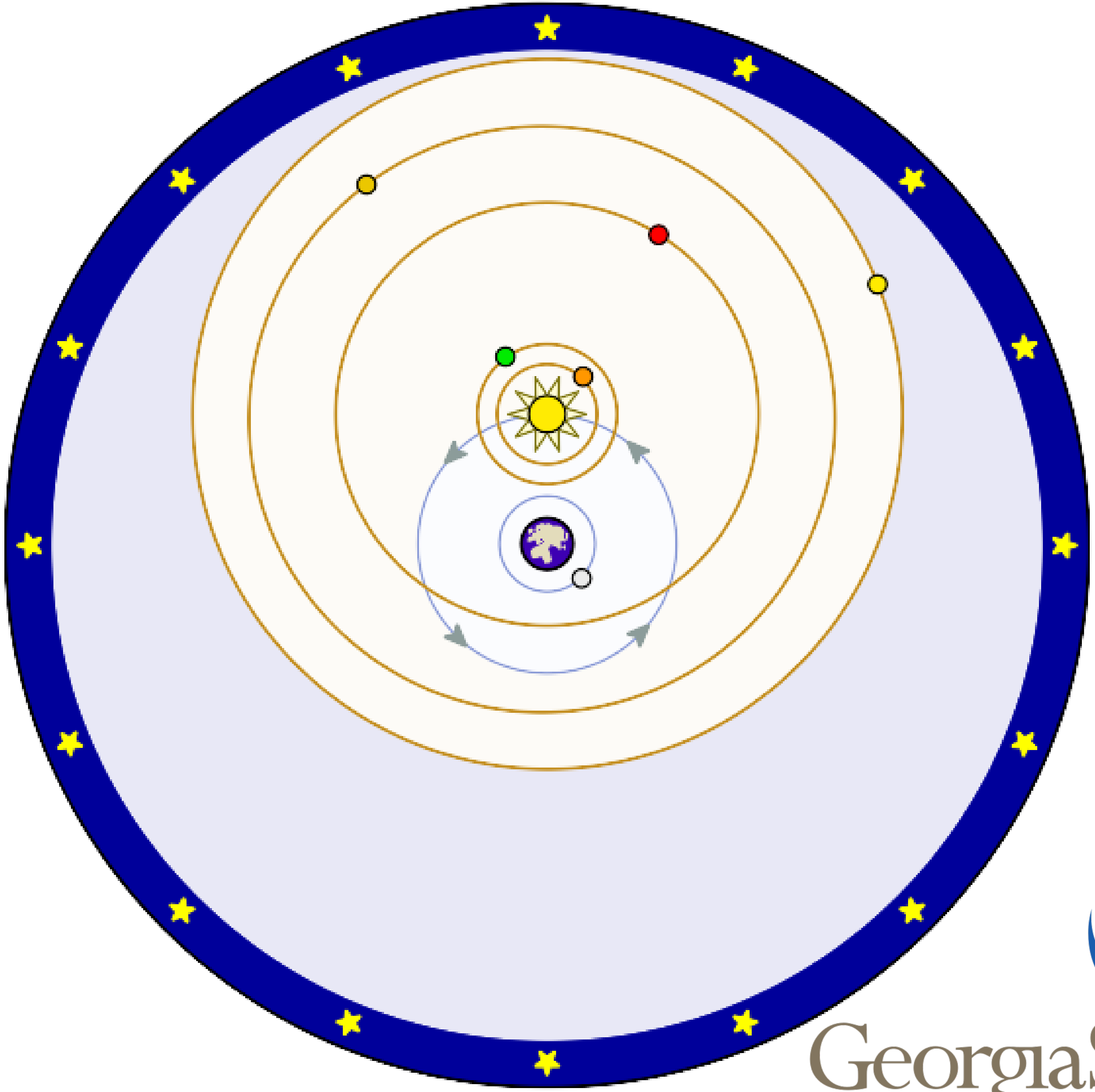
Orbits and Gravity

DR. JANE PRATT



Outline

1) Galileo and the study of falling bodies.

2) Newton and ideas about gravitation.

3) Early observations and theories: the path toward understanding orbiting planets, stars, and comets.

4) What does an orbit look like? Ellipses and conical sections!

5) The combination of Newton’s work and Kepler's laws apply to any two bodies, explaining how they orbit each other.

Gravity: constant acceleration on Earth

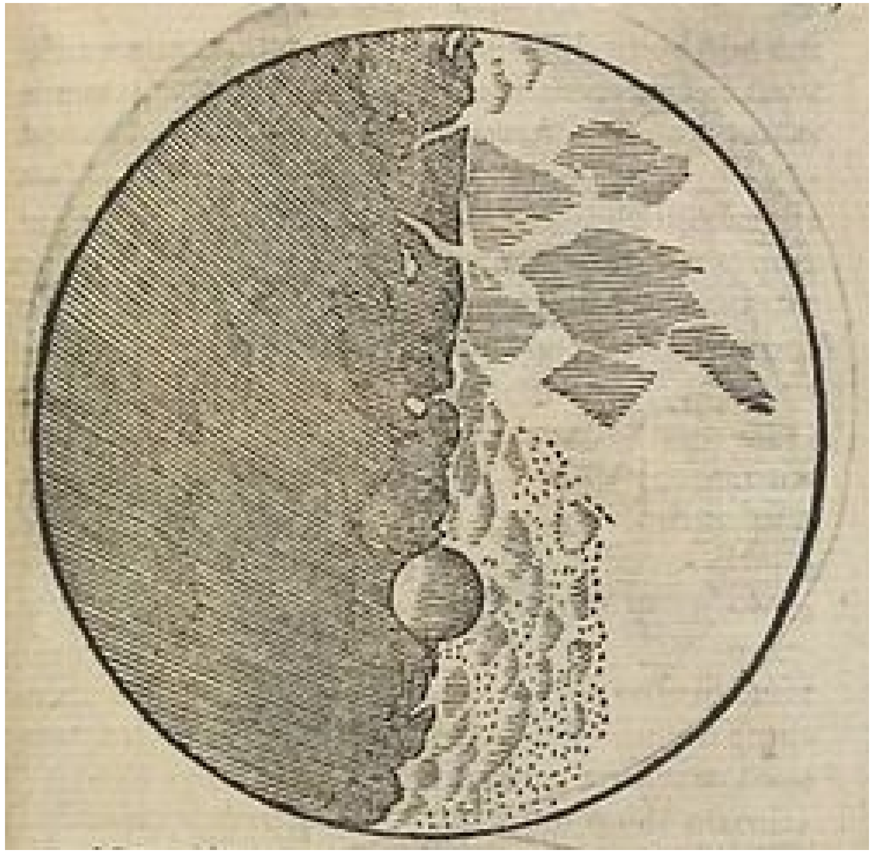


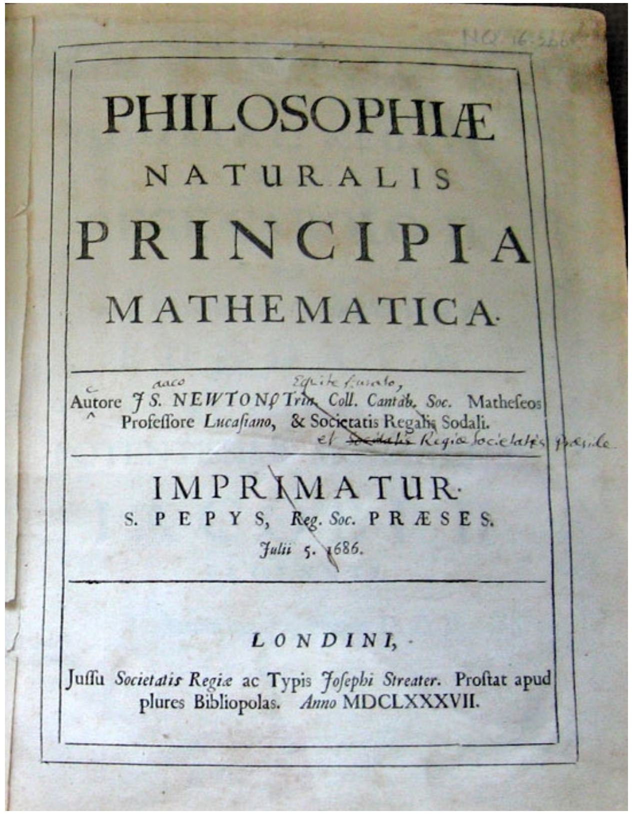
Illustration of the moon by Galileo, published in 1610 in “In Palthenius” (credit: wikipedia)

- Galileo di Vincenzo Bonaiuti de' Galilei (1564 -1642) performed fundamental research on motion (in addition to astronomy!)
- He explored the rate of falling bodies by dropping different weights, or sliding them down inclined planes.
- <u>Law of Falling Bodies:</u> In the absence of air, heavy objects and light objects fall at the same, constant rate of acceleration.

