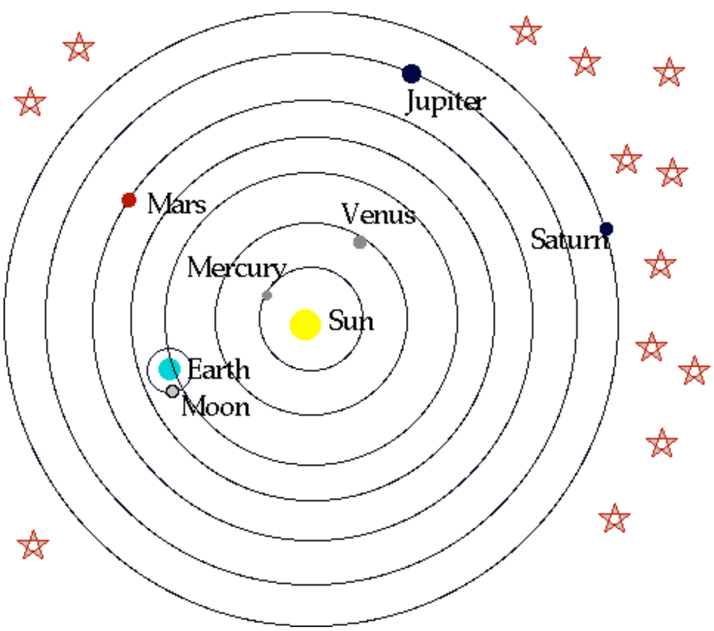
Heliocentric Universe



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1 Nicolaus Copernicus – Sun, Not Earth, at Center of Universe

Since the beginning of human existence it was always assumed (known for certain) that the Earth was the center of the universe. After all, that is what we have always experienced. The Earth is stationary, unmovable, with the Sun, moon, planets, and the stars all revolving around the Earth.

Nicolaus Copernicus (1473 – 1543), a Polish Catholic cleric, mathematician and astronomer, was the first to assert that the Sun was the center of the universe, not the Earth. That in fact the Earth circled the Sun, not the other way around. His theory profoundly altered the view of the universe, but was strongly rejected by the Catholic church and many others. In a sense, such a radical proposal was out of character for Copernicus who wanted to live a quiet life carrying out his cleric duties conscientiously and devoting his spare time to observing and developing his theories of the universe.

One of the problems that had perplexed astronomers for centuries was the retrograde motion of Mars, Jupiter, and Saturn (Uranus and Neptune were unknown at the time). Mars, for example, appears to move from west to east through the background constellations. However, for a couple of months every two years or so Mars seems to change direction moving instead from east to west. It then resumes its normal west to east motion as illustrated in Figure 1. Mercury and Venus do not exhibit this problem.

Copernicus discovered that the retrograde motion of Mars could be explained if the Sun, instead of the Earth, were the center of the universe. He reasoned that the Earth would orbit the Sun faster than Mars if Earth were closer to the Sun (Figure 2). About every 26 months, Earth would approach from behind and overtake Mars. As it did so, Mars would appear to reverses direction and then resume its original movement as Earth got further away. This is exactly what happens. Today we know that Earth orbits the Sun twice in the time it takes Mars to complete one orbit.

Figure 1 Retrograde Motion of Mars (source: NASA)

Around 1514 Copernicus gave a small hand written book to a few of his friends. The book did not list an author but they knew that he had written it. The book, usually called the "Little Commentary", described Copernicus's theory of the universe with the Sun at its center. The book contains the following seven axioms:

1. There is no one center in the universe.
2. The Earth's center is not the center of the universe.
3. The center of the universe is near the Sun.
4. The distance from the Earth to the Sun is imperceptible compared with the distance to the stars.

5. The rotation of the Earth accounts for the apparent daily rotation of the stars.

6. The apparent annual cycle of movements of the Sun is caused by the Earth revolving round it.

7. The apparent retrograde motion of the planets is caused by the motion of the Earth from which one observes.

Copernicus was the first to correctly explain the retrograde motion of Mars, Jupiter, and Saturn, the planets beyond Earth's orbit as illustrated in Figure 15.

