding two centuries. Most of the discoveries presented were by earlier geometers. Euclid's major contribution was mainly the excellent organization of the subject matter.

In the third century BC, Greek geometry entered its golden age, which was dominated by the discoveries of two men: Archimedes and Apollonius.

Archimedes of Syracuse (Sicily, 287?-212 BC) discovered how to compute the area and volume of the sphere and many other complex shapes. He also showed how the number "pi", the ratio of the circumference of a circle to its diameter, could be computed to any desired accuracy. His approximation of 3.14 for "pi" was used well into the Middle Ages. Archimedes' writings deeply influenced later mathematicians and scientists, most notably Galileo and Newton.

Apollonius of Perga (southwestern coast of Turkey, 262-190 BC) studied and taught in Alexandria. He came to be known by his contemporaries as the Great Geometer. His main surviving work, "Conics", is among the greatest scientific works from the ancient world. Conics are a family of geometric curves, so called because they can all be generated by cutting across a cone in various ways. Among them are the familiar circle, the ellipse and the parabola, about which more will be said later. As we will see, conics have played an important role in physics. They provide one of many instances of knowledge initially pursued for its own sake, and later found very useful for practical as well as theoretical purposes.

Greek Astronomy

Greek astronomers were the first to use geometry to develop their field into a science. Like their predecessors, they believed in a geocentric (Earth-centered) universe: the Sun, the Moon and the five known planets were all believed to revolve around the Earth, which stood still at the center of a rotating sphere to which all the stars were attached in a fixed pattern.

Some heliocentric (Sun-centered) proposals were made, but were rejected because the notion of a moving Earth seemed totally contrary to common-sense intuition. In the 4th century BC, Heracleides was the first to maintain that the Earth rotates about its axis, and that Mercury and Venus (the two planets between the Sun and the Earth) revolve around the Sun. Aristarchus is believed to have been the first to propose, in the 3rd century BC, a completely heliocentric theory similar to the one that Copernicus was to propose in the 16th century.

To describe the motions of the seven "planets", Greek astronomers used only circular motions or combinations of circular motions. In this, they were influenced by the teachings of the great philosopher Plato (428-348

BC). He believed that heavenly bodies were divine and, therefore, perfect. As such, they had to be endowed with perfect motion which, by Plato's definition, was circular uniform motion (i.e., motion along a circle at constant speed).

Greek astronomers viewed their geometric schemes simply as tools for predicting planetary positions. They did not know how the "planets" actually moved, or why.

An earlier scheme was based on a complex system of interconnected "homocentric" (concentric) spheres, all nested inside one another. The Earth stood still at the common center. The "planets" rode on the equators of seven of the spheres. It is this scheme that was incorporated by Aristotle in his "System of the World", a grand account of the whole Universe.

Aristotle's "System of the World"

No philosopher has influenced Western thought more than Aristotle. His intellectual interests covered most of the sciences and many of the arts. His greatest achievement was his system of formal logic, which for centuries represented the totality of logic. Aristotle's philosophical and scientific system became the foundation of both Christian and Islamic thinking in the Middle Ages. Until the 17th century, Western culture was strongly Aristotelian, and even today many Aristotelian concepts remain embedded in Western thinking.

Aristotle was born in 384 BC in Northern Greece; his father was court physician to the king of Macedonia. He studied in Athens under Plato for 20 years. After Plato's death, he traveled for 12 years. During this period, he spent three years at the court of Macedonia as the tutor of the king's son, who would become known as Alexander the Great. After returning to Athens, he opened a center for studies in all fields.

Aristotle viewed the universe or "cosmos" as an ordered structure. Indeed, the word cosmos comes from the Greek word for order. This order was believed to be that of an organism: all parts of the universe had purposes in the overall scheme of things, and objects moved naturally toward the ends they were intended to follow.

Aristotle adopted the system of homocentric spheres as the actual physical machinery of the heavens. His cosmos was like an onion consisting of "crystalline" (transparent) spheres all nested around the Earth. The ultimate cause of all motion was a Prime Mover (God), who stood outside the cosmos.