Isaac Newton (1643–1727)

- Isaac Newton was in his early 20s when the Great Plague hit in 1665. At the time he was a student studying at Trinity College, Cambridge University. The university closed and he was sent home for almost 2 years. This time away from university and professors allowed him to produce some of his best work.
- Newton's work on the laws of motion, gravity, optics, and mathematics laid the basis for many later discoveries in physics.
- In <u>"Principia"</u>, Newton compiled several basic ideas about how gravity functions:

1) Gravity is an attractive force that draws objects closer together.
2) Gravity operates everywhere in the universe.
3) Gravity works between pairs of objects, as long as they have mass.



PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.

S. PEPYS, Reg. Soc. PRÆSES.

Julii 5. 1686.

LONDINI,

Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Front page of Newton's Principia, published in 1687 (credit: wikipedia)

Law of Gravity

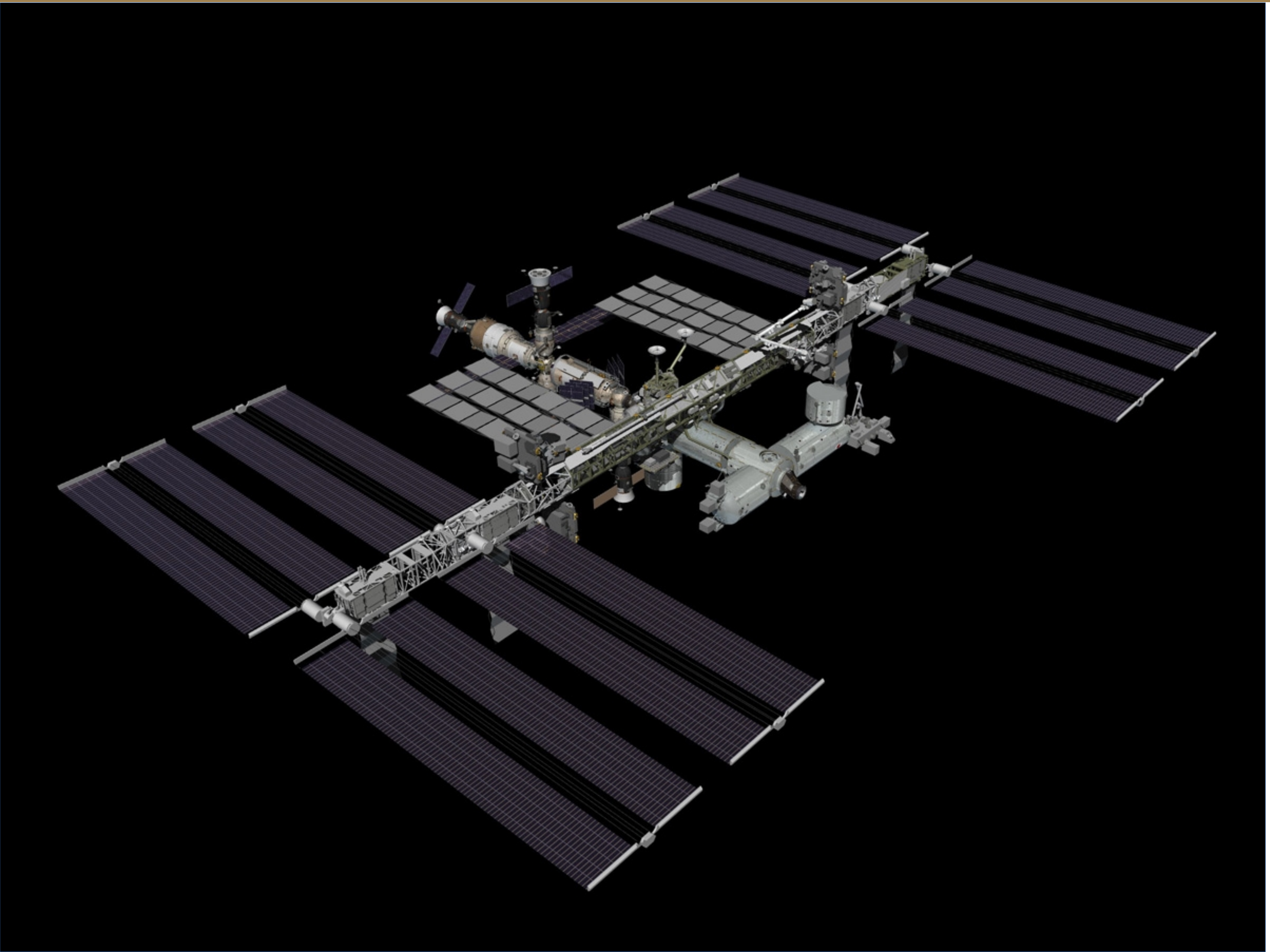
While in space, astronauts are falling freely just like in Galileo's experiments, so they experience weightlessness. (credit: NASA, via Openstax Astronomy)

The law of gravitation is that every object in the universe attracts every other object with a force which for any two bodies is (1) proportional to the mass of each object and (2) varies inversely as the square of the distance between them.

An object responds to a force by accelerating in the direction of the force by an amount that is inversely proportional to the mass of the object.

As we will see, the orbital motions of stars, planets, and other objects result from gravitational forces.