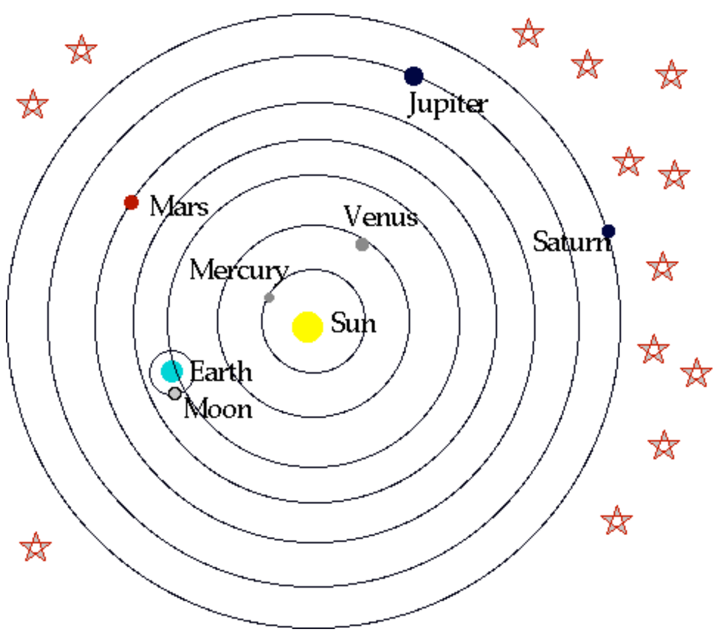

Figure 2 Copernicus Model of the Solar System (source: Carleton University)

It appears that "Little Commentary" was Copernicus's first step in writing his major work titled "De revolutionibus". It is believed that he wrote "Little Commentary" in 1514 and began work on "De revolutionibus" the following year. Copernicus spent the rest of his life writing "De revolutionibus", its full title becoming "De revolutionibus orbium coelestium".

It is possible that the book would never have been published were it not for a young professor of mathematics and astronomy at the University of Wittenberg named Georg Joachim Rheticus. Rheticus strongly encouraged Copernicus to publish his work.

Copernicus's 200 page manuscript (written in Latin) was finally ready for publication in August 1541. Rheticus took the manuscript to Nürnberg for printing. Andreas Osiander, a

Lutheran theologian with experience printing mathematical texts supervised the printing of the book.

Copernicus was fully aware of the criticisms that his book would generate. In the Preface to the book he wrote:

“Perhaps there will be babblers who, although completely ignorant of mathematics, nevertheless take it upon themselves to pass judgment on mathematical questions and, badly distorting some passages of Scripture to their purpose, will dare find fault with my undertaking and censure it. I disregard them even to the extent as despising their criticism as unfounded.”

Osiander replaced Copernicus's Preface with a letter to the reader. The unsigned letter stipulated that the results in the book were not intended as truth, but rather presented a simpler way to calculate the positions of the heavenly bodies. Many were appalled by Osiander’s actions. He had no authorization from either Copernicus or Rhetius to make such a substantial change to the book. However, others feel that it is only because of the letter that Copernicus's work was read and not immediately condemned.

It is believed that Copernicus first saw the printed book on his deathbed in 1543.

2 Tycho Brahe – The Leading Astronomer of the Time

Tycho Brahe (1546 – 1601) was a Danish astronomer, born of Danish nobility, who is best known for the astronomical observations which led Kepler to his theories of planetary motion.

Tycho was educated at the University of Copenhagen and the University of Leipzig in Germany. He also frequently visited the German universities in Wittenberg and Rostock. In 1566, while at Rostock, he was involved in an argument with another student and in the resulting duel part of Tycho’s nose was cut off. To remedy the situation Tycho had an artificial nose made from silver and gold. However, he was disfigured for life.

Tycho became the greatest observational genius in the age before the telescope. He built huge mechanical devices to accurately determine the positions of the planets and stars as they moved through the night sky. His observations were carefully recorded producing the most complete and accurate astronomical data of the time.

On 11 November 1572, Tycho observed and document the occurrence of an extra star in the constellation of Cassiopeia. In later years it was determined that the extra star was in fact a supernova. In his usual meticulous style he carefully recorded the appearance of the “new star”, watched it slowly intensify in brightness, and then fade away over a period of 18 months. The event caused Tycho and his contemporaries to begin questioning the widely held notion of a perfect unchanging universe.

In 1576, with financial help from King Frederick of Denmark, Tycho built an observatory on the island of Hven in Copenhagen Sound. The observatory, called Uraniborg, was equipped with exceptionally large and accurate instruments. Tycho spent twenty years at Uraniborg making the most complete astronomical observations of the time.

One of Tycho's most exciting astronomical events at Uraniborg was observation of a comet which he first spotted on November 13, 1577. At the time it was believed that comets passed between the Earth and the moon based on Aristotle's model of the universe. Tycho made detailed measurements of the comet's path. From these measurements he concluded that Aristotle's model was incorrect. Comets did not pass between the Earth and the Moon. In fact, Tycho was able to show that the comet was further away than Venus.

