Part 1: The Sky; History of Astronomy; How Science Works

- Tuesday, January 17 — Reading: Chapters 1 & 2.1, Appendix A
  - Introduction, syllabus, class rules; units, scales,
  - rotation of the Earth, time zones, constellations; tour – where we go in the course
- Thursday, January 19 — Reading: Chapters 2, 3 — HW 1 assigned
  - The sky: Rotation of Earth, seasons, phases, eclipses
- Tuesday, January 24 — Reading: Chapter 4-1, 4-2, 4-3
  - History of Astronomy: Greeks, Copernicus, Tycho, Kepler
- Thursday, January 26 — Reading: Chapter 4-4, 4-5
  - History of Astronomy: Galileo, Newton
- Tuesday, January 31 — Reading: "Windows on science" sections or "How do we know?" sections in Chapters 1, 2, 3, 4
  - How science works
- Thursday, February 2 — Reading: Chapter 5 — HW 1 due
  - The nature of light, telescopes, spectra
- Monday, February 6 — Help session from 4 — 6 PM in RLM 4.102
- Tuesday, February 7 — Exam 1

Lectures 3 and 4 Reading

For today and next class: Please read Chapter 4.

Key Points to Understand:

- 2 — 3 sentence outline of each person’s contributions
- Very rough idea of dates (± 50 years)
- Development of the modern scientific method
  - How it happened
  - What it means

You do not need to know detailed dates and personal histories!

The Origin of Modern Astronomy
is
The Origin of Modern Science

Ancient Astronomy

Aristotle

Ptolemy

Evidence that the Earth is round

Eratosthenes: Size of the Earth

Aristarchus: Size and distance of the Moon

Origin of Modern Astronomy

Copernicus

Tycho

Kepler

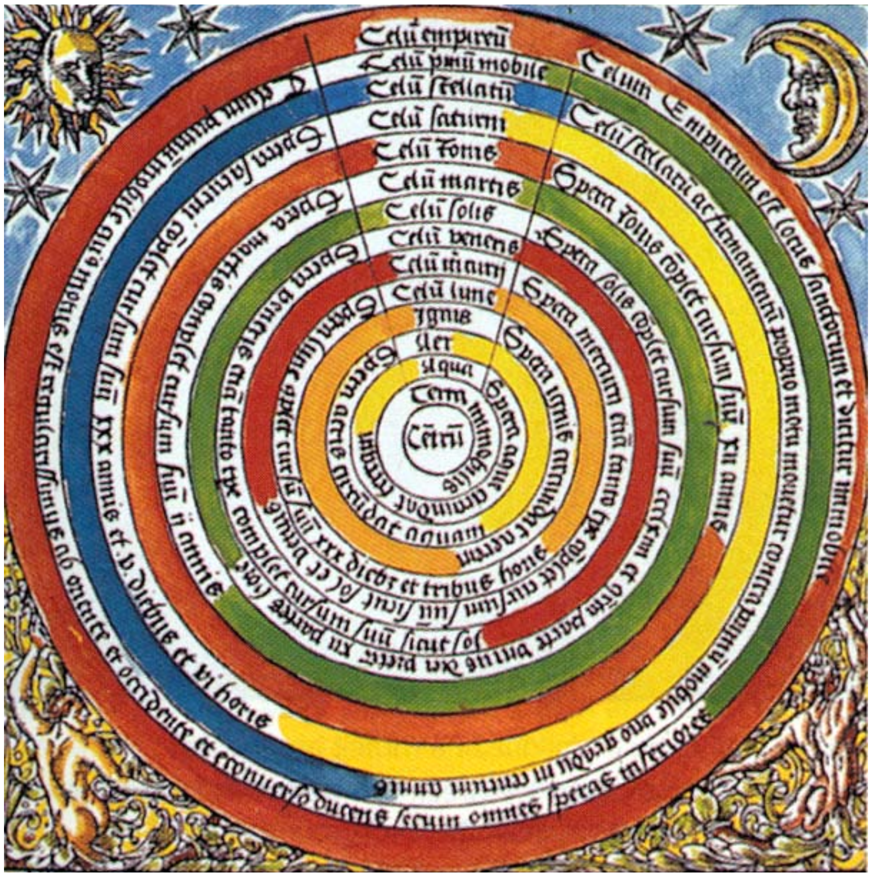
Galileo

Newton

Ancient Astronomy

- The ideas of Greek philosophers dominated astronomy for over 1500 years. **The scientific method had not been invented yet.** Most ideas were based only slightly on observations of the world; instead, they were mostly based on pure thought. This is almost guaranteed to get you in trouble:
- Plato and Aristotle (384 — 322 BC):
  - The heavens are perfect and unchanging.
  - Earth is at the center of the Universe and the planets and stars are carried by crystalline spheres that rotate around the Earth.
- Ptolemy (active around 140 AD):
  - Devised a model to explain why planets sometimes move backward in the sky: proposed that planets move around small circles (epicycles) which themselves move around larger circles (deferent) centered (not quite) on the Earth.
  - This allowed fairly accurate descriptions and predictions of planetary motions.

Aristotle's Universe



According to Aristotle, Earth is motionless ("Terra immobilis") at the center of the universe. Earth is surrounded by spheres of water, air, and fire ("ignus"), above which lie spheres carrying the celestial bodies beginning with the moon ("lune") in the lowest celestial sphere.

This woodcut is from Cornipolitanus's book Chronographia of 1537.