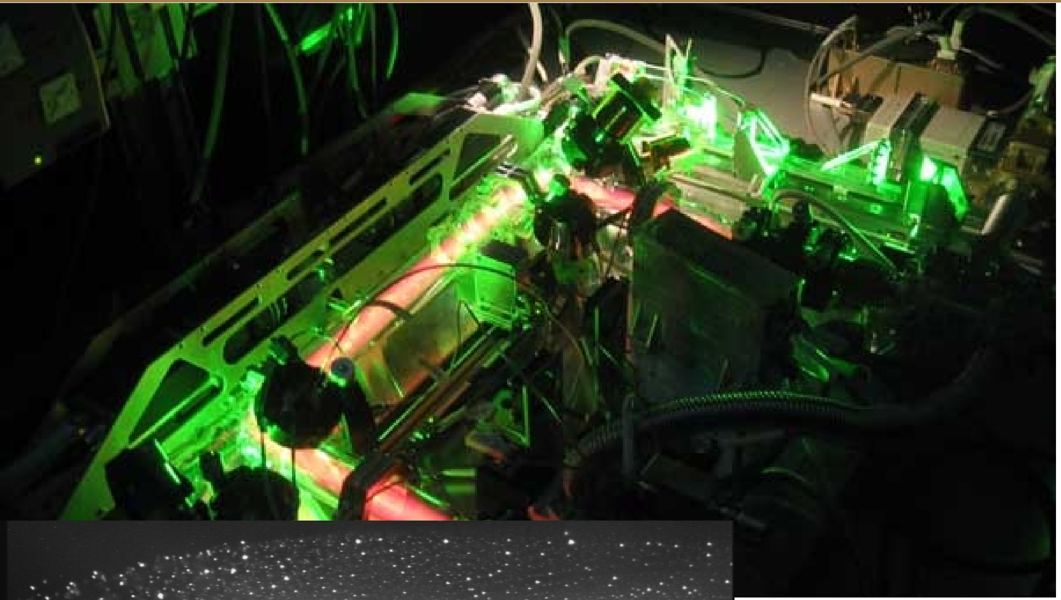
International Space Station

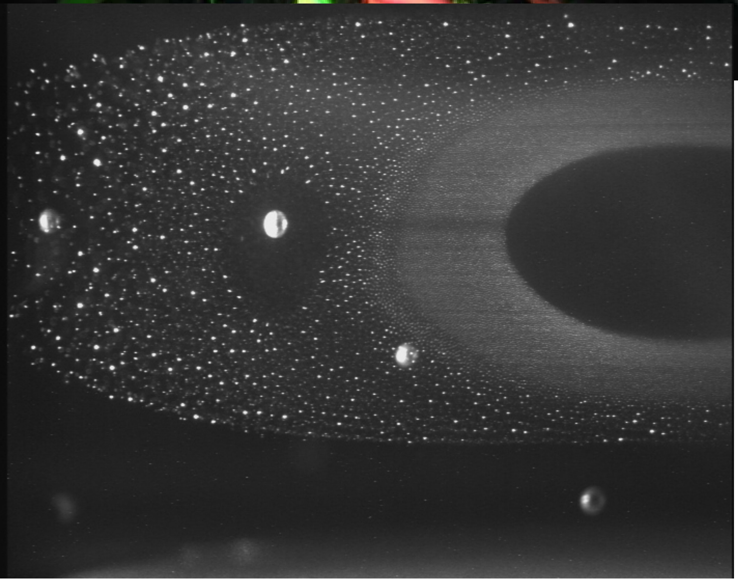


Credit NASA/JPL

- The international space station (ISS) is on average 254 mi above the surface of the Earth, in *low-Earth orbit*.
- It orbits Earth roughly every 96 minutes, completing 15 orbits in a day.
- Five countries participate in the ISS: Russia, Japan, Europe, Canada, and the US.
- The station serves as a research laboratory where *microgravity* and space environment can be studied.

Gravity, Microgravity, and experiments on the ISS





(Above) a neon tube in the PK-4 experiment. (Left) large and small particles interacting in the PK-3 experiment.. Image Credit MPE.

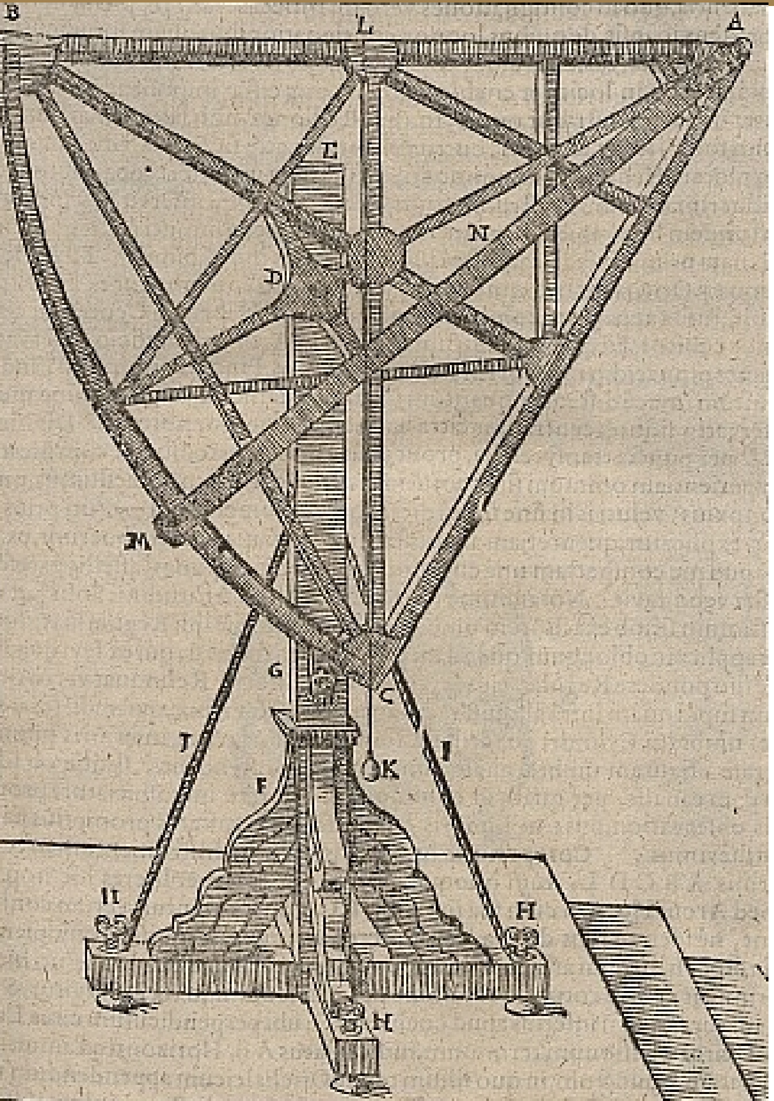
- Microgravity is described as “weightlessness” or “free fall”. It is the very weak gravity, that is experienced in an orbiting spacecraft.

- One of the experiments on the ISS is the plasma crystal experiment, and several generations of this experiment have been conducted there (PK-3, PK-4).

- This is an experiment on complex or “dusty” plasmas. Plasmas, ionized gasses, make up 99% of the visible matter of the universe.

- The microgravity allows scientists to see how particles spread out, and explore melting, crystallization, and how shock waves move through material: fundamental science about matter.

Tycho Brahe (1546–1601)