Aristotle's universe is divided into a terrestrial, or earthly, realm and a celestial, or heavenly, realm. All terrestrial objects are made of one or more of four elements: earth, water, air and fire. Each element has its assigned natural place: earth at the center is surrounded by concentric spheres of water, air and fire. The fixed stars, the Sun, the Moon and the planets, which move in the celestial region, are all composed of a fifth essence, or quintessence, called "ether".

Different laws govern the celestial and terrestrial realms. In the celestial realm, uniform circular motion is the natural form of motion. In the terrestrial realm, instead, natural motion is either up or down. Light bodies (like smoke), by their nature, tend to move up. On the other hand, heavy bodies, by their nature, seek the center of the universe, and tend to move down. When a body (object) falls freely through air, the heavier the body, the faster it falls.

An external cause is needed to put a body in motion. As long as the body moves, a force must be in constant, direct contact with it, causing it to move. This theory, however, does not satisfactorily explain why a stone thrown from a sling continues to move up before it starts falling down.

Aristotle's "system of the world" was a magnificent attempt to unify all the branches of human knowledge within a single conceptual framework. After the fall of the Roman Empire, Aristotle's works (like those of many ancient authors) were lost in the West; they were preserved, however, by Arabic and Jewish scholars. Muslim scholars kept alive the Aristotelian heritage, and in the 12th and 13th centuries passed it back to Europe, where it became the philosophical basis of Christian theology.

Epicyclic Motions

After Aristotle, Greek astronomers abandoned the scheme of homocentric spheres and adopted a new geometric scheme, which reflected two phenomena observed in the motions of planets. One was the fact that planets could be observed to change in brightness, which suggested that they were not always at the same distance from the Earth.

The other phenomenon was the puzzling to-and-fro motion of a planet, called "retrograde" motion. When viewed against the background of the fixed stars at the same hour on many consecutive nights, the motion of a planet appears to be generally eastward, with occasional stops followed by temporary reversals to a westward direction, until the planet appears to stop again and then resume its eastward motion.

Both retrograde motion and changes in brightness could be accounted for by the scheme of "epicyclic" motions, as illustrated in **Figure 2.1**. (For this figure, as well as most of the others, the text discussing the figure appears right under it, in Italics. In general, skipping a figure and its description will result in loss of continuity.)

A major contributor to the theory of epicycles was Hipparchus of Nicaea (northwestern Turkey, 190-120 BC), who was, most likely, the greatest astronomer of antiquity. Among his achievements was a catalog of stars, the first ever to be compiled. Started in 134 BC and completed 5 years later, this catalog listed about 850 stars classified by brightness.