Tycho developed a theory of the solar system based on a stationary Earth round which the Moon and Sun revolved. The other planets, according to Tycho's theory, revolved round the Sun. Originally Tycho had been a supporter of Copernicus's Sun centered model. The problem was that in a such model a parallax shift in the positions of the stars should be observed as the Earth revolved around the Sun. However, he could not detect one. In fact there is a parallax shift but the shift is 100 times small than Tycho was capable of measuring, despite the quality of his instruments.

King Frederick died in April 1588 and, his son became King Christian IV. Some years later a dispute arose between Tycho and King Christian over ownership of Uraniborg. Tycho closed down the observatory and in 1599 moved his family to Prague where he was appointed Imperial Mathematician to the Holy Roman Emperor, Rudolph II (at that time Prague was the capital of the Holy Roman Empire). Johannes Kepler was persuaded to join him as an assistant to help with mathematical calculations. Tycho hoped that Kepler's work would prove that his (Tycho's) cosmological model was correct. For his part Kepler hoped that Tycho's vast astronomical records would show that his own theory of the universe was correct. In fact, it turned out that both of their theories were wrong.

The relationship between Tycho and Kepler was not a good one. Tycho was a flamboyant figure, festooned with his golden nose, and surrounded by an entourage of assistants and assorted hangers-on. In contrast, Kepler was a provincial school teacher of humble origins unknown only to a few mathematicians. Unwilling to turn over his life time of observational data to a competitor (Kepler), Tycho fed Kepler only small scraps of data at a time. The two quarreled constantly and were repeatedly reconciled. Tycho died October 24, 1601. On his deathbed Tycho bequeathed his observations to Kepler. Kepler became the new Imperial Mathematician following Tycho's death.

3 Johannes Kepler – Planetary Motion and Extensive Study of Light

The German astronomer, mathematician, and astrologer Johannes Kepler (1571 – 1630) is best known for his laws of planetary motion. These laws were based on the extensive detailed astronomical observation that he inherited from Tycho Brahe.

However, Kepler also did considerable work in the field of optics making the first significant advances in the understanding of light since the time of al-Haytham. Kepler provided the first correct explanation of how the human eye works. He correctly explained long and short sightedness. He also studied the reflection of light by flat and curved mirrors. Based on this work he determined that the intensity of light varies by the inverse square of the distance between the observer and the light source. However, he maintained the majority view at the time that the speed of light was infinite and could not be measured. His rational for this view was that the vacuum of space could not offer any resistance to the motion of light. He published the results of this work on optics in 1604.

Kepler was born in the small town of Weil der Stadt and moved with his parents to nearby Leonberg in 1576. Leonberg is 16 km west of Stuttgart, Germany. His father was a mercenary soldier and his mother the daughter of an innkeeper. His father left home when Kepler was 5 years old and never returned. It is believed that he died in the Netherlands war. As a child, Kepler lived with his mother in his grandfather's inn

Kepler began his education at a local school followed by two years at the nearby seminary in Maulbronn. Kepler left Maulbronn in 1589 to study for the clergy at the University of Tübingen. Teaching at Tübingen was in Latin. In addition to Latin, Kepler learned Greek and Hebrew since both were necessary for reading the scriptures in their original languages. Mathematical sciences (arithmetic, geometry, astronomy and music) were part of the curriculum at Tübingen. Kepler was taught traditional Ptolemaic geocentric astronomy, that is the universe consisted of six planets – Mercury, Venus, Sun, Mars, Jupiter and Saturn – all of which revolved round the Earth. The course was taught by one of the leading astronomers of the day, Michael Mastlin (1550 - 1631). In addition to his normal studies, Kepler was one of the few select students that Mastlin chose to teach more advanced astronomy, including the new heliocentric cosmology of Copernicus.

Throughout his life, Kepler was a profoundly religious man. All his writings contain numerous references to God. He saw his work as a fulfillment of his Christian duty to understand the works of God. However, his religious beliefs were not entirely in accord with the orthodox Lutheran teaching at Tübingen. Perhaps for this reason, Mastlin persuaded Kepler to abandon plans for ordination and instead take a position teaching mathematics in Graz, Austria, which he did in April 1594 at the age of 22.

In 1595, while teaching in Graz, Kepler began questioning why there were only six planets (Mercury, Venus, Earth, Mars, Jupiter and Saturn) circling the Sun. Why were there not more, perhaps many more?

There are five solids, known since the time of Pythagoras, whose sides are regular polygons. These regular solids are shown in Figure 3. One of the solids, for example, is a cube that has six sides each of which is a perfect square.