From the Granger collection
New York

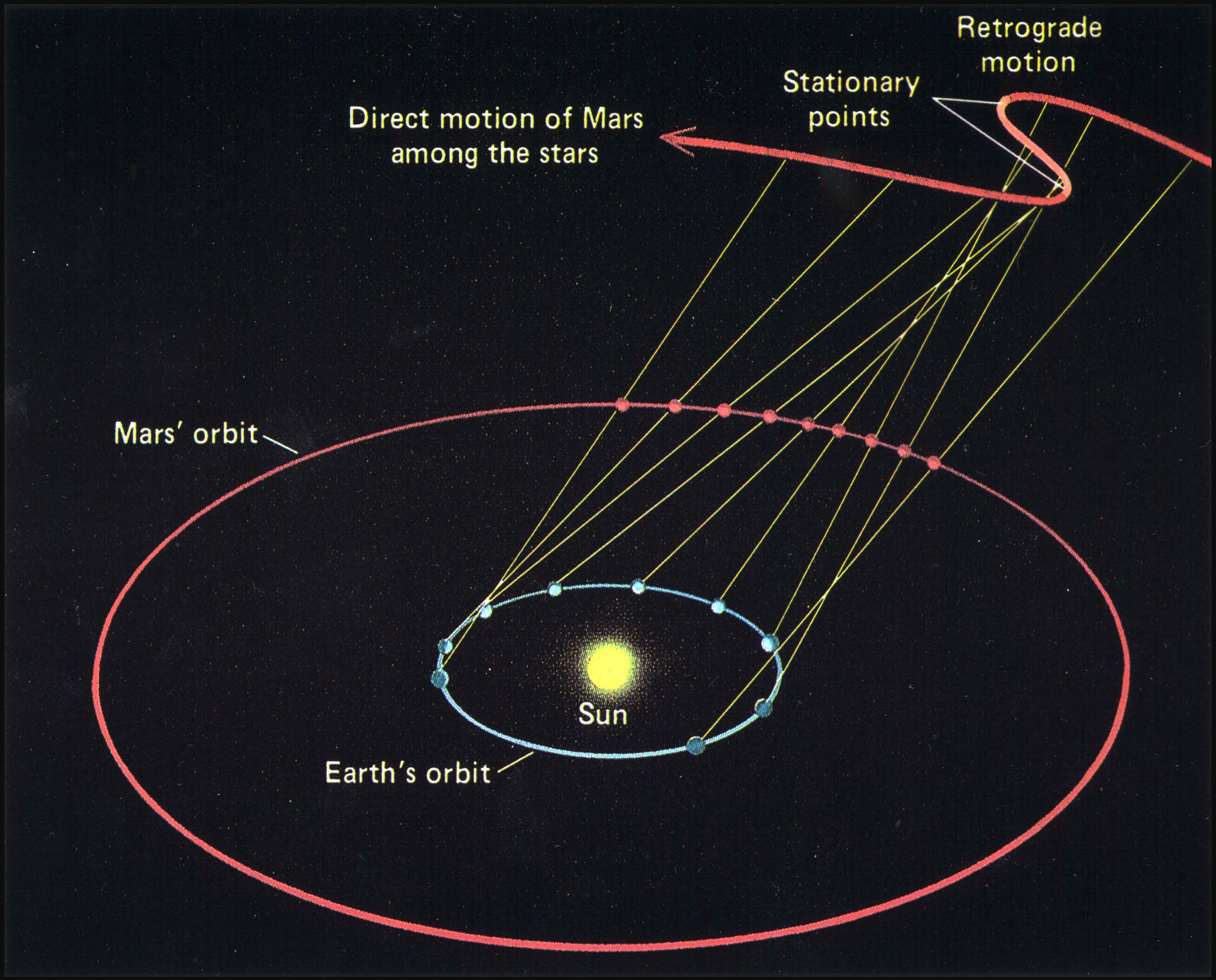
Parallax

Left Eye

Right Eye

Aristotle's followers argued that Earth could not move because they saw no **parallax** in the positions of the stars.