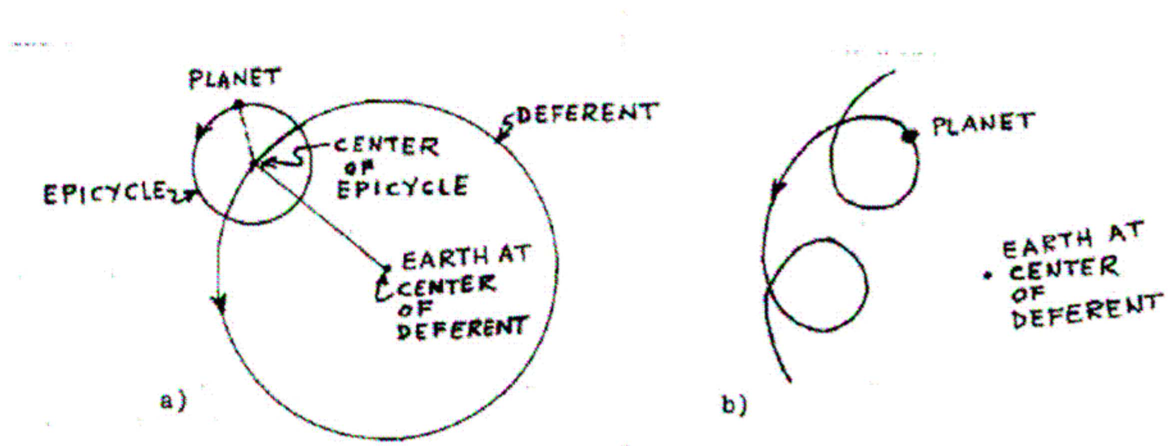

Figure 2.1 - Epicyclic motion

As shown on the left, a planet (represented as a point) is imagined to move along a circle, the "epicycle", whose center in turn moves along a larger circle, the "deferent". The latter's center is at the center of the Earth. The resulting motion of the planet is shown on the right. There is a back-and-forth retrograde motion combined with a motion toward, or away from, the Earth.

The Ptolemaic System

Although most works of Greek astronomers were lost, their contents are known primarily through a major book on astronomy by Claudius Ptolemy of Alexandria (100-170 AD). This book, originally called "The Mathematical Composition", eventually became better known as the "Almagest (The Greatest)", from the title of its Arabic translation. It provided a compendium of Greek astronomy, comparable in thoroughness to Euclid's compendium of geometry. It shaped astronomy for 1400 years until Copernicus.

Expanding on Hipparchus' work, Ptolemy formulated what is popularly known as the Ptolemaic system. In the first part of the Almagest, Ptolemy describes the system, and presents various arguments to prove that the Earth must be standing still at the center of the universe. Since, according to Aristotelian physics, all bodies tend to fall toward the center of the universe, the Earth must be fixed there, otherwise objects would not be observed to fall toward the Earth. Also, if the Earth rotated once every 24 hours, as claimed by some, a body thrown vertically up would not be observed to fall back to the same place. On the strength of such arguments, geocentrism was eventually elevated to the status of almost religious dogma.

Like his predecessors, Ptolemy placed the seven heavenly bodies in the following order, starting from the Earth: Moon, Mercury, Venus, Sun, Mars, Jupiter and Saturn. The detailed geometric models he adopted for each of the seven "planets" fitted the available data with sufficient accuracy to give good validity to the system.

FROM PTOLEMY TO COPERNICUS

Without major breakthroughs, Western science continued to operate within the framework of Aristotle's physics and Ptolemy's astronomy for some 1400 years until the scientific revolution that started in the 16th century with Copernicus.

The Roman Empire

After the Romans conquered Greece, they were greatly impressed by the intellectual achievements of the Greeks, but doubtful about their practical value. The Greeks' pursuit of knowledge for its own sake was alien to the practical Roman mind (whose greatest legacy, instead, was jurisprudence, the philosophy of law). As a result, scientific innovation came to a halt under the Romans.

By Ptolemy's time in the 2nd century AD, the Roman Empire had reached its greatest extent to include all the lands bordering on the Mediterranean. Eventually, the empire became so unwieldy that, in 395 AD, it was split in two. The Western Empire lasted less than another century: in 476 AD, Rome fell as Western Europe was overrun by barbaric tribes. The Eastern Empire became known as the Byzantine Empire from its capital, the ancient city of Byzantium, later renamed Constantinople and now called Istanbul. The Eastern Empire lasted another thousand years until it fell in 1453 under the attack of the Ottoman Turks, who originated from central Asia.

The Middle Ages

After the fall of Rome, ancient learning barely survived in the West. Its basics continued to be taught in monasteries; its surviving works were faithfully copied by monks. In the Byzantine Empire, the ancient traditions continued, but little original work was done in science.

The torch of scholarship passed to the Arabs, who made major contributions to mathematics (including the invention of algebra) and built great astronomical observatories. In the 7th century, inspired by Islam, the new religion founded by Mohammed, the Arabs launched the conquest of a great empire, which eventually extended toward India and, to the West, included Northern Africa and Spain.

In Spain, when the Moslem conquerors were gradually pushed south by the Christian armies, among the treasures they left behind were Arabic translations of Greek works of science and philosophy. In 1085, the city of Toledo, with one of the finest libraries in the Islamic world, fell to the Christians. Soon, Christian monks started translating ancient works from Arabic into Latin. By the end of the 12th century, much of the ancient heritage was again available in the West, bringing about a revival of Greek science.