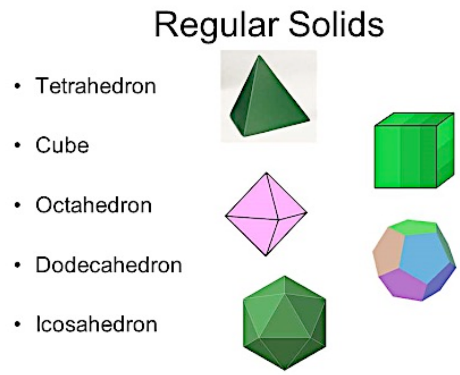

Figure 3 Regular Solids (source: http://www.sliderbase.com)

Kepler concluded that the reason there were only six planets is that there were only five regular solids, no more. He discovered that if the five solids were nested one inside the other, and each solid was circumscribed by a sphere, then six spheres would be produced at precise distances from one an other. The six spheres, of course, corresponded to the orbits of the six planets. In Kepler's mind, such a beautiful solution could only result from the work of God. He called his theory "The Cosmic Mystery" which he published in 1596.

Kepler built mechanical models to test his theory (Figure 4). However, no matter how hard he tried he could not get the spheres in his models to agree with the orbits determined by Copernicus. He believed his theory was so elegant, driven by the hand of God, there could be only one answer. The data defining the Copernicus orbits had to be wrong.

Kepler hoped that better observations would prove his theory correct. So he sent a copy of his paper "The Cosmic Mystery" to the foremost observational astronomers of the time, Tycho Brahe. Tycho was by then Imperial Mathematician to the Holy Roman Emperor, Rudolph II in Prague. It turned out that Tycho had been looking for a mathematical assistant to assist him in proving the validity of his own theory of the cosmos. Kepler join Tycho hoping to gain access to Tycho's extensive planetary data.

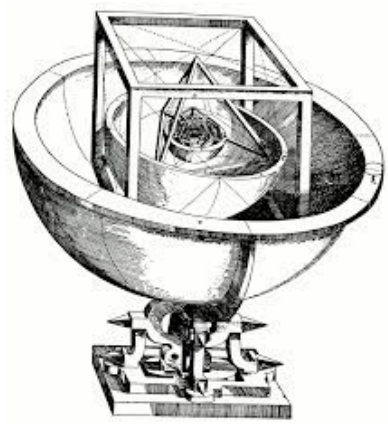

Figure 4 Kepler's Cosmic Mystery Theory (source: Wikipedia)

Kepler's expectation were not fulfilled. As described earlier, the relationship between Tycho and Kepler was not a good one. Tycho was unwilling to turn over his extensive observational data, that he had spent a life time collecting, to a competitor (Kepler). Instead Tycho fed Kepler only small scraps of data at a time. The two quarreled constantly. Finally, on his deathbed, Tycho bequeathed his observations to Kepler.

Tycho's data did not support Kepler's theory either. Kepler was forced to conclude that his theory was wrong.

Tycho had insisted that Kepler study the motion of Mars since its motions was the most anomalous. It was assumed by everyone from the time of Ptolemy that the orbits of the planets were circular. Following Tycho's death, Kepler worked for three years trying to determine the correct values for the circular orbit of Mars. But his calculations did not agree with Tycho's observations. Reluctantly, Kepler had to accept that the orbit of Mars was not circular.

Eventually he discovered that Mar moved around the Sun in an elliptical orbit instead of a circular one. The other planets have orbits which are much less elliptical than that of Mars. Had Tycho urged Kepler to study one of the other planets, for example Venus, Kepler may never have discovered the true shape of the planetary orbits.

The Sun is not at the center of an elliptical orbit but instead at one of the ellipse focal points. This lead to Kepler's First Law of Planetary Motion, illustrated in Figure 5:

"The orbit of every planet is an ellipse with the Sun at one of the two foci"

One of the characteristics of an elliptical orbit is that a planet does not travel at a constant speed. Instead, it speeds up as it approaches the Sun, whips around the Sun, and is flung back out to the outer most part of its orbit. The planet travels at its slowest speed when it is furthest from the Sun. It then "falls" back toward the Sun accelerating as it goes.

