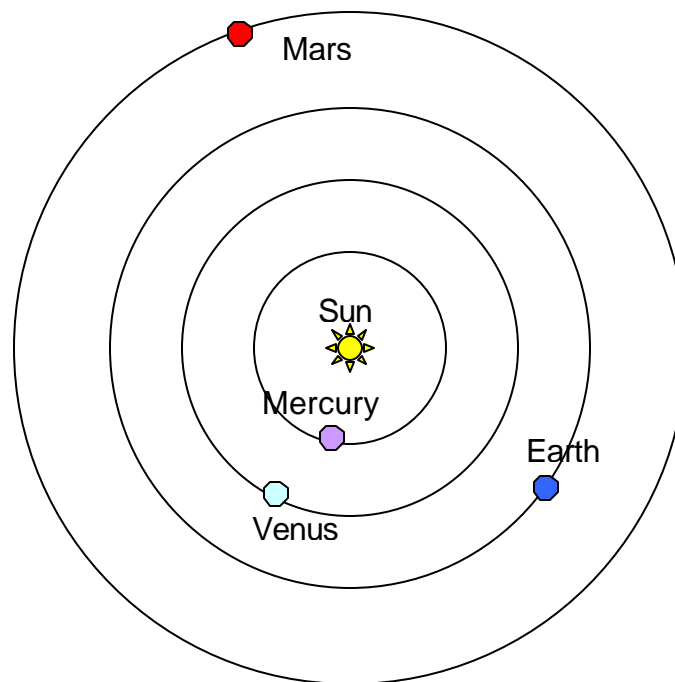


Nicolas Copernicus (1473 – 1543)

Nicolas Copernicus was born in Torun, Poland in 1473 and died in 1543. He studied both law and medicine in Italy, but spent most of his life as Canon of Frombork Cathedral in Poland. He published his great work “***On the Revolutions of the Heavenly Spheres***” in 1543, the year he died. In this book he detailed a heliocentric system (sun centered) and described advantages it had over the geocentric system of Ptolemy. Over the space of about 75 years, this new view of the solar system gradually gained acceptance throughout Europe.

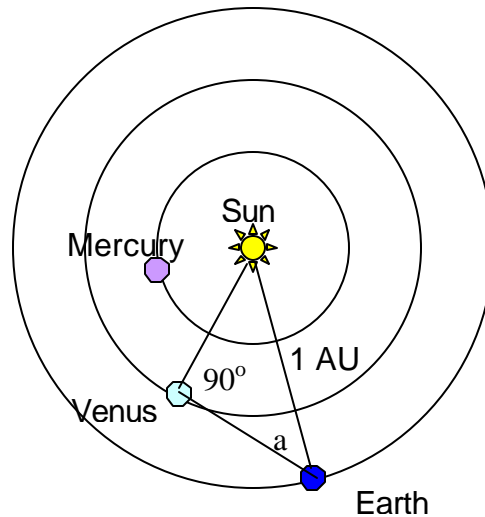
Copernicus’ system:



Main features:

1. Planets move in circular orbits around the sun
2. Earth is one of the planets
3. Night and day on the earth are due to the rotation of the earth on its axis (one rotation every 24 hours).
4. The apparent motion of the sun along the ecliptic is due to the revolution of the earth around the sun (one complete revolution in one year).
5. Retrograde motion of the planets is an illusion produced by the earth passing the planets as it journeys around the sun (much like the way the car you pass on the freeway seems to be moving backward relative to your car.)

6. Mercury and Venus are always found close to the sun because their orbits lie between the earth and the sun
7. The scale of the solar system can be established in astronomical units (AU – the distance from the earth to the sun). Using the inner planets this is accomplished as in the following diagram:



This is how it works: When Venus is at its maximum distance from the sun, the triangle defined by the sun, the earth and Venus is as shown above. The angle a is known because that is the angular distance between Venus and the sun as viewed from the earth. Geometrical theorems can show that the angle at Venus is always 90 degrees when a is a maximum. The length of the hypotenuse of this right triangle is one AU by definition. Knowing all the angles and one side of a triangle allows us to determine the length of all the other sides, in this case the distance from Earth to Venus and Venus to the sun.