After the fall of the Western Empire, the Church became the intellectual, as well as the spiritual, center of Western Europe. During most of the Middle Ages, classical studies and virtually all intellectual endeavors were pursued by members of various religious orders.

Medieval thinking culminated in the philosophical system of "Scholasticism", whose leading exponent was Thomas Aquinas (Italian Dominican monk and theologian, 1224-1274). Borrowing freely from Aristotle's philosophy, the Scholastics made a systematic attempt to establish theology as a science, in which reason played an important role, not as the opponent of faith, but as its supplement.

The Renaissance

The Middle Ages were followed by the Renaissance (rebirth), a period that saw a great revival of classical learning and values. This led to cultural achievements of an extraordinary nature. Some historians define the Renaissance as the period extending roughly from the mid-1300's to the early 1600's.

The Renaissance started with the intellectual movement called Humanism, which originated in Italy. Humanism was started by lay men of letters, rather than the clerical scholars who had dominated intellectual life in the Middle Ages.

Humanism was greatly propelled by the fall of Constantinople to the Turks in 1453, as many scholars fled to Italy, bringing with them important books and a tradition of Greek scholarship.

Humanism derived its name from the Latin word "humanitas", a term used to convey the Greek ideal of education as the full development of the best in human nature. As scholars and teachers, the Humanists promoted first-hand reading of the classics and the study of such disciplines as grammar, rhetoric, poetry, moral philosophy and history (we still call them the humanities).

Humanism exalted the dignity of man as the center of the universe, with unlimited capacities for development. Instead of the medieval ideal of a life of penance as the noblest form of existence, the Humanists glorified creativity and mastery over nature.

From Italy, Humanism and the Renaissance it created spread north to all parts of Europe, greatly aided by the invention of the printing press, which increased enormously the availability of classical texts.

While generally faithful to Christian beliefs, Humanism inspired scientific inquiry free of the constraints of rigid religious orthodoxy.

The Reformation

Over the centuries, the Church's increasing power and wealth, combined with its deep involvement in the political intrigues of Western Europe, led to its spiritual deterioration. Corruption and abuses within the Church led to the Reformation movement, which at first demanded reform and ultimately chose separation, leading to the establishment of Protestantism.

The Reformation started in Germany in 1517 when the Augustinian monk Martin Luther publicly protested against the corruption of the Church, and later denied the authority of the Pope. The political and religious repercussions were enormous. The Church's response was the Counter-Reformation movement for the elimination of corruption, the reassertion of papal authority, and the suppression of heresy.

PRE-GALILEO ASTRONOMY

Copernicus (1473-1543)

Nicolaus Copernicus was the Latin name of Mikolaj Kopernik, born in East Prussia, in a region that is now part of Poland. After his father died, he was raised by an uncle, a priest, who later became an influential bishop. In 1496, he was sent to study in Italy. During the ten years he spent there, he studied both law and medicine. He also became well versed in Greek, mathematics and, particularly, astronomy.

After returning to his country, he served for six years as physician to his uncle the bishop until the latter's death. He then assumed his duties as a canon of the wealthy cathedral of Frauenburg, a well-paid post his uncle had secured for him years before. While involved in his daily occupation, he continued to pursue his interest in astronomy.

In the course of his studies, Copernicus had become increasingly dissatisfied with the Ptolemaic system. Over the centuries after Ptolemy, as astronomical observations became more accurate, in order to achieve a better match between the geometric models used and the observed positions of the planets, adjustments were made by adding epicycles riding on other epicycles, until the system became very cumbersome. Right after his return from Italy, Copernicus started developing his own system.

He proposed that it is the Sun that is fixed at the center of the universe, and that the Earth and the other planets revolve around the Sun. The Earth also rotates about its axis, thus accounting for the apparent motion of the fixed stars. Starting from the Sun, he correctly adopted the following order for the planets: Mercury, Venus, Earth, Mars, Jupiter and Saturn.