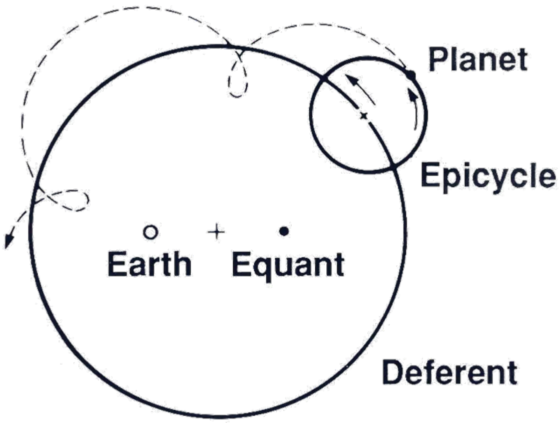
Retrograde Motion



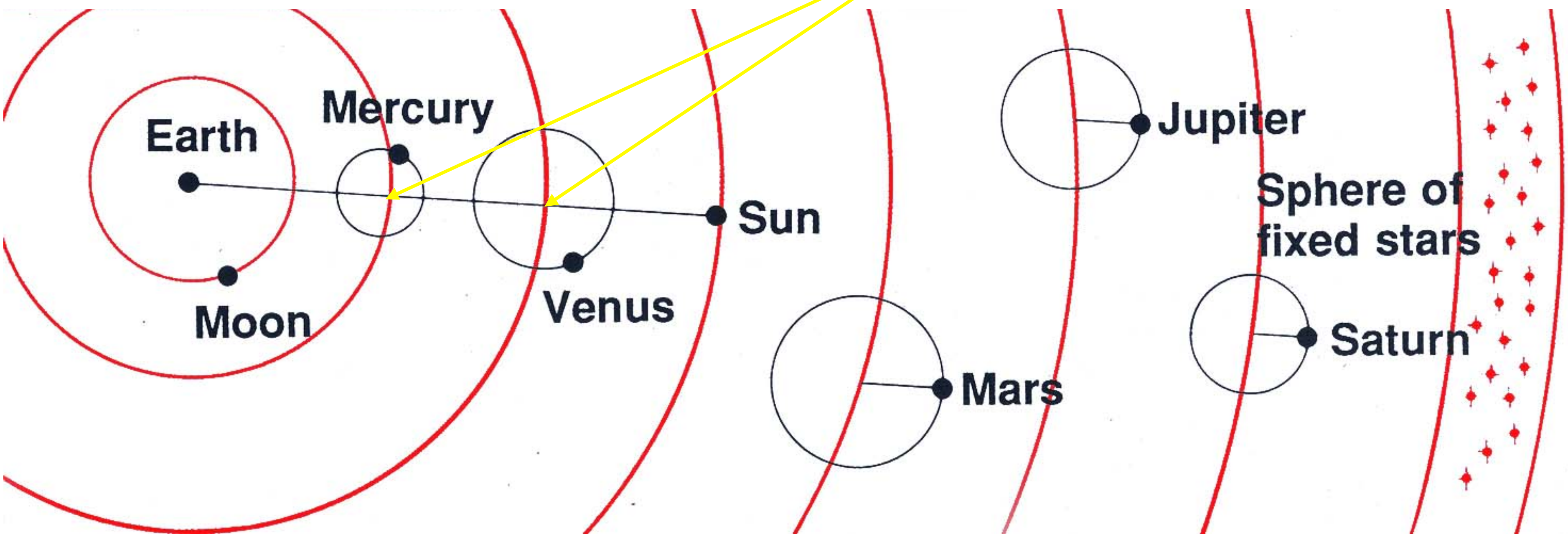
There is a link to a demo of retrograde motion on the class web site.

There is now also a mini-lecture on retrograde motion on the class web site.

The Ptolemaic System



The centers of the epicycles of Mercury and Venus must always lie on the Earth-Sun line.

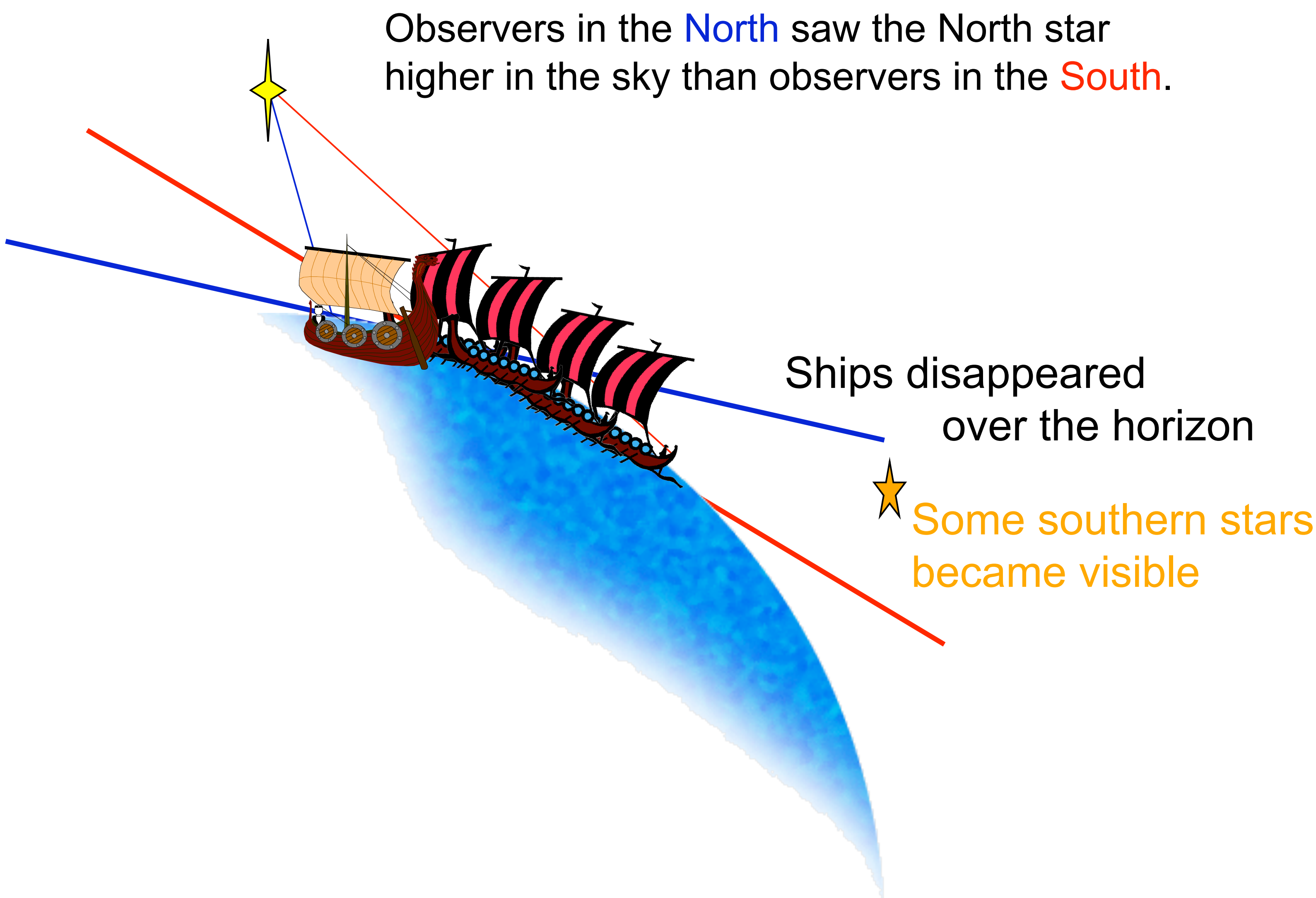


Ancient Astronomy — II

A few Greek astronomers used surprisingly modern techniques to get surprisingly correct and accurate answers.