Scholars were initially attracted to Copernicus' system because it (1) it explained retrograde motion in an elegant way (2) it explained why Mercury and Venus were always close to the sun, and (3) it provided a way for establishing the scale of the solar system. There were, however, two drawbacks: (1) it was hard to explain physically (for example, why don't we notice that the earth is moving?) and (2) although elegant, it didn't predict the future position of the planets any better than Ptolemy's system.

Tycho Brahe (1546 – 1601)

Tycho was born into a noble Danish family and was educated to be a lawyer and diplomat. He had a rather rowdy youth, and at one point his nose was cut off during a duel over a women. Throughout the rest of his life he wore an assortment of artificial noses, one of gold.

Although his family expected him to have a standard career in the government, he became interested in astronomy at an early age. The event that permanently oriented him toward an astronomical career was the appearance in 1572 of a “new star” or ***nova*** in the constellation of Cassiopeia.

The philosophy of the day, directly descended from Aristotle, held that the heavens were perfect and unchanging. Any apparent changes had to be local phenomena occurring in the atmosphere. This was the explanation commonly used for comets. Many months of observation on the “new star”, however, convinced Tycho that it had to be a celestial phenomenon, largely because no parallax could be detected. That is, it appeared to remain located in exactly the same spot on the celestial sphere when observed from any location on earth.

The well - connected Tycho was able to acquire an island in off the Danish coast and build an observatory to chart the heavens with unprecedented accuracy. Although he designed and built many precision astronomical instruments, none incorporated the telescope or other optics – all observations were ultimately made with the unaided eye. Thus, Tycho is often designated the “***last great naked eye astronomer***”. His star maps and the data on planetary positions were of such accuracy that Johannes Kepler was able to deduce that planetary orbits must be elliptical, rather than perfect circles, as had been assumed by both Ptolemy and Copernicus.

Johannes Kepler (1571 - 1630)

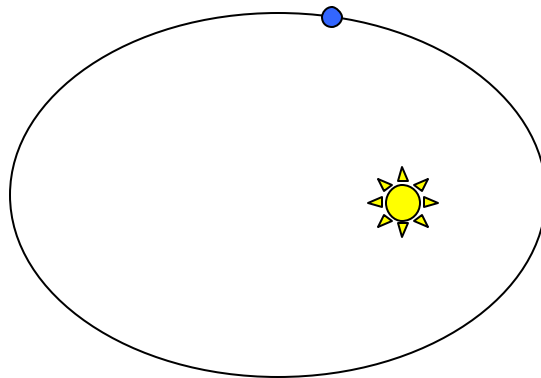
With respect to social status and personality, Johannes Kepler was as far from Tycho Brahe as is possible to imagine. Whereas Tycho was a wealthy aristocrat with vast resources and had a voracious appetite for life's pleasures, Kepler was born into abject poverty and practiced a strict and pious form of Protestantism. Yet Kepler and Tycho ultimately collaborated to sweep away the ancient concept of perfectly circular motion in the heavens and to replace it with planets moving in elliptical orbits.

Kepler developed a fascination with the sky and its movements as a student of mathematics in Tübingen, Germany and became a convert to Copernicus' new heliocentric system. He was determined to show how the Copernican system could lead to more accurate predictions than Ptolemy's.

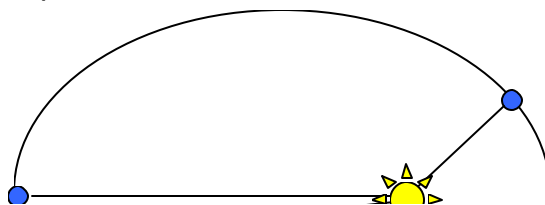
Kepler began working with Tycho in 1600 to take advantage of the fact that Tycho had the most accurate planetary position data available anywhere. Using this data, he began trying to fit the orbit of Mars into a curve that could be used to predict positions of that planet in the future as well as to specify its position in the past. Tycho died in 1601, but Kepler stayed with Tycho's organization and was ultimately successful in demonstrating that planets must move in elliptical orbits. With that innovation, Copernicus' heliocentric model was much better at prediction than Ptolemy's and the number of scholars who believed in a sun-centered universe began to rise.