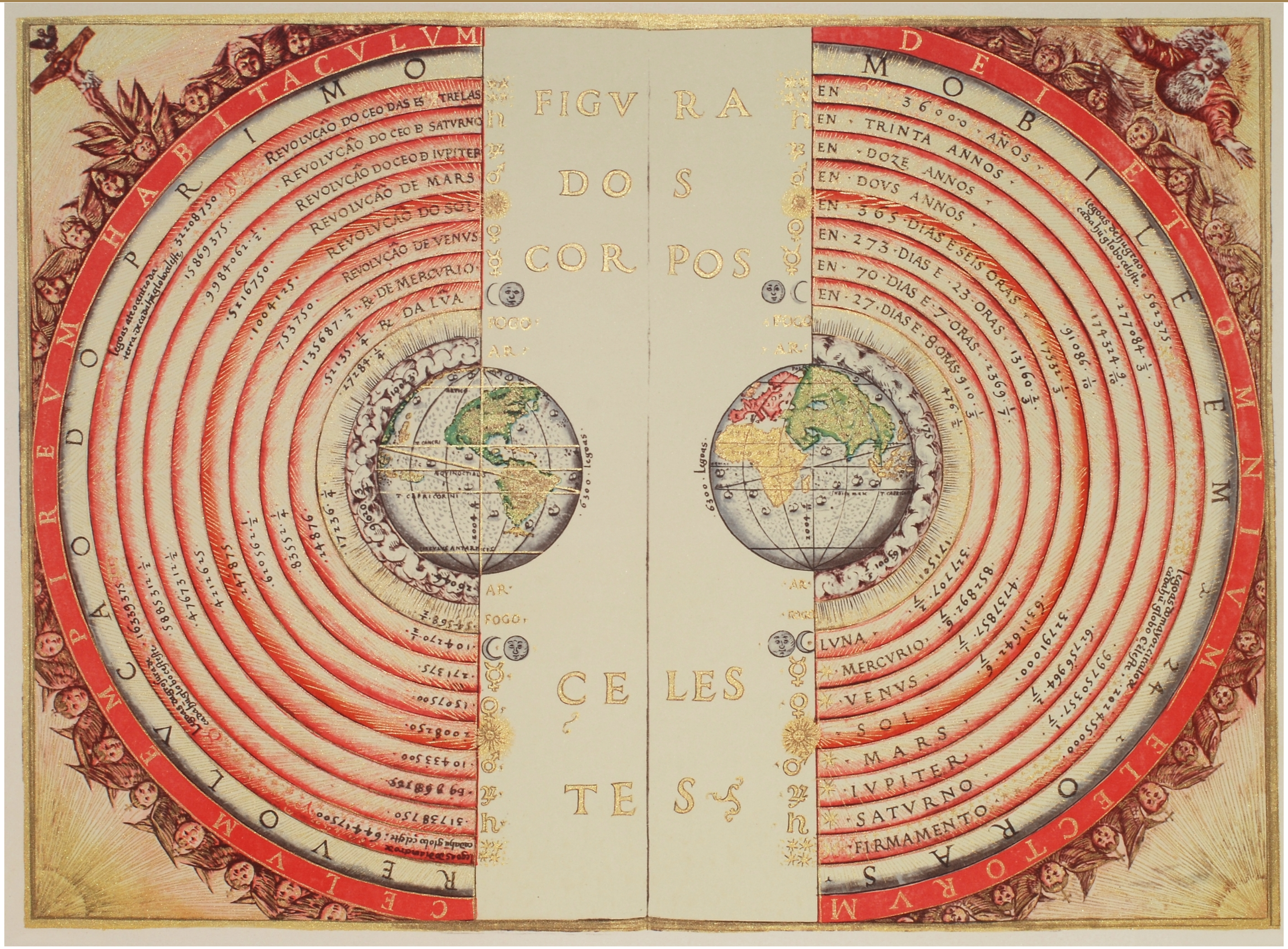


Drawing of a large sextant used by Tycho Brahe from the Deutsche FotothekAstronomie & Messinstrument

- Tycho Brahe was a wealthy Danish nobleman interested in astronomy.
- He was one of the last astronomers to observe the sky without a telescope. He did use other instruments, such as the sextant pictured here.
- A sextant allows one to measure the angular distance between two objects in the sky. Brahe was known for making precise angular measurements.
- He built an observatory and alchemy laboratory named Uraniborg on the island of Hven (Sweden).
- When he was 20, he had his nose sliced off in a duel over a drunken argument. He then wore a false nose, reputedly made of gold, and held in place by glue.
- He reputedly died of a burst bladder just after a feast in Prague.

Early ideas about orbits

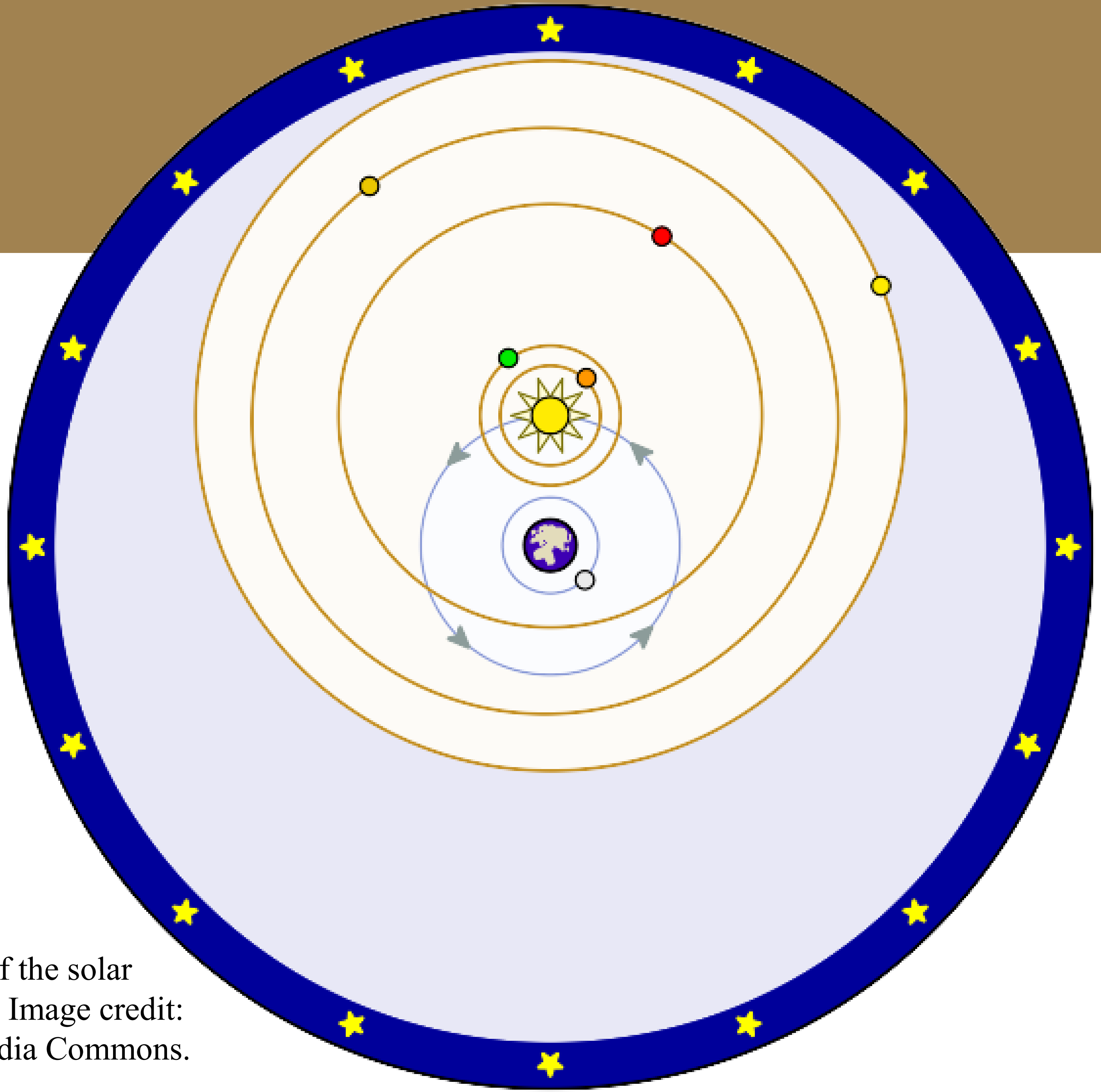
Early Greek astronomers believed the Earth to be at the center of the universe, with the Sun, planets and stars moving in circular orbits around the Earth.



An illustration of the Ptolemaic geocentric system by Portuguese cosmographer and cartographer Bartolomeu Velho, 1568. Source: wikipedia.