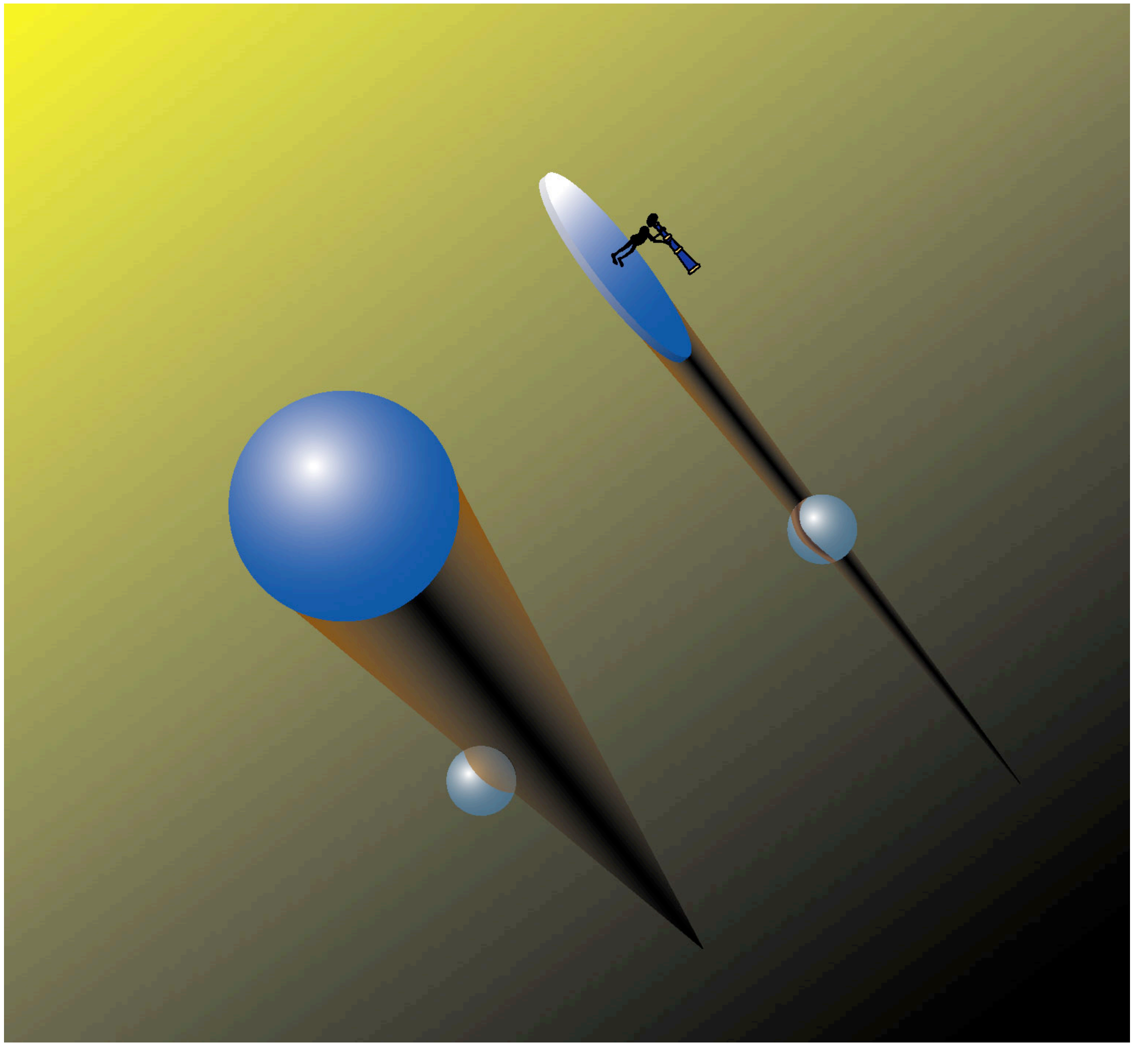
Few people listened.

Evidence for a Round Earth



Evidence for a Round Earth

The Earth's shadow on the Moon during an eclipse is always circular. If the Earth were flat, the shadow would be a thin stripe whenever the eclipse is seen near moonrise or moonset.