Kepler was able to formulate three laws of motion that describes how planets move about the sun.

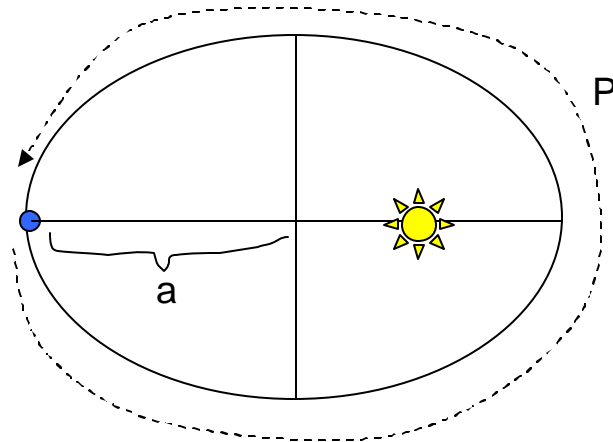
Kepler's Three Laws of Motion



1. Planets move around the sun in elliptical orbits. The sun is at one of the foci of the ellipse.



2. Planets move faster when they are near the sun than when they are at a large distance from the sun. However, the area defined by two positions of the planet and the sun is always the same if the two points are separated by the same amount of time.



3. The **square** of the period **P** is equal to the **cube** of **a**, the average distance between the planet and the sun (a.k.a., the semi-major axis).

$$P^2 = a^3$$



Galileo Galilei

A Brief Biography

Galileo Galilei is widely considered to be the "father" of modern science, and, hence, of the world we know today. He was the first experimental physicist in the modern sense, and his work was the foundation on which Isaac Newton would, in the following generation, build the science of mechanics. However, Galileo achieved his greatest fame (and notoriety) for a series of sensational discoveries with the newly invented telescope. These discoveries include craters on the moon, spots on the sun, the phases of Venus, stars invisible to the naked eye and the moons of Jupiter. More than any one man, Galileo was responsible for the replacement of Ptolemy's geocentric (Earth centered) universe with the heliocentric (Sun centered) universe of Copernicus.

Galileo was born in 1564 in **Pisa**, Tuscany. His early schooling was in nearby Florence, but he returned to Pisa to attend the university there. He later became a professor of mathematics at that same institution and began the study of bodies in motion. His studies led him to conclude that physics of Aristotle, then still accepted as authoritative throughout Europe, was seriously flawed. Legend has it that he disproved Aristotle's assertion that heavy bodies fall faster than light bodies by dropping two unequal weights off the leaning tower of Pisa.

Galileo was an ambitious man, so, much like scholars today, he sought to enhance his position by seeking employment at a more prestigious university. This led him to **Padua**, then under the control of Venice, and home of the second oldest institution of higher learning in Italy. The University of Padua (nicknamed *Ill Bo*, "the Ox", from a nearby tavern) could boast of several illustrious alumni, in particular the poet Dante, who's *Divine Comedy* summarized the medieval view of the world (Earth in the center, hell below and heaven above) and the astronomer Copernicus, who had sent the Earth spinning around the Sun some 50 years before Galileo's time. Galileo became a professor at the university in 1592 and remained there until 1610. His stay at Padua was momentous, because it was here that he became convinced that Copernicus was right about the Earth moving around the Sun and set out to find evidence to support this view. He was helped tremendously in this project when he heard about the invention in Holland of a device which made distant objects appear nearer. We, of course, call this device a *telescope*, and Galileo immediately set out to make one for himself. Galileo did not just duplicate the telescopes that were then available in northern Europe, he improved their performance. His best early telescope had a magnifying power of about 30 times, and

with this he was able to make his celebrated discoveries of craters on the moon, the phases of Venus, Sunspots, and, perhaps the greatest of all, the moons of Jupiter.