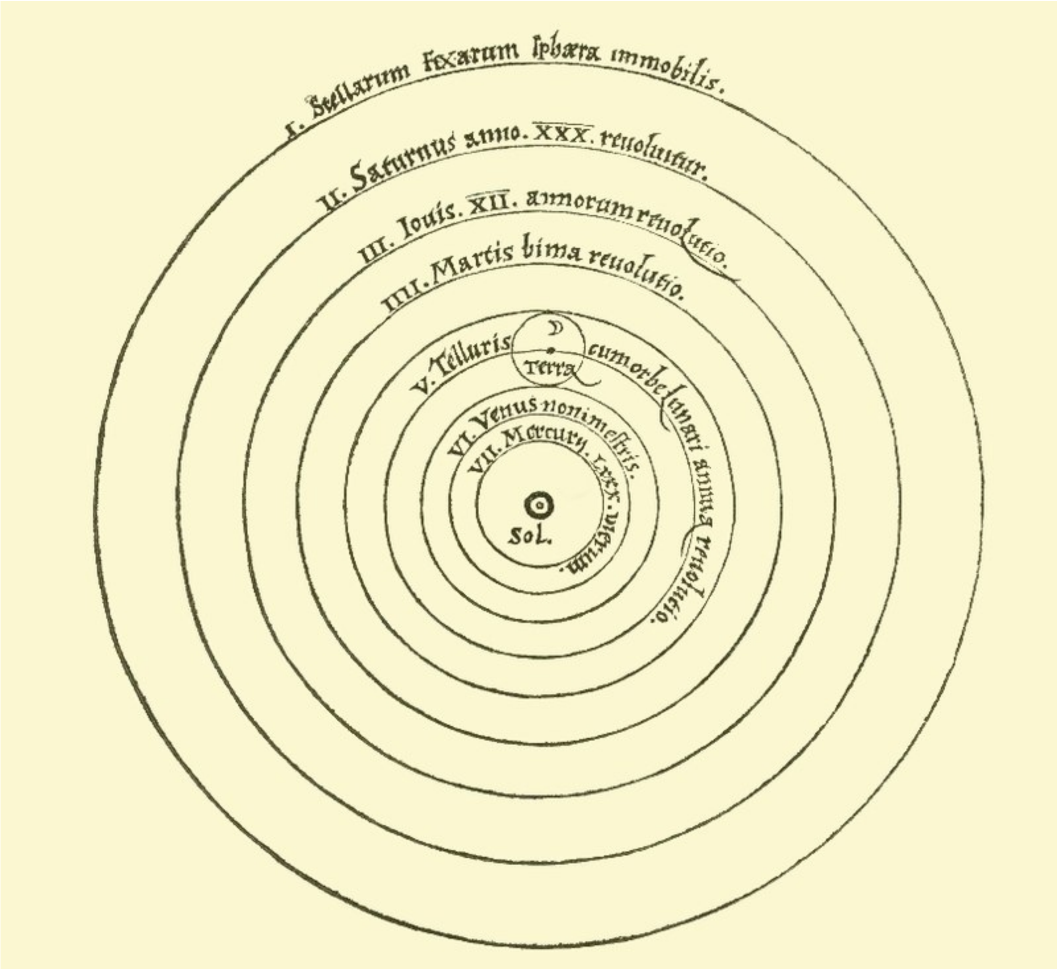
Early ideas about orbits

In Tycho Brahe’s model of the universe, both the sun and moon orbited the Earth with a circular orbit. Other planets orbited the Sun.



Brahe’s model of the solar system. Image credit: Wikimedia Commons.

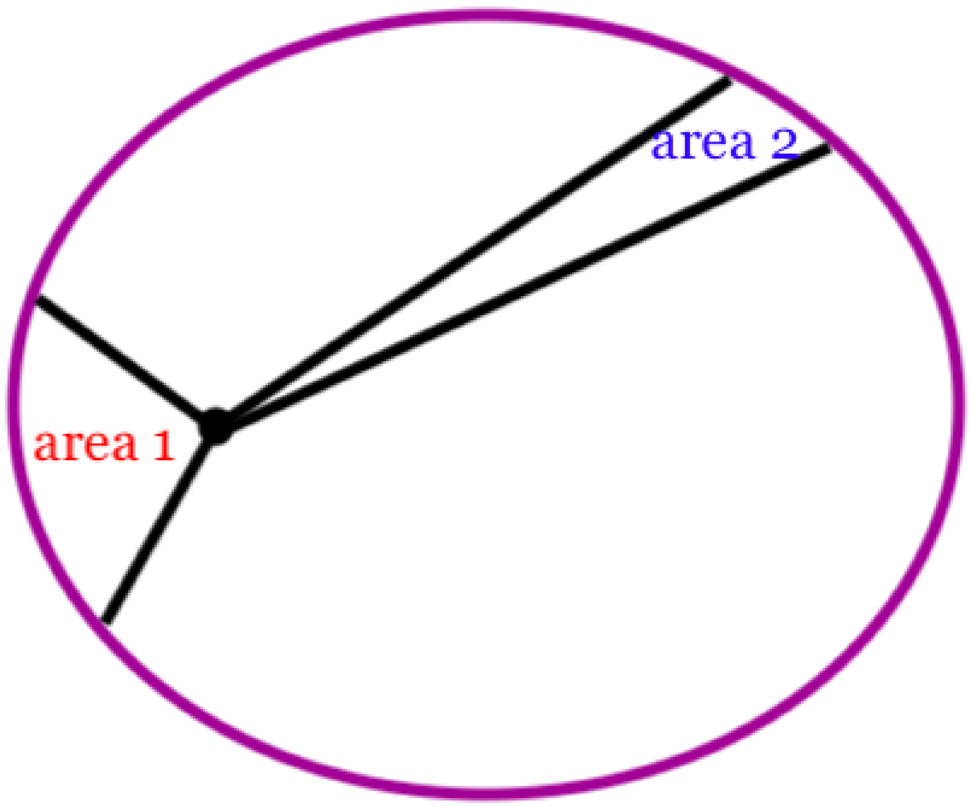
The heliocentric model



Copernicus' heliocentric model of the solar system. Image credit: Wikimedia Commons.

- Nicolaus Copernicus (1473 – 1543) placed the Sun rather than Earth at the center of the universe.
- Johannes Kepler (1571–1630) was a German mathematician and astronomer, and a student of Tycho Brahe.
- Kepler's discovery of the basic physical laws that describe planetary motion established the heliocentric model of Copernicus (and not that of Brahe).

Elliptical Orbits



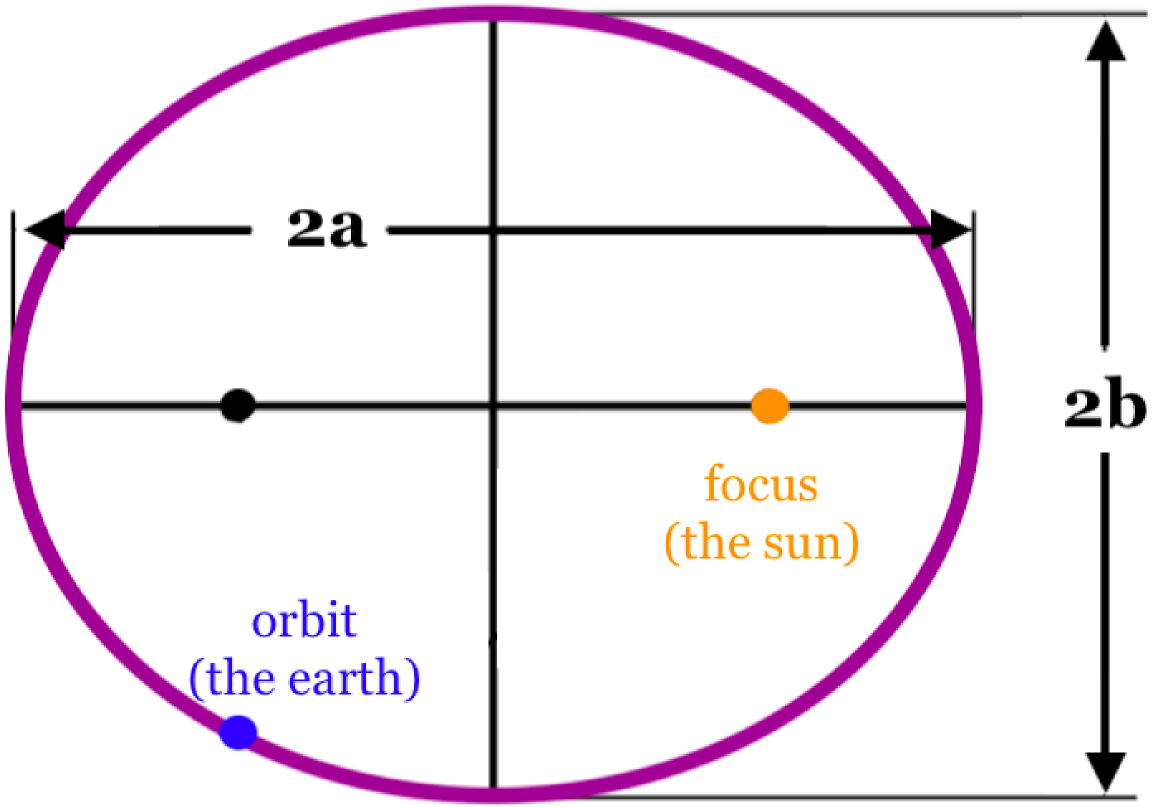
- Kepler noticed that the planets do not go around the sun at a uniform speed, but move across the sky faster when they are nearer the sun and more slowly when they are farther from the sun (see angular momentum in your reading assignment).

- Imagine a planet is observed two different times, say a week apart, and that a radius is drawn to the planet for each observed position.

- If two similar observations are made a week apart, at a part of the orbit farther from the sun (where the planet moves more slowly), the similarly bounded area is exactly the same as in the first case. So the orbital speed of each planet is such that the radius “sweeps out” equal areas in equal times.