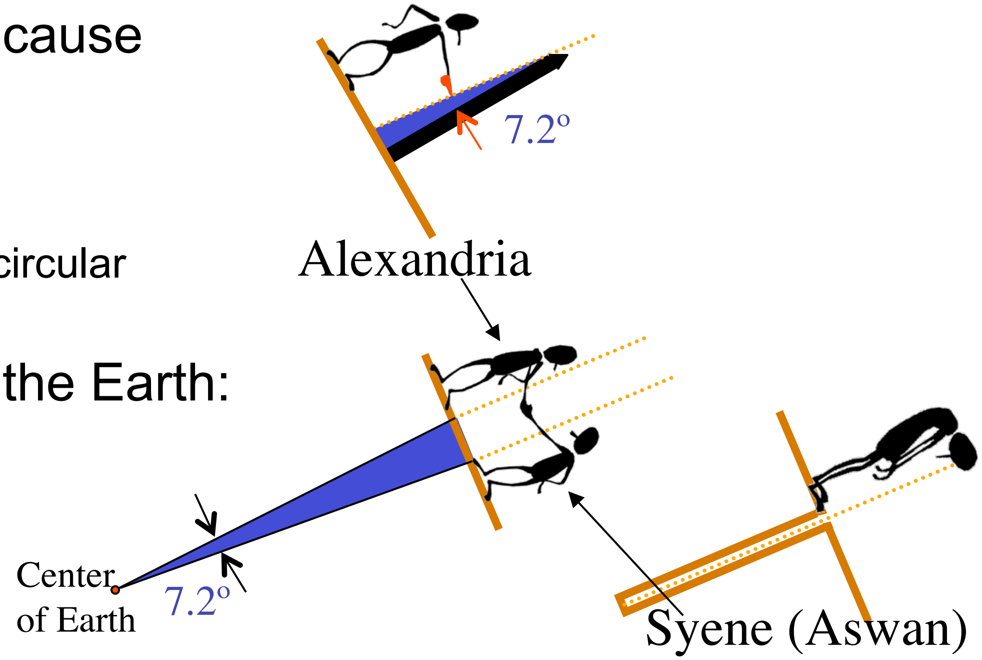
A Lunar eclipse photo series shows the size of Earth’s shadow.

APOD 2008 August 20

Estimating the Size of the Earth

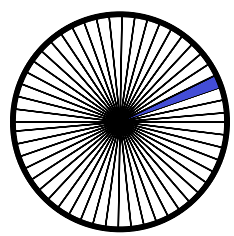
We know that the Earth is round because

- Ships disappear over the horizon
- The pole star is higher in Northern skies
- New stars appear as you sail South
- The Earth's shadow on the Moon looks circular



Eratosthenes estimated the size of the Earth:

At noon on the summer solstice, the Sun is 7.2º from the vertical in Alexandria (A), but directly overhead in Syene (S), Egypt. Eratosthenes realized that the angle between the two cities measured from the center of the Earth is also 7.2º or 1/50 of a full circle. Therefore the circumference of the Earth is 50 times the distance between Alexandria & Syene or 50 x 500 = 25,000 miles. So the diameter of the Earth is 25,000/π = 8,000 miles. He got the right answer in ~ 200 BC!



The Math Behind the Words

$$\frac{\text{Distance A} \rightarrow \text{S}}{\text{Earth's circumference}} = \frac{\angle\text{Shadow}}{360^\circ}$$

$$\frac{500 \text{ miles}}{\text{Earth's circumference}} = \frac{7.2^\circ}{360^\circ} \approx \frac{1}{50}$$

$$\text{Earth's circumference} = 500 \text{ miles} \times \frac{50}{1}$$

$$= 25{,}000 \text{ miles}$$

Estimating the Size and Distance of the Moon

Aristarchus of Samos (~ 310 — 230 BC) is credited with the first arguments that the Earth revolves around the Sun. He also estimated the distance to the Sun and Moon. But his writings were lost in the fire that destroyed the library at Alexandria, Egypt, so we don't know his work in detail.

Aristarchus thought that the diameter of the Earth's shadow at the Moon's distance is about twice the diameter of the Moon. Since he had already determined that the Sun is much farther away than the Moon, he concluded that the Moon is half the size of the Earth. (The correct answer is 0.27 times the size of the Earth.)

He thought that the Moon's angular size is about 2° (the correct answer is 0.5°), so 360° / 2° = 180 Moon diameters make up the circumference of the Moon's orbit. Hence he got the distance to the Moon. His answer was a factor of 2 too small.

Distance Scales

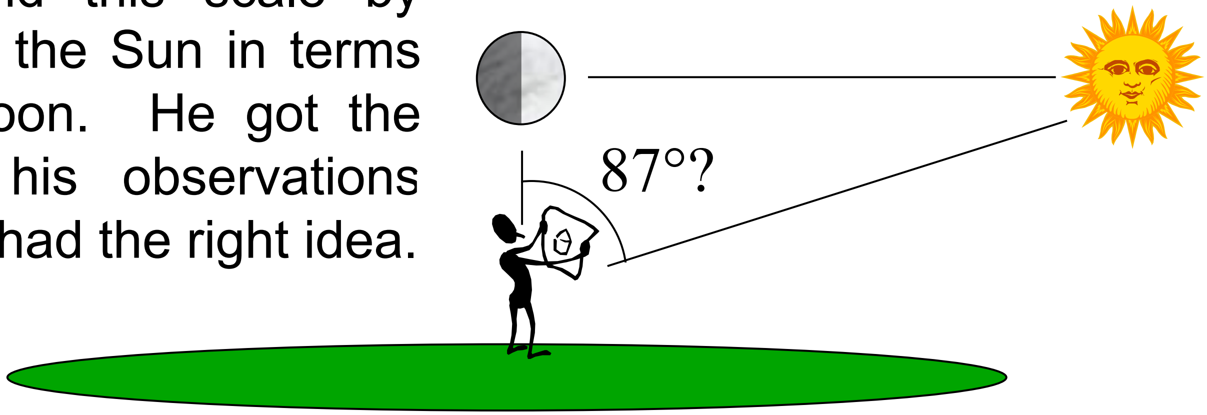
These estimates of the Earth's diameter and the Moon's distance are the first known astronomical distance scale:

- The distance between Alexandria and Syene was measured directly.
- The diameter of the Earth was measured in terms of the distance between Alexandria and Syene.
- The distance to the Moon was measured in terms of the diameter of the Earth.