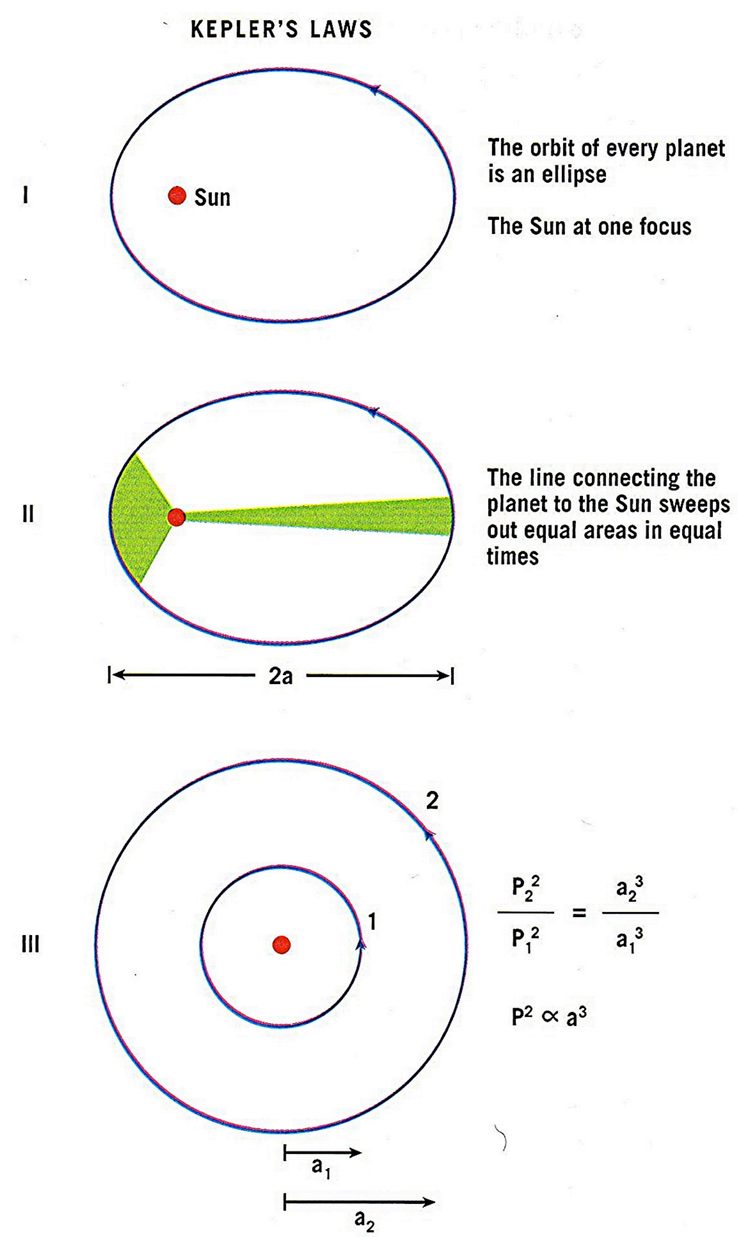

Figure 5 Kepler's Laws of Planetary Motion (source: Tyson)

Kepler noticed that a planet sweeps out a wedge shaped area within the ellipse as the planet moves in its orbit around the Sun (Figure 5). The planet moves fast when it is close to the Sun tracing out a relatively large arc in a given period of time. The area represented by the arc is short and wide. When the planet is far from the Sun, and moving slow, it traverses a much smaller arc in the same period of time. In this case the area represented by the arc is long and narrow because the planet is more distant from the Sun.

Kepler found that these two areas were precisely the same no mater how elliptical the orbit. This lead to Kepler's Second Law of Planetary Motion (Figure 5):

> "Planets sweep out equal areas in equal times."

Kepler published these two laws in 1609.

In 1611, growing political-religious tension in Prague forced Emperor Rudolf II, who was in failing health, to abdicate as Holy Roman Emperor to his brother Matthias. This change was not particularly good for Kepler since the strong relationship between Kepler and Rudolf did not extend to Matthias. In the same year Kepler's wife Barbara died as did his son Friedrich.

Kepler remained in Prague until Rudolf's death in early 1612. Matthias re-affirmed Kepler's position as imperial mathematician but allowed him to move to Linz, Austria.

In Linz, Kepler taught at the district school and provided astrological and astronomical services. His first years there were good years. He enjoyed financial security and religious freedom that he did not have in Prague.

On October 30, 1613, Kepler married 24-year-old Susanna Reuttinger (1595 - 1635). The first three children of this marriage died in childhood. Three more survived into adulthood. Apparently this was a much happier marriage than his first.

The Thirty Year's War broke out in 1618. The conflict, fought primarily in modern day Germany and central Europe, was supposedly a holy war between Catholics and Protestants. However, it was more an exploitation of religious fanaticism by those hungry for power and land. At the end of the war in 1648 entire regions of present day Germany were stripped of their inhabitants, livestock, and supplies while many cities were in ruins. It is considered one of the most destructive conflicts in European history. Combined military and civilian deaths are estimated to range from 4.5 to 8 million due to military action, pillage, famine, and disease.