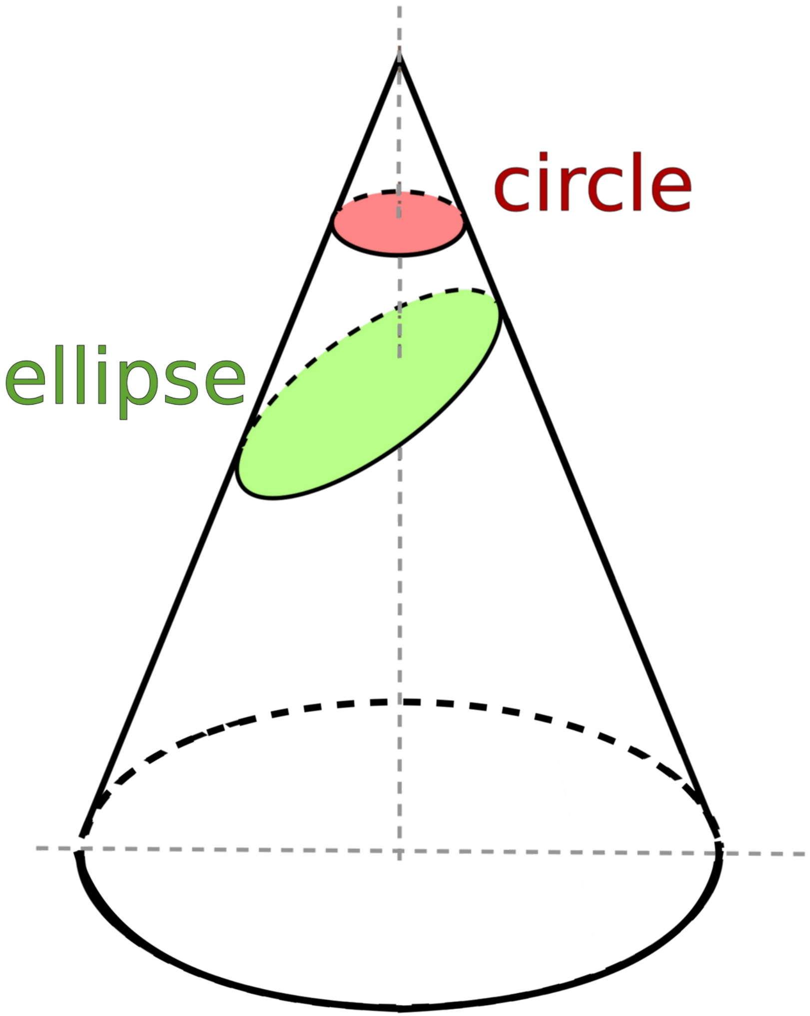
- The orbital motion follows the shape of an ellipse.

Defining elliptical orbits



- Kepler found that each planet goes around the sun in a curve called an ellipse, with the sun at a focus of the ellipse.
- An ellipse is not just an oval. It can be produced by pushing two tacks (each tack is a focus) into a piece of paper, and then looping a string around the tacks. Stretch the string tight using a pencil, and then move the pencil around the tacks. The length of the string remains the same, so that the sum of the distances from any point on the ellipse to the foci is always constant.
- The distance 2*a* is called the major axis of the ellipse. “a” is the semi-major axis. The distance 2b is the minor axis of the ellipse.

Circles vs. Ellipses



- A circle and an ellipse are each formed by the intersection of a different plane with a cone. This is why these curves are both called conic sections.

- Elliptical orbits can turn into circles over time.

Planetary Motion

- Before Galileo, one of the theories for why the planets moved in orbits was that there were invisible angels, beating their wings and driving the planets forward.

- Galileo discovered the principle of inertia. This principle can be summarized: if something is moving it will keep moving forever unless something is touching it to stop or change its motion.

- Newton added to this the idea that a force is required to change the speed or the direction of a body in motion. If a ball is attached to a string and is whirling around in a circle, it takes a force to keep it in the circle. That force comes from pulling on the string.

- The force needed to control the motion of a planet around the sun is not a force-field around the sun but the force of gravity pulling it toward the sun.

Summary of Physical Laws

- Kepler’s three laws are:

1) Each planet moves around the sun in an ellipse, with the sun at one focus.
2) The radius vector from the sun to the planet sweeps out equal areas in equal intervals of time.
3) The squares of the periods of any two planets are proportional to the cubes of the semi-major axes of their respective orbits.

- Newton’s three laws are:

1) Every object will continue to be in a state of rest or move at a constant speed in a straight line unless it is compelled to change by an outside force.
2) The change of motion of a body is proportional to and in the direction of the force acting on it.
3) For every action there is an equal and opposite reaction.

Newton showed that Kepler's Laws can be derived from his Laws!