At each step, a new distance was measured in terms of a distance already known.

Astronomers today use the same idea to measure the distances to stars and galaxies.

Aristarchus tried to extend this scale by measuring the distance to the Sun in terms of the distance to the Moon. He got the wrong answer because his observations were not accurate. But he had the right idea.



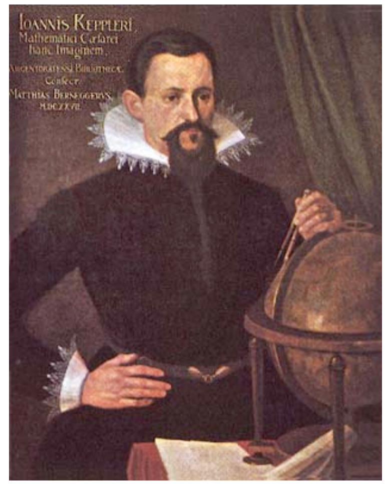
History of Astronomy

The struggle to explain planetary motions is central to the development of modern science.

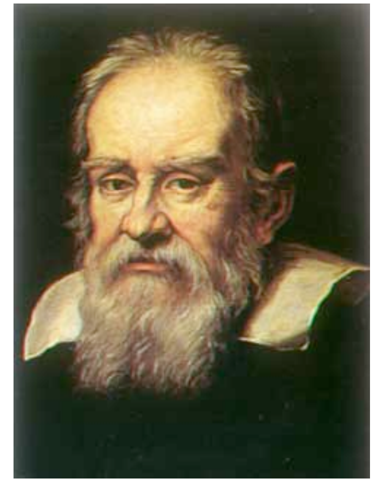
Aristotle	~350 BC	Earth is the center of the Universe; the stars, the Sun and the planets revolve around the Earth in circles.
Ptolemy	~140 AD	Ditto; epicycles explain retrograde motions.
Copernicus	1473 — 1543	The Sun is the center of the Universe; the stars and the planets revolve around the Sun in circles. Still need epicycles.
Tycho	1546 — 1601	First measurements of planetary positions that were accurate enough to allow development of the correct theory. He was the first modern observational astronomer.
Kepler	1571 — 1630	Kepler's laws describe planetary motion; Beginning of mathematical scientific laws.
Galileo	1564 — 1642	Public support for Copernican theory; first extensive use of the telescope in astronomy; many revolutionary discoveries: mountains on Moon, moons of Jupiter, phases of Venus, many faint stars in the Milky Way.
Newton	1642 — 1727	Mathematical theory of gravity explains Kepler's laws.
Einstein	1879 — 1955	Special and general relativity: generalization of Newton's laws.

History is made by a few people with vision.

Copernicus
(1473-1543)

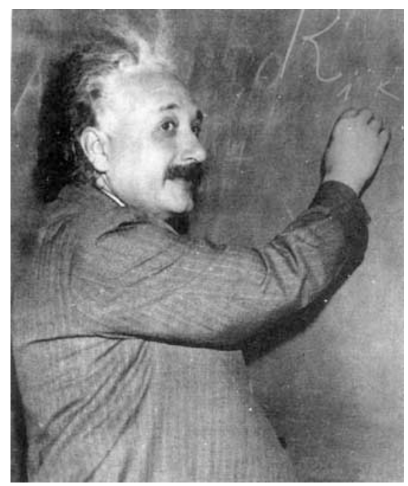


Kepler
(1571-1630)



Galileo
(1564-1642)

Newton
(1642-1727)

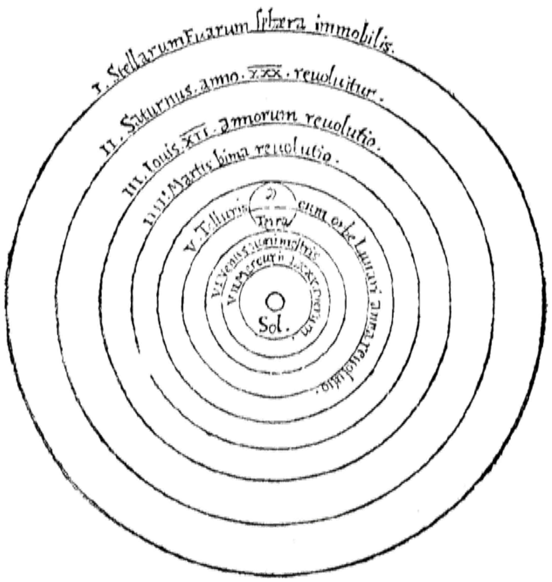


Einstein
(1879-1955)

De Revolutionibus Orbium Coelestium

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono menſe reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum ſpacio circũ currens. In medio uero omnium reſidet Sol. Quis enim in hoc



pulcherrimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum ſimul poſsit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegiſtus uiſibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in ſolio regali Sol reſidens circum agentem gubernat Aſtrorum familiam. Tellus quoque minime fraudatur lunari miniſterio, ſed ut Ariſtoteles de animalibus ait, maximam Luna cum terra cognationẽ habet. Cõcipit interea à Sole terra, & impregnatur annno partu. Inuenimus igitur ſub hac

Copernicus knew that the Ptolemaic system made inaccurate predictions. But:

Copernicus proposed his Sun-centered Universe for metaphysical reasons bordering on Sun-worship and not as a result of confrontation of theory with observations.