In his system, Copernicus placed all the centers of planetary orbits at the center of the Sun. More faithful to Plato's doctrine than Ptolemy had been, Copernicus strongly believed that the planets had to follow true uniform circular motion. Since the planets, however, do not move in this manner, he too was forced to resort to epicycles and other corrections. Ironically, Copernicus' system ended up requiring 48 separate circular motions, whereas the Ptolemaic system had required only 40.

In 1533, Copernicus gave lectures on the basic principles of his system before the Pope, who gave his approval. Three years later, he received a formal request to publish his thoughts. Probably in 1530, he had completed the manuscript of his book, "On the Revolutions of the Celestial Spheres", which was written in Latin, at the time the international language of scholars. Only in 1540, however, at the urging of friends, he agreed to submit the book for printing. Supposedly, Copernicus first saw an advance copy of his book on his deathbed, in 1543.

The main advantage of Copernicus' system was its ability to explain the puzzling to-and-fro "retrograde" motion of the planets. Let us consider, for instance, the Earth and Mars, as they both revolve around the Sun. As the Earth passes closest to Mars and then overtakes it, Mars - as seen from the Earth - appears to slow down, stop and then go backwards for a while.

In the view of most contemporary scholars, however, this advantage did not offset the formidable objections it raised, such as:

- According to Aristotelian-Scholastic philosophy, the Earth - the home of Man created in God's image - was located at the center of the universe. In Copernicus' system, the Earth was just one more planet revolving around the Sun.
- The new system appeared to contradict the Bible. As Luther remarked, "the sacred scriptures tell us that Joshua commanded the Sun to stand still, not the Earth".
- According to Aristotelian physics, bodies fell to the ground because they were seeking their natural place at the center of the universe. A new explanation was needed if the Earth was not at the center of the universe.
- The notion of a moving Earth was very difficult to reconcile with every-day experience. It was felt that, if the Earth were moving through space at great speed (actually, about 19 miles per second), everything on it would surely be

swept off its surface.

Because of these objections and the fact that Copernicus' system offered no advantage of simplicity with respect to the Ptolemaic system, the new system was largely ignored for decades.

Tycho Brahe (1546-1601)

A compromise between Ptolemy and Copernicus was proposed by a Danish astronomer, Tycho Brahe. He was born in a noble family three years after Copernicus' death. He studied law to please his family, but his true passion was astronomy.

He became a recognized astronomer at age 27, after reporting his discovery of a new star. In 1576, King Frederick II of Denmark gave him generous financial support to establish a large observatory. Tycho devoted great care to the design of his instruments, and lavished money to secure the finest materials and the best craftsmen. (These were all naked-eye instruments; the first use of the telescope was made by Galileo in 1609, eight years after Tycho's death.)

The mission Tycho undertook for himself and his assistants was to measure the position of every visible star with the highest possible precision, and to achieve the same accuracy in very frequent measurements of planetary positions over long periods of time. All previous astronomers had been satisfied to make only occasional observations.

After the death of Frederick II in 1588, royal support greatly diminished. Nine years later, Tycho left Denmark and, in 1599, he settled in Prague as official astronomer to the Holy Roman Emperor.

With the extensive data accumulated during the 21 years spent at his observatory in Denmark, Tycho felt ready to develop his own system, the Tychonic system, in which the five known planets revolved around the Sun, while the Sun and the Moon revolved around the Earth. This was an appealing compromise since it kept the Earth still at the center of the universe.

To develop his system, Tycho needed an assistant highly skilled in mathematics. In 1600, he hired a young German astronomer, Johannes Kepler.

Johannes Kepler (1571-1630)

Kepler came from a poor family, but a superior intelligence earned him scholarships that enabled him to study philosophy, mathematics and astronomy. After receiving his college degree in 1591, he began to study theology with the intention of becoming a Lutheran minister. In 1594, however, he was offered a post to teach mathematics. Reluctantly, he accepted it at the urging of his professors. For a number of years, he supplemented his income by publishing an astrological calendar. Throughout his life, his skill at astrological prediction was in great demand.

In 1597, Kepler published a book, which displayed his skills as a mathematician and his knowledge of astronomy. They impressed Tycho Brahe, who offered him a job.