On weekends Galileo went down to **Venice** to relax with friends, especially Gianfrancesco Sagredo, a wealthy nobleman who had a palace (Palazzo Sagredo) on the Grand Canal and who shared Galileo's scientific enthusiasms. It was here that he met a woman named Marina Gamba with whom he established a long term relationship. This liaison eventually resulted in three children. (Galileo was particularly close to his eldest daughter and maintained a life long literary correspondence with her, some of which survives to this day.) Sagredo was well connected to the rulers of the Venetian state, and having friends in high places gave Galileo an opportunity to impress people who were in a position to further his career. He demonstrated his telescope from the top of the Campanile (bell tower) in Piazza San Marco and showed how it could be used as an early warning system to determine whether a distant approaching ship was "friend or foe". The Venetian power brokers liked what they saw and offered Galileo permanent employment in Venice.

This was all well and good, but Galileo's real ambition was to return to **Florence** as a full professor of philosophy, both because of Florence's preeminence in Renaissance culture (hence, carrying more prestige) and because it was in his native Tuscany, near his daughter who was by that time a nun in the convent of *San Matteo*. Today Venice and Tuscany are part of a united Italy, but then they were separate states. During this period Tuscany was ruled by the powerful Medici family who had final say on all professional appointments in their territory. Galileo's strategy to get back to Florence involved using the offer from Venice to pad his resume and buttering up the Medici by naming the newly discovered moons of Jupiter in their honor. Thus the moons of Jupiter were christened the *Medician Stars*. Conveniently, there were four powerful Medici brothers to match the four moons, but no one outside of Tuscany ever thought much of these names, and they were quickly discarded in the rest of Europe in favor of the classical *Io, Ganeymede, Europa, and Collisto*. However, it was a good move for Galileo, as he was welcomed to Florence with open arms, honors and a permanent position as mathematician and philosopher to the Medici court.

Galileo set up housekeeping in the Villa dell'Ombrellino, a mansion in the fashionable Bellosguardo district of Florence. Here he continued his studies on motion and his astronomical observations. This was perhaps the most productive period of his life and he wrote a number of books announcing new discoveries and stating his clear belief in the truth of the heliocentric system proposed by Copernicus. This view was not well received by either the academic or religious establishments and concerted attacks Galileo and his beliefs were launched from all directions. The first public challenge was delivered in a sermon by father by Father Tommaso Caccini on December 21, 1614 at the church of *Santa Maria Novella*. Father Caccini began with a reading from the New Testament "*Ye men of Galilee why stand ye gazing into the heavens?*", and then proceeded to denounce the heliocentric system and all those who supported it. From then on, for the next 17 years, Galileo was on the defensive, playing a "cat and mouse" game with the authorities, sometimes seeming to pretend that he really thought of the