"In this most beautiful temple, who would place this lamp [the Sun] in another or better position than that from which it can light up everything at the same time? For the Sun is not inappropriately called by some people the lantern of the Universe, its mind by others, and its ruler by still others."

He quotes Hermes Trismegistus and Sophocles' Electra as authorities.

Copernicus still needed epicycles. His model was not much more accurate than Ptolemy's.

Copernicus was only partly a scientist!

He was more nearly a philosopher steeped in the tradition of Aristotle who got the right answer for the wrong reasons.

But he is credited for the crucial idea, even though Aristarchus got there first and for much better reasons.

The judgments of history are not necessarily fair.

What is missing? Observations!

Tycho Brahe


BRAHER
BILLER
RVDER
VLSTANDER
LONGER
RØNNOR
ROSENKRANS
TROLLER
AXELLSØNNER
LONGER
MARCKEMAN
ROSENSPAR
KABBELER
STORMVASE
GVLDENSTEREN
AXELLSØNNER
NON HABERI
SED ESSE
EFFIGIES TYCHONIS BRAHE OTTONIDIS DANI
DÑI DE KNVDSTRVP ET ARCIS VRANIENBVRG IN
INSVLA HELLISPONTI DANICI HVENNA FVNDATORIS
INSTRVMENTORVMQ' ASTRONOMICORVM IN EADEM
DISPOSITORVM INVENTORIS ET STRVCTORIS
ÆTATIS SVÆ ANNO 40. ANNO DÑI. 1586. COMPL.

Tycho Brahe

1546 — 1602

Tycho Brahe was the first modern observational astronomer. He made decades of excruciatingly accurate measurements of planetary positions. These were the first observations that were accurate enough to allow someone else (Johannes Kepler) to discover the correct description of the orbits of the planets.

At age 14, Tycho saw a partial solar eclipse that was predicted by Ptolemy. It struck him as "something divine that men could know the motions of the stars so accurately that they could long before foretell their places and relative positions."

But soon he was impressed by the <u>inaccuracy</u> of Ptolemy's predictions:

On Aug. 24, 1563, he watched a spectacular "conjunction" of Saturn and Jupiter: the Ptolemaic tables got the time of closest approach wrong by several days. This gave him a lifelong passion for accuracy and for consulting the sky as opposed to ancient authority.

Tycho Brahe

Observatories need money! Luckily, Tycho's father had saved Denmark's King Frederick II from drowning. The king financed a private astronomical empire on the island of Hveen (between Copenhagen and Elsinore castle). It included:

- A palatial residence and gardens,
- Uraniborg observatory + state-of-the-art instruments,
- Tycho's own printing plant and paper mill, and
- Even a private jail.

Tycho drove himself and his assistants mercilessly to get and publish the most accurate possible observations for over 20 years.

Tycho's 1572 discovery of Tycho's supernova astonished him and brought him additional fame. It further convinced him – and others – that the heavens are not immutable and that Aristotle didn't know everything.

But he was so hated by the people of Hveen that, when Frederick II died and Tycho left, they destroyed his estate.

Tycho's Observatory "Uraniborg"

Island of Hven Today

Johannes Kepler

1571 — 1630

Kepler was a prototypical outsider: myopic, sickly, and (in his words) “doglike” in appearance. His father was a mercenary soldier and wife-beater. His mother was nearly burned at the stake as a witch. He was “neurotic, self-loathing, and arrogant, but he tested no ideas more rigorously than his own.” As a person, he was almost the opposite of the aristocratic, energetic, despotic Brahe.

But both were dedicated.

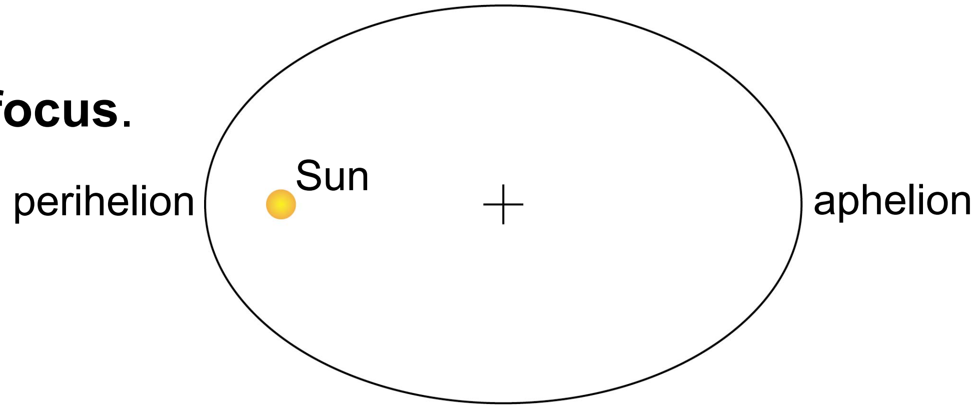
Kepler was inspired by faith that the complicated real world was built on “harmonious and symmetrical law. If the motions of the planets seemed discordant, that is because we have not learned how to hear their song. Kepler wanted to hear it before he died.” He succeeded.

Kepler became Tycho's assistant in 1600. After Tycho died in 1601, Kepler inherited his observations. After almost a decade of hard work — of constant conflict between what everybody thought was “harmonious” and what the observations said — in 1609 he got the right answer:

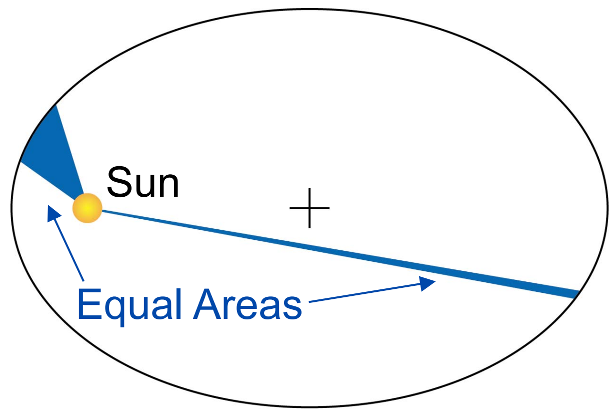
The orbit of each planet is an ellipse with the Sun at one focus.

Kepler's Laws

Law 1: Each planet moves in an **elliptical** orbit with the Sun at one **focus**.



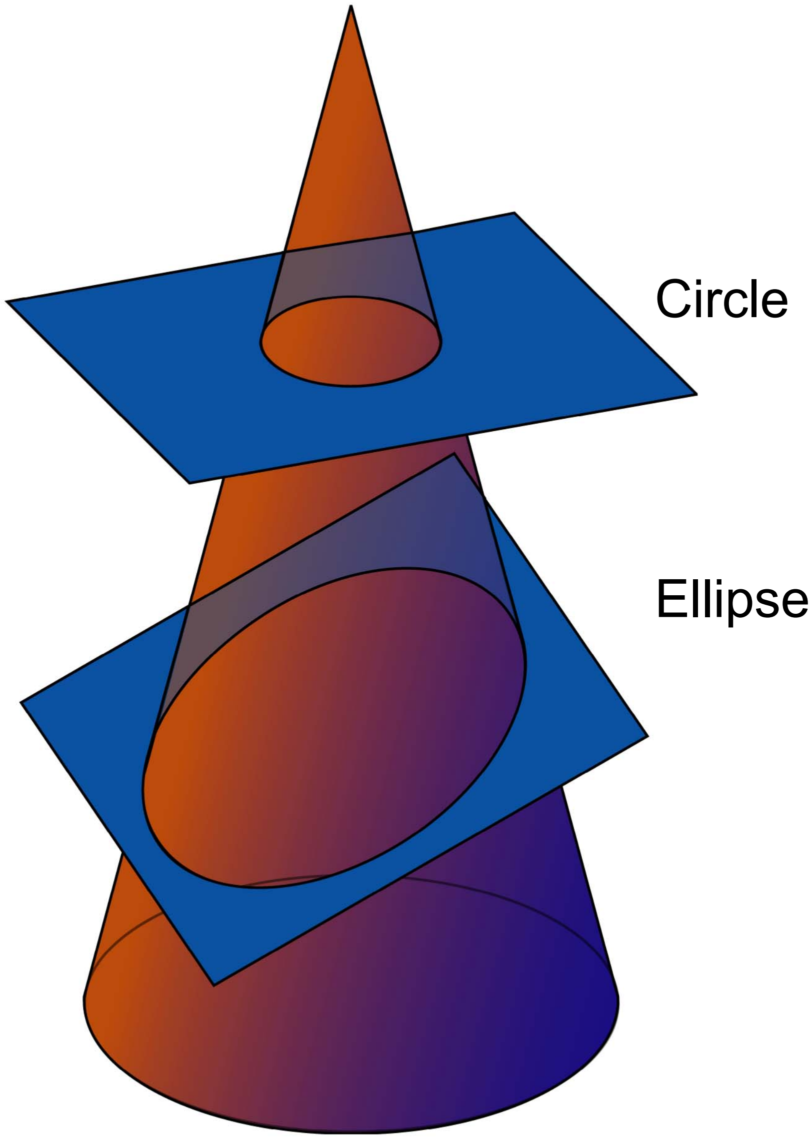
Law 2: In any two equal intervals of time, a line from the Sun to a planet sweeps out two equal areas.



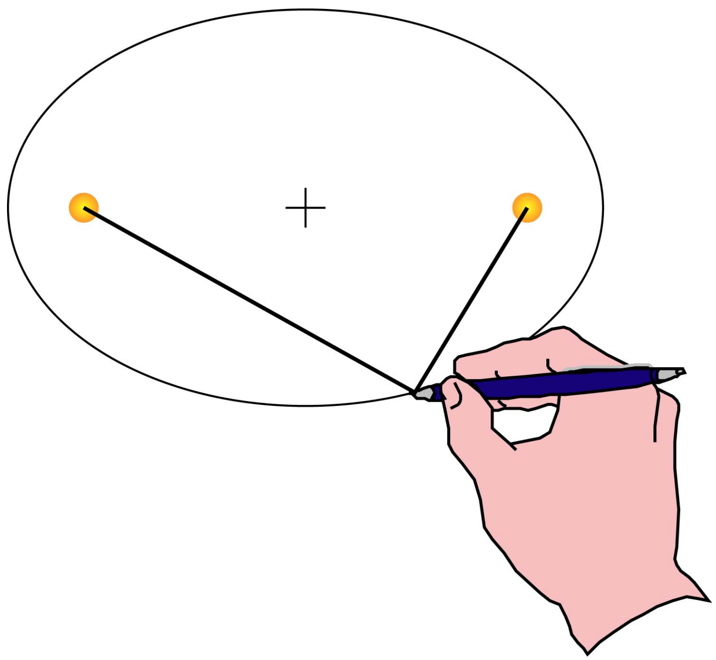
Law 3: The cube of the semimajor axis, *a*, divided by the square of the orbital period, *P*, is the same for all the planets.