Kepler discovered his third and final law of planetary motion only a few days prior to the incidents in Prague that triggered the Thirty Years' War. His Third Law of Planetary Motion (Figure 5) states that:

> "The squares of the periods of the planets are proportional to the cubes of their average distances from the Sun"

In equation form

$$\frac{P_1^2}{P_2^2} = \frac{a_1^3}{a_2^3}$$

where

P = the period of a planet (the time in years for it to circle the Sun once)

a = the distance of the planet from the Sun in astronomical units (AU)

1 AU = distance from the Sun to the Earth.

Rearranging terms, the square of a planet's period is proportional to the cube of its distance from the Sun

$$P^2 \propto a^3$$

For example, what is the distance of Jupiter (a_1) from the Sun if its orbital period (P_1) is 11 years. We know that the orbital period of Earth (P_2) is one year and its distance from the Sun (a_2) is 1 AU. Thus

$$a_1^3 = a_2^3 \frac{P_1^2}{P_2^2} = 1^3 \frac{(11)^2}{(1)^2} = (11)^2$$

thus

$$a = 4.9\ AU$$

In 1619 Kepler published his third law in his book "The Harmonies of the World".

While all of this was happening, Kepler's mother, Katharina, was accused of witchcraft. She was imprisoned for fourteen months from August 1620 until her release in October 1621. Her release was due in large part to Kepler's extensive legal defense.

In 1628 Kepler became an official advisor to General Wallenstein, one of the few successful military leaders in the Thirty Years' War. Kepler's duties included providing astronomical calculations for Wallenstein's astrologers and occasionally writing horoscopes himself.

In his final years, Kepler spent much of his time traveling from the imperial court in Prague, to Linz, and Regensburg. Kepler fell ill and died in Regensburg on November 15, 1630 at the age of 59.

4 Galileo – Discovered the Four Largest Moons of Jupiter

Galileo Galilei (1564 – 1642) was the brilliant Italian mathematician and scientist who discovered the four largest moons of Jupiter and formulated the basic law of falling bodies.

Galileo's father was a music teacher and an accomplished lute player. He was also a scientist of sorts conducting experiments on strings to support his musical theories.

Galileo’s initial education was at the Camaldolese Monastery in Vallombrosa 33 km southeast of Florence. Galileo enjoyed his life at the monastery and planned to join its Religious Order. However, this was unacceptable to his father who had decided that Galileo should become a medical doctor.

In 1581 Galileo was enrolled at the University of Pisa for the purpose of becoming a doctor. It seems that Galileo never took his medical studies seriously. Instead his interests were in mathematics and natural philosophy. In 1585 he left the university without completing his medical degree.

Galileo began teaching mathematics in Florence. He quickly acquired a reputation as an outstanding mathematician and was appointed head of mathematics at the University of Pisa in 1589. Galileo spent three years at Pisa during which time he wrote a series of essays on the theory of motion titled “De Moute”. However the essays were never published.

In 1592 Galileo was appointed professor of mathematics at the University of Padua earning a salary three times that he had received at Pisa. He spent 18 years at the university which he later described as the happiest years of his life.

At Padua he taught mainly Euclid geometry and standard geocentric astronomy (the Sun, planets, and stars all revolve around the Earth), even though privately he disagreed with the geocentric approach. He believed instead that the heliocentric theory proposed by Copernicus was the correct view of the universe (the Earth, planets, and stars revolve around the Sun). Galileo also disagreed, privately of course, with Aristotle’s view of astronomy and natural philosophy. The Aristotelian belief at the time was that all changes in the heavens had to occur in the lunar region close to the Earth since the stars were permanently and unalterably fixed in the heavens. Galileo used parallax arguments to prove that a new star discovered by Kepler was far from the Earth and moon. Today the new star is known as Kepler’s supernova.

Galileo began studying inclined planes and the pendulum in 1602. Over the next two years he correctly formulated the law of falling bodies and concluded that projectiles followed a parabolic path. These important results were not published for another 35 years.

In 1609 Galileo learned that the previous year Hans Lippershey in the Netherlands had invented a telescope. Using his mathematical knowledge and craftsman skills, Galileo began building his own series of telescopes that improved on Lippershey’s design. Galileo built his first telescope using available lenses, achieving a magnification of about 4X. To get better performance he learned how to grind and polish his own lenses, permitting him to build a telescope with a magnification of 8X.

Using his new telescope, Galileo quickly discovered the craters on the moon. The moon was not the perfectly smooth sphere that had always been believed. Shortly after that he discovered the four largest moons of Jupiter. He described these discoveries in a short book called the “Starry Messenger” which he published in Venice in May 1610. Later that year he discovered that Venus went through phases very similar to those of the moon. This discovery strongly suggested that Venus circled the Sun in an orbit that lay between Earth and the Sun. Galileo also observed Saturn, but his telescope did not have sufficient magnification to resolve the rings of Saturn. Instead, Saturn appeared to have two lobes, one on either side of the planet. In addition, he discovered that the Milky Way was actually made up of tiny stars.