The missing pieces: discovering a planet

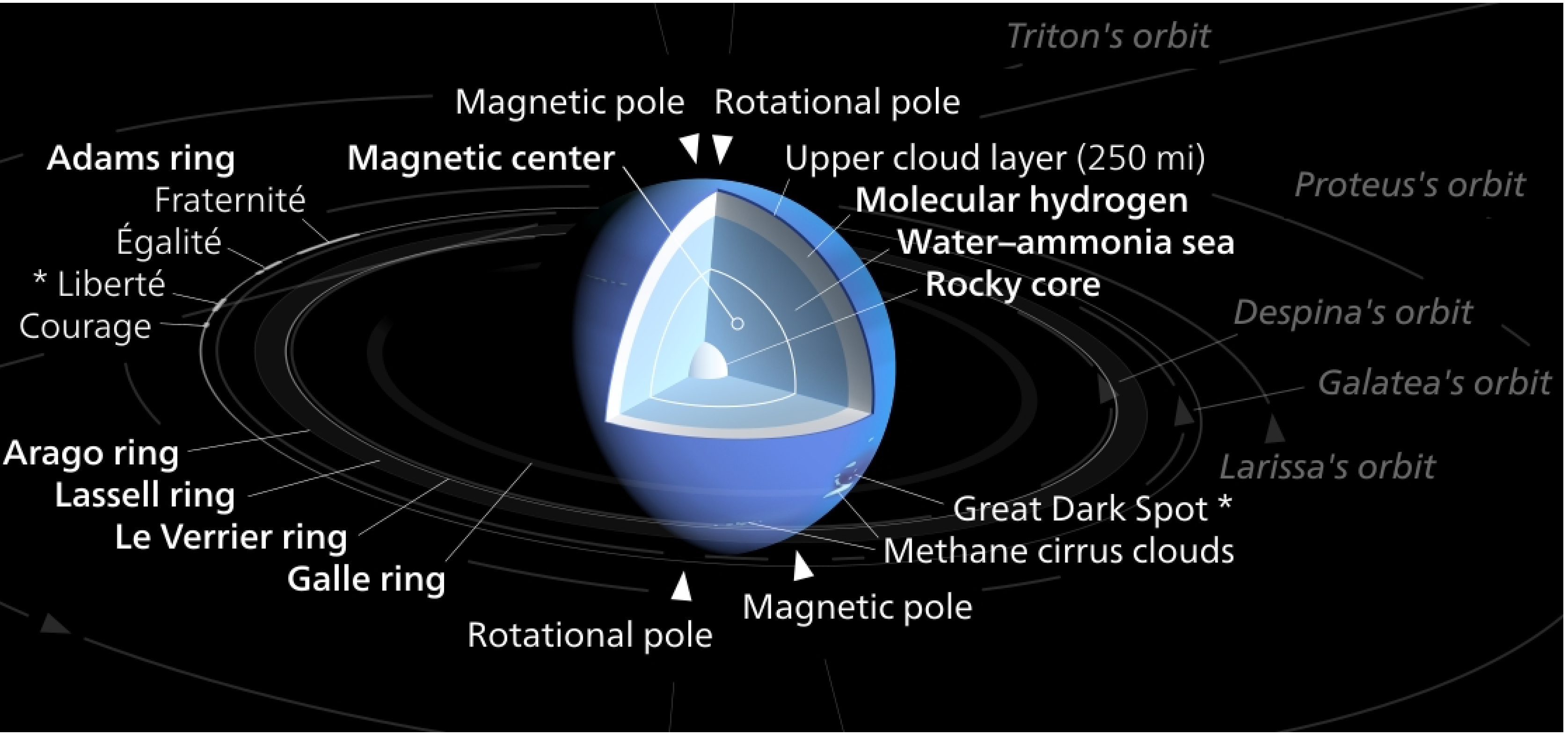


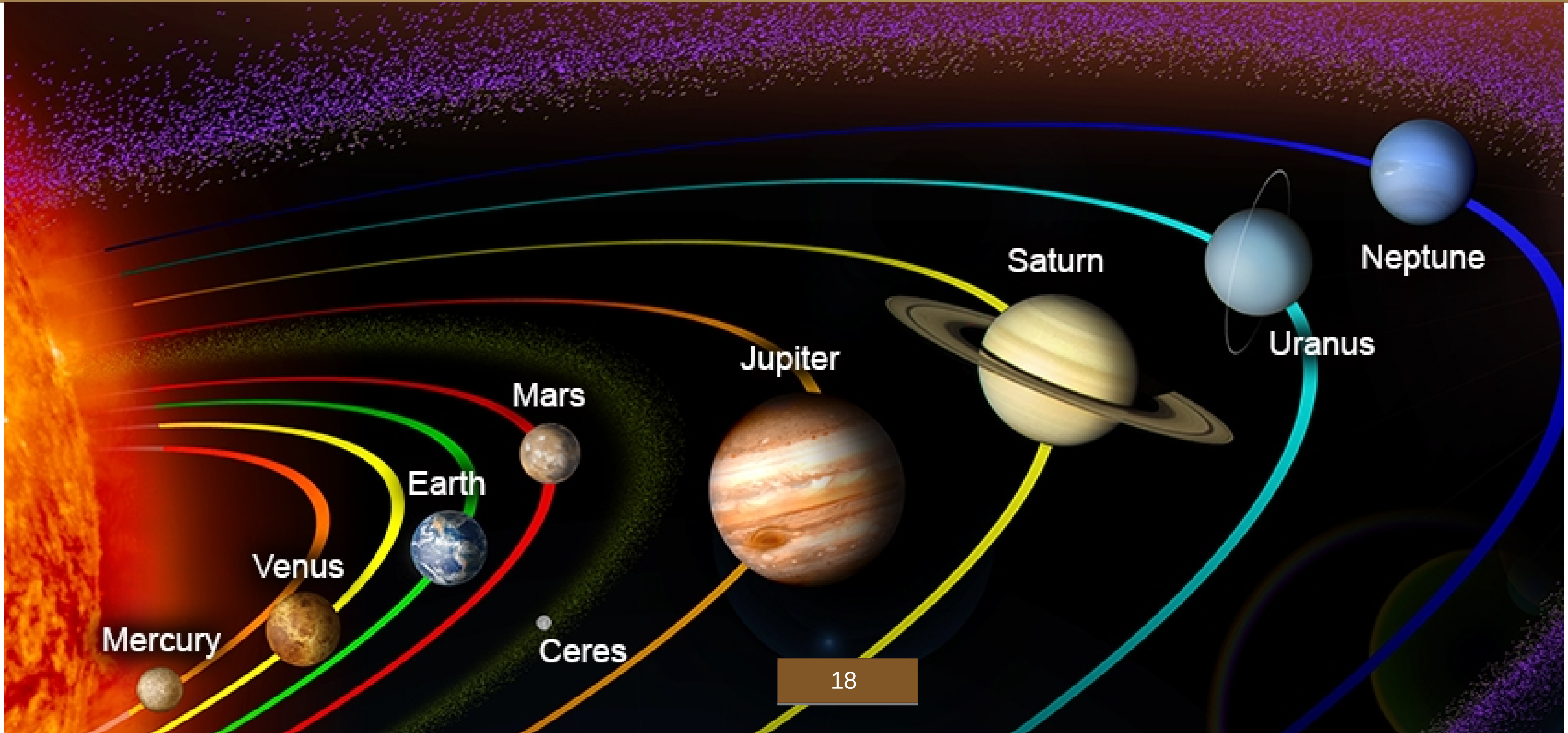
Diagram of Neptune and its moons. Credit wikipedia.

At the same time, but unknown to each other, John Couch Adams (1819–1892) and Urbain J. J. Le Verrier (1811–1877) theoretically calculated the existence and position of Neptune.

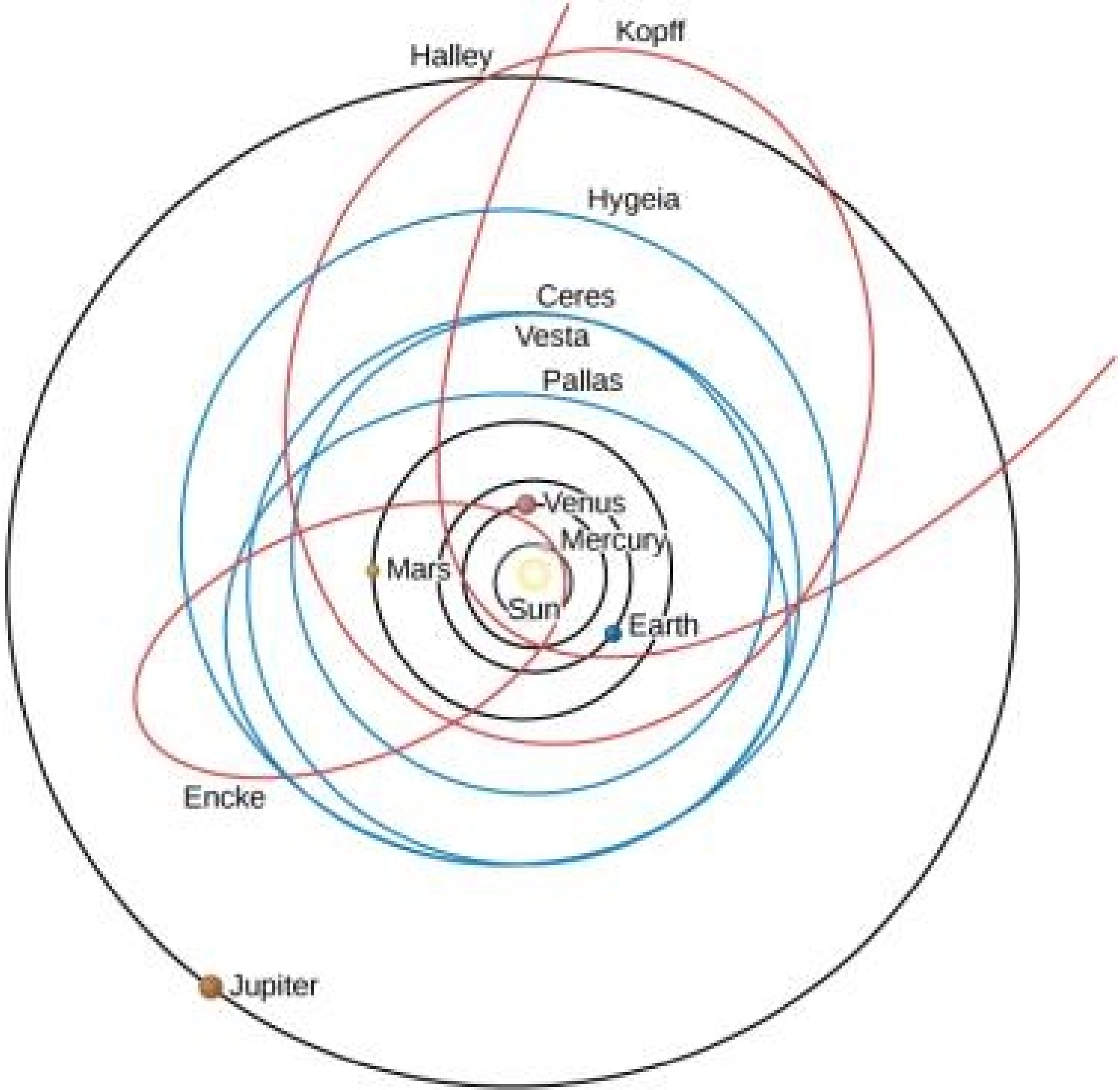
The existence of Neptune explained discrepancies with Uranus's orbit and reconciled the works of Kepler and Newton.