When Tycho died a year later, Kepler at 30 was appointed his successor as imperial mathematician. He also inherited Tycho's data - but only after a considerable struggle with the heirs. This was the best collection of astronomical data that had ever been assembled.

As a member of Tycho's team, Kepler's first assignment had been to calculate an orbit that would describe the position of Mars at any time within the accuracy of Tycho's observations. Kepler boasted that he would have a solution in eight days. Actually, it took him more than six years before he mastered the problem!

His results, published in 1609, could be stated in two laws that applied not only to Mars but also to any planet. Before we can learn about these laws, we must digress to **Figure 2.2** to see what an "ellipse" is.

Kepler's two laws constitute a complete denial of Plato's doctrine since they assert that the motion of a planet is neither circular nor uniform, but elliptical at variable speed. The two laws are illustrated in **Figure 2.3**.

Ten years later, Kepler published his third law, a mathematical relationship between a planet's average distance to the Sun, and the time it takes to complete one orbit around the Sun. In general terms, the law states that, the greater the average distance of a planet from the Sun, the longer it takes to complete one orbit.

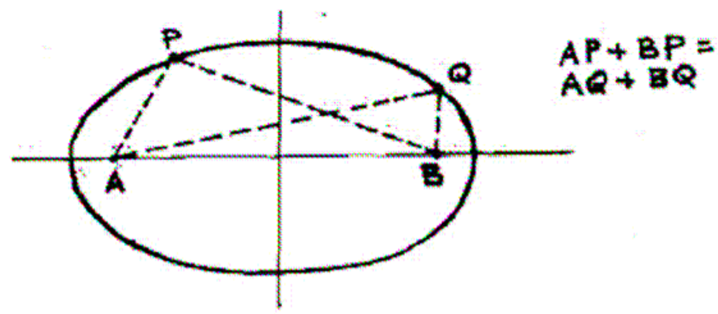

Figure 2.2 - An ellipse

To draw an ellipse, imagine driving two nails on a board at points A and B, and tying to them the ends of a string longer than the distance AB. If you keep the string taut with the point of a pencil and move it around, you will draw an ellipse. Points A and B are each called a "focus" of the ellipse.

By varying the distance between the "foci" and the length of the string, you can vary the size and shape of the ellipse. The closer the foci, the more the ellipse resembles a circle. In fact, when the foci coincide, they become the center of a circle.

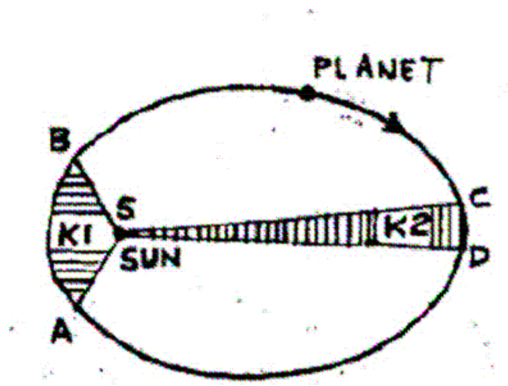

Figure 2.3 - Kepler's 1st and 2nd laws

Both the Sun and a planet are shown above as points. Kepler's first law states that the orbit of a planet is an ellipse with the Sun at one focus.

Kepler's second law states that the line that connects the Sun and a planet sweeps equal areas in equal times, such as the areas K1 and K2 shaded above. This means that the longer arc AB is traversed in the same time as the shorter CD. Thus, within its orbit, the closer a planet is to the Sun, the faster it moves.

Kepler's system superseded the complex systems of epicycles and deferents that had been used before him. It was more than another geometrical scheme contrived to predict planetary positions. It described the actual motions of the planets with respect to the Sun, and did so in mathematical terms.

Still, Kepler lacked an explanation for what made the planets move the way they did. He tried to solve this problem by invoking magnetism, the only force known at the time that appeared to be cosmic in nature. Kepler vaguely speculated that some sort of magnetic force emanating from the Sun acted to push each planet in the direction of its orbital motion.