A month after publishing the “Starry Messenger”, Galileo resigned his position at Padua and became Chief Mathematician at the University of Pisa. He also served as the Mathematician and Philosopher for the Grand Duke of Tuscany.

Galileo continued observing with his telescope and discovered sunspots on the Sun in 1612. Contrary to the belief since the time of Aristotle, the Sun was not perfect either. Instead it had blemishes. Galileo reported these findings in a paper titled “Letters on the Sunspots” which he published in 1613.

While Galileo supported Copernicus’s theory of a Sun centered universe, he tried to avoid controversy by not making any public statements on the issue.

The person in the Catholic Church responsible at that time (1613 -1614) for interpreting Holy Scripture was Cardinal Robert Bellarmine. Bellarmine saw little reason for the Church to be concerned with Copernican theory. His view was based on the letter inserted by Osiander at the beginning of Copernicus’s book which stated that the book was simply a mathematical theory which better enabled calculating the positions of heavenly bodies. As such the book did not threaten the established Christian belief regarding the structure of the universe.

Not convinced, Pope Paul V ordered Bellarmine to assemble selected cardinals to rule on the Copernican theory. The Inquisition condemned the teachings of Copernicus in February 1616 after listening to evidence from various theological experts. Bellarmine conveyed their decision to Galileo who was, from that point on, forbidden to express Copernican views.

Seven years later (in 1623) Cardinal Maffeo Barberini, an admirer of Galileo, was elected as Pope Urban VIII. Galileo dedicated the book that he had just written “*Il saggiatore* (The Assayer)” to the new Pope. Galileo visited the Pope on several occasions. Because of his good relationship with the Pope, Galileo believed that he could publish his views on Copernican theory in a book titled “Dialogue” without serious consequences from the Church. At this stage in his life Galileo's health was poor with frequent bouts of severe illness. Consequently, it took Galileo six years to complete work on “Dialogue” finishing the book in 1630. Galileo attempted to obtain permission from Rome to publish the book was unable to do so. He eventually received permission from Florence to publish the book in February 1632.

The Church banned sale of the book shortly after its publication. In addition, Galileo was ordered to appear in Rome before the Inquisition. Illness prevented Galileo from traveling to Rome until 1633. The Inquisition found him guilty of violating Church doctrine by publishing his views on Copernican theory. Galileo was sentence to life imprisonment. However, he was placed under house arrest rather than being send to prison. Initially he lived with the Archbishop of Siena. Later he was allowed to return to his home in Arcetri, near Florence.

In 1634 Galileo began writing a book on mechanics titled “Discourses and mathematical demonstrations concerning the two new sciences”. Much of the work was based on his unpublished ideas dating back to 1590 – 1605. The book included his ideas on inclined planes, moments, and centers of gravity. He experimented with pendulums to better understand the properties of inclined planes. This work lead to his famous results that:

> “The distance that a body moves from rest under uniform acceleration is proportional to the square of the time taken.”

The book was smuggled out of Italy and taken to Leyden in Holland where it was published.

One would have expected that Galileo's understanding of pendulums would have led him to design a pendulum clock. He finally did design a pendulum clock near the end of his life. After his death in early 1642, his son Vincenzo attempted to build a clock according to Galileo's design, but failed.

References

Carroll, Bradley W.; Ostlie, Dale A.; *An Introduction to Modern Astrophysics*; 1996, Addison-Wesley Publishing Company Inc.

Foukal, Peter; *Solar Astrophysics*; 2013 Wiley-VCH Verlag GmbH & Co.

Golub, Leon; Pasachoff, Jay M.; *The Nearest Star The Surprising Science of Our Sun*; 2014 Cambridge University Press

Zettili, Nouredine; *Quantum Mechanics Concepts and Applications*; 2009 John Wiley & Sons, Ltd.

Masi, Marco; *Quantum Physics: an overview of a weird world*; 2018 Marco Masi

Halliday, David; Resnick, Robert; *Physics For Students of Science and Engineering Part I*; 1962 John Wiley & Sons, Inc.

Halliday, David; Resnick, Robert; *Physics For Students of Science and Engineering Part II*; 1962 John Wiley & Sons, Inc.

Klus, Dr. Helen; *How We Came to Know the Cosmos: Light & Matter*; 2017, The Star Garden, UK.

Ling, Samuel J.; Sanny, Jeff; Moefs, William; *University Physics Volume 3*; 2018 Openstax Rice University

Dampier, W. C.; *A History of Science*; 1961 Cambridge University Press

Cajori, Florian; *A History of Physics in its Elementary Branches*; 1917, The Macmillan Company

Williams, Henry Smith; *A History of Science Part 1*; 1904 Kessinger Publishing

Williams, Henry Smith; *A History of Science Part 1*; 1904 Kessinger Publishing

Pannekoek, A.; *A History of Astronomy*; 1961, George Allen and Unwin Ltd.