Neptune has 14 moons orbiting it.

Planetary orbits in the solar system

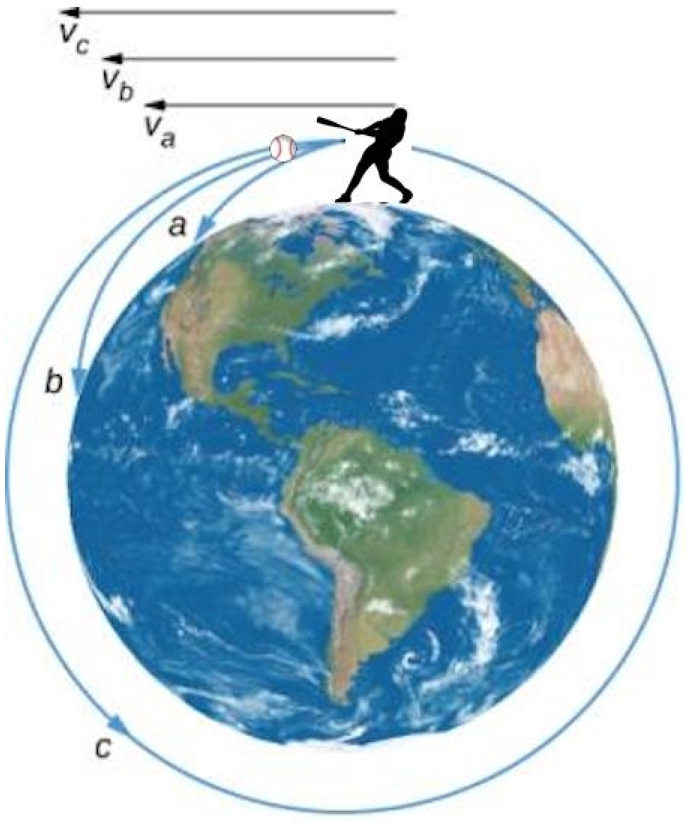


Other objects that orbit in the solar system

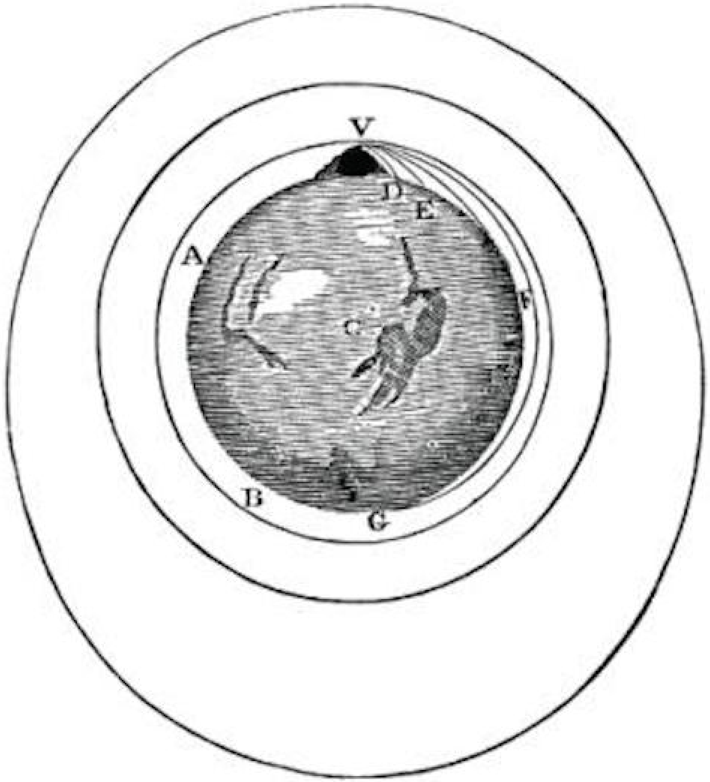


- Black lines: orbits of the planets Mercury, Venus, Earth, Mars, and Jupiter.
- Red lines: Halley's comet, Kopff's comet, and Encke's comet.
- Blue lines: the four largest asteroids -- Ceres, Pallas, Vesta, and Hygeia.
- Notice that some orbits are a lot more elliptical than others!

Hitting a baseball into orbit



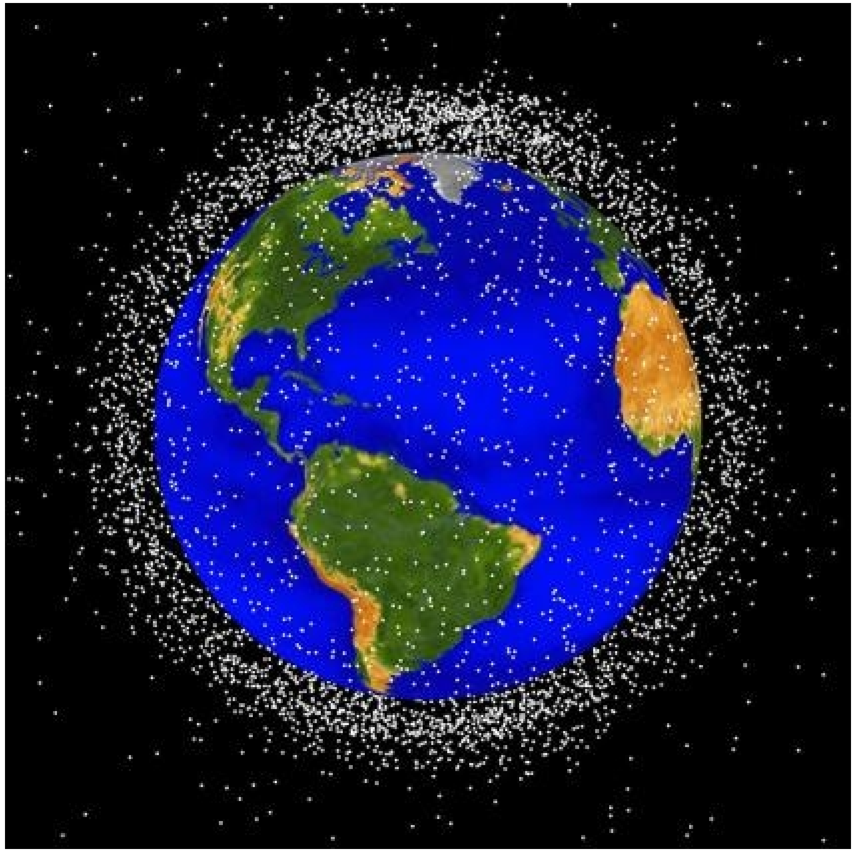
(a)



(b)

- For paths *a* and *b*, the velocity is not enough to prevent gravity from pulling the baseball back to Earth; in case *c*, the velocity allows the baseball to fall completely around Earth, i.e. to move into orbit.
- The diagram in (b) was drawn by Newton in his *De Mundi Systemate* published in 1731. It illustrates the same concept as the cartoon in (a).
- The same ideas apply to launching rocket ships into orbit.

Satellites in Earth’s Orbit



credit:
NASA/JSC

- Mary large pieces of debris (or space trash) in Earth’s orbit are tracked by NASA.

- In the last few years, SpaceX has started deploying thousands of satellites for its “Starlink” program. These satellites will all be in low-earth orbit, and their use will be sold for profit.

- Astronomers have complained that the Starlink satellites interfere with readings from telescopes. The number of satellites will outnumber the visible stars in the sky.

Supercomputing and Astronomy

Image credit: NASA

- NASA has an Advanced Supercomputing Division. Large computations are necessary to follow many objects in their orbital motions (among many other computational projects at NASA). These problems are called *many-body problems*.
- The Pleiades supercomputer at NASA (left) is capable of tracking the motions of more than a million objects under their mutual gravitation.
- Pleiades consists of 11,207 nodes, each with approximately 28 processors. Compare that to a "quad-core" desktop with 4 processors!

Orbits and gravity