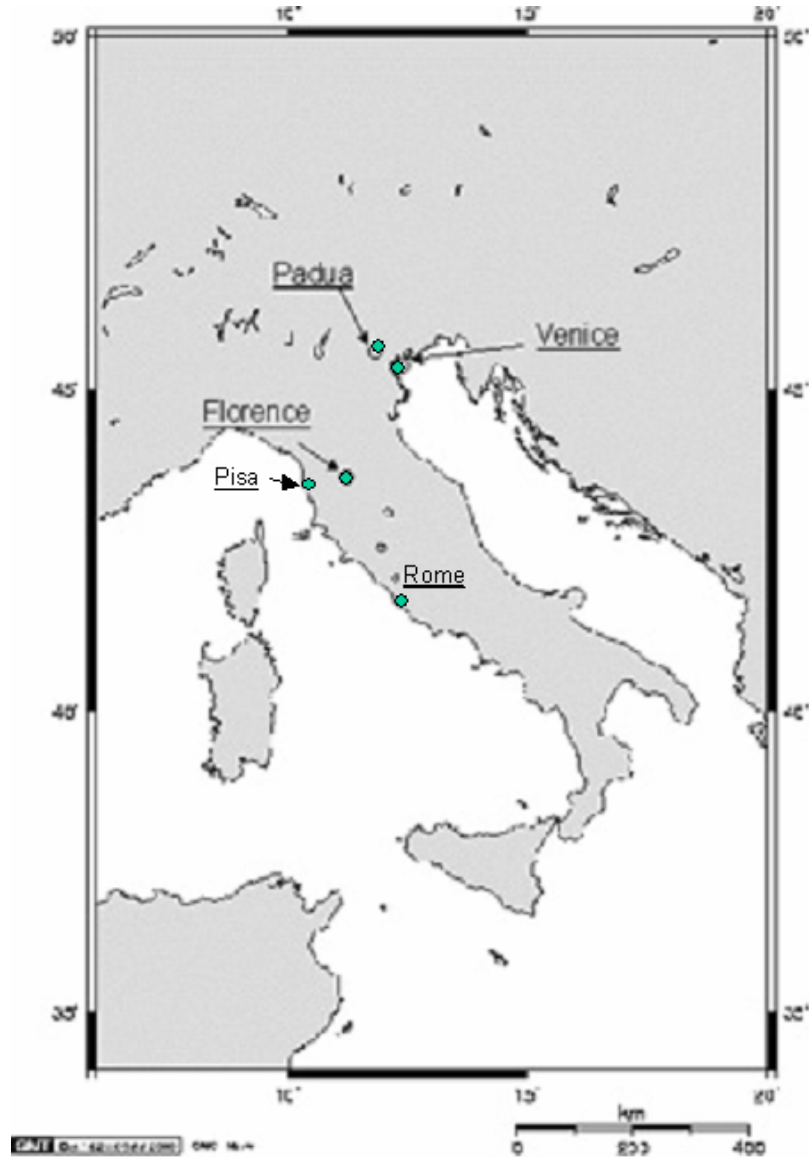
heliocentric system only as an interesting mathematical hypothesis, while at other times strongly implying that Copernicus' model was the only true way to view the world.

Galileo's problems with the Catholic Church is a complicated subject. Briefly, he was forbidden by the Pope to publish anything stating that Copernicus' system was a proven fact. However, he was still allowed to discuss the heliocentric idea in print as long as it was clearly stated that the system was no more than an unproven hypothesis. In 1632, while still at the Villa dell'Ombrellino he wrote *Dialogue on the Two Chief World Systems*, a book that he hoped would satisfy the demands of ecclesiastical establishment while at the same time presenting rigorous arguments in favor of Copernicus. Instead, the book proved to be his undoing. Although Galileo maintained that his *Dialogue* was an even handed presentation of both geocentric and heliocentric systems, it was clear that the sympathies of the author was overwhelmingly with the new heliocentric view of the world. The church authorities felt that Galileo had violated the Pope's injunction and, therefore, had to be punished. Galileo was summoned to **Rome**, put on trial and found guilty. He was sentenced to live under house arrest for the rest of his life and was forbidden to teach, write or otherwise discuss the Copernican system or any other matter pertaining to cosmology.

Galileo spent the last ten years of his life at the villa il Giorello in **Arcetri**, a suburb of Florence in the hills overlooking the city. As this house was a only a short distance from his daughter's convent, one small modification to his terms of confinement was that he was allowed take the short walk to San Matteo to visit her. Galileo visited her often until her death in April of 1634. Although he was not allowed to discuss cosmology, in his final years he was able to publish what many consider his most important scientific work, *Discourse on Two New Sciences*, which laid the foundation for the science of mechanics.

Galileo died on January 8, 1642 and was buried in Franciscan church of *Santa Croce* in Florence. His original tomb was in a small room in the *Novices' Chapel*, but in 1737 after the cosmological controversy of the previous century had faded, Galileo's admirers were able to persuade the authorities to allow his body to be relocated into the main basilica in a place of honor. Here they erected an elaborate mausoleum facing that of another of Florence's famous sons, Michelangelo. Despite this concession, Galileo's official rehabilitation by the church took much longer. The *Dialogue* remained on the index of forbidden books until 1835 and it was not until 1992 that Pope John Paul II fully exonerated him, acknowledging "mistakes were made" by the ecclesiastical authorities in handling the issue back in 1633.

Galileo's Italy



Galileo Galilei (1564 – 1642)

Highlights of his life:

- **(1564 – 1589)** Born and educated in Pisa, Italy
- **(1589)** Becomes Professor of mathematics at the University of Pisa. Here he begins investigations into the properties of gravity.
- **(1592)** Becomes professor of mathematics at the University of Padua (near Venice). Here he became a convert to the Copernican solar system and began a correspondence with Johannes Kepler.
- **(1609)** Becomes aware of the telescope invented by Hans Lipperhey in Holland and begins to make his own. After some experimentation he increases the magnification of the telescope to about 20 X and begins astronomical observations. He shows the moon and Jupiter to skeptical philosophers at Padua. Some of them insist that the images seen in the telescope are due to imperfections in the instrument.
- **(1610)** Publishes *Sidereus Nuncius (The Starry Messenger)*. Here he describes his observations of the surface of the moon and the moons of Jupiter. The book becomes a sensation and others begin making their own telescopes.
- **(1613)** Publishes *Letters on Sunspots* where, in addition to sunspots, he describes the phases of Venus. The phases observed are explainable only if Venus revolves around the sun. The accumulation of these observations lead Galileo to assert that the Copernican system is true physically, not just a neat way of calculating planetary positions. This begins to be controversial within some circles of academe and the church.
- **(1614)** Galileo and the Copernican system denounced from the pulpit of Santa Maria Novella church in Florence
- **(1615)** Cardinal Robert Bellarmine urges Galileo to describe the Copernican system as nothing more than an unproven hypothesis.
- **(1616)** Copernicus' book is banned by the Holy Office. Galileo is again warned again not to defend Copernicus as *fact*.
- **(1632)** Galileo publishes *Dialogue on the Two Chief World Systems* where three philosophers discuss the merits of Ptolemy and Copernicus. Although ostensibly equal weight is given to both sides, it is clear that the book favors Copernicus. Pope Urban VIII considers this a direct affront to the church's prohibition and orders Galileo to Rome.
- **(1633)** Galileo put on trial and his *Dialogue* banned. He is put under house arrest in Florence for the rest of his life and forbidden to publish anything about the solar system ever again.
- **(1633 – 1642)** Galileo spends rest of his life in a house located in the Florence suburb of Arcetri. He summarizes his early work in mechanics in a book entitled *Discourse on Two New Sciences*.
- **(1642)** Galileo dies.

Galileo's Greatest Hits

1. The surface of the moon
 - a. A rough surface, having the appearance of a landscape seen from above.
 - b. Demonstrated that the moon is a "world" like the earth
 - c. Contradicted the Aristotelian assumption that objects in the heavens were perfect spheres
2. Spots on the sun
 - a. Demonstrated that the sun was rotating
 - b. Again, contradicted Aristotle's idea that the sun was an unblemished sphere
3. The Milky Way resolved into stars
 - a. Implied that the universe was three dimensional, since the new stars discovered by the telescope must be more distant than the stars bright enough to be seen with the naked eye.
 - b. This implied that the crystalline spheres of Aristotle did not exist
 - c. Gave weight to the idea that the reason that no parallax is seen is because the stars are much farther away than hitherto believed.
4. Planets were disks in the telescope
 - a. The planets looked something like the moon in a telescope.
 - b. Since the moon in the telescope appeared to be a world like the earth, this implied that the planets were also worlds.
5. Saturn appeared to be oblong or to have "ears". This was something Galileo could not explain, foreshadowing discoveries to come of objects in the heavens hitherto unknown.
6. The phases of Venus
 - a. Venus went through a full set of phases from *full* to *new*, just like the moon.
 - b. This implied that Venus is orbiting the sun and is, thus, is sometimes between the sun and the earth and sometimes on the opposite of the sun from the earth. In Ptolemy's system Venus was always between the earth and the sun and could never show the *full* phase.
7. The moons of Jupiter
 - a. Jupiter was revealed to have four "stars" which revolved around the planet in a systematic manner. Galileo called them *satellites*, a term that originally referred to patrons of aristocrats.
 - b. The fact that anything was moving around an object other than the earth directly contradicted Aristotle's physics.
 - c. Here was a solar system in miniature, just as described by Copernicus and Kepler.