Merzbech, Uta C.; Boyer, Carl B.; *A History of Mathematics*: 2011, John Wiley & Sons, Inc.

Friedman, Herbert; *The Astronomer's Universe Stars, Galaxies, and Cosmos*; 1990, The Commonwealth Fund Book Program

Piccioni, Robert L.; *Everyone's guide to Atoms Einstein and the Universe*; 2010 Robert L. Piccioni; Real Science Publishing

J. J. O'Connor and E. F. Robertson; *Light through the ages: Ancient Greece to Maxwell*; MacTutor History of Mathematics, (University of St. Andrews, Scotland) 2002, http://www-history.mcs.st-andrews.ac.uk/HistTopics/Light_1.html

UVA Physics Department; *Newton's Particles Theory of Light-Galileo;* University of Virginia; http://galileo.phys.virginia.edu/classes/609.ral5q.fall04/Lecture:PDF/L20LIGHTII.pdf

Fowler, Michael; UVA Physics Department, *The Speed of Light,* University of Virginia, http://galileoandeinstein.physics.virginia.edu/lectures/spedlite.html
Walbank; Frank W.; Alexander the Great; Encyclopedia Britannica

Setterfield, Barry; *A Brief History of c*; 1987

Spring, Kenneth R.; Fellers, Thomas J.; Zuckerman, Lawrence D.; Davidson, Michael; *Speed of Light*; Olympus-Life Science, Olympus America Inc.

Abramowitz, Mortimer; Spring, Kenneth R.; Parry-Hill,Matthew; Flynn, Brian O.; Tchourioukanov, Kirill I. Fellers, Thomas J.; Davidson, Michael W.; *The Physics of Light and Color*; Olympus-Life Science, Olympus America Inc. https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/

Urone, Paul Perter; *Image Formation by Mirrors*; LibreTexts

Kovacs, Peter; *History of the reading stones*; Light Microscopes

Herivel, John; *Christiaan Huygens Dutch Scientist And Mathematician*; Feb 14, 2019; Encyclopedia Britannica

Rodriguez, Emily; *Robert Hooke British Scientist*; Feb 27, 2019; Encyclopedia Britannica

Westfall, Richard S; *Sir Isaac Newton English Physicist and Mathematician*; Feb 1, 2019; Encyclopedia Britannica

Crowley, Theodore; *Roger Bacon*; Encyclopedia Britannica

Westman, Robert S.; *Johannes Kepler*; Encyclopedia Britannica

Van Helden, Albert; *Galileo*; Encyclopedia Britannica

J J O'Connor and E F Robertson; *André Marie Ampère*; School of Mathematics and Statistics University of St Andrews, Scotland, February 1998

J J O'Connor and E F Robertson; *Roger Bacon*; School of Mathematics and Statistics University of St Andrews, Scotland, December 2003

J J O'Connor and E F Robertson; *Jean Baptiste Biot*; School of Mathematics and Statistics University of St Andrews, Scotland, May 2010

J J O'Connor and E F Robertson; *Nicolaus Copernicus*; School of Mathematics and Statistics University of St Andrews, Scotland, November 2002

J J O'Connor and E F Robertson; *Charles Augustin de Coulomb*; School of Mathematics and Statistics University of St Andrews, Scotland, July 2000

J J O'Connor and E F Robertson; *Michael Faraday*; School of Mathematics and Statistics University of St Andrews, Scotland, May 2001

J J O'Connor and E F Robertson; *Galileo Galilei*; School of Mathematics and Statistics University of St Andrews, Scotland, November 2002

J J O'Connor and E F Robertson; *Johann Carl Friedrich Gauss*; School of Mathematics and Statistics University of St Andrews, Scotland, December 1996

J. V. Fields; *Johannes Kepler*; School of Mathematics and Statistics University of St Andrews, Scotland, April 1999

J J O'Connor and E F Robertson; *James Clerk Maxwell*; School of Mathematics and Statistics University of St Andrews, Scotland, November 1997

J J O'Connor and E F Robertson; *Isaac Newton*; School of Mathematics and Statistics University of St Andrews, Scotland, January 2000

J J O'Connor and E F Robertson; *Georg Simon Ohm*; School of Mathematics and Statistics University of St Andrews, Scotland, January 2000

J J O'Connor and E F Robertson; *Félix Savart*; School of Mathematics and Statistics University of St Andrews, Scotland, July 2007

J J O'Connor and E F Robertson; *Tycho Brahe*; School of Mathematics and Statistics University of St Andrews, Scotland, April 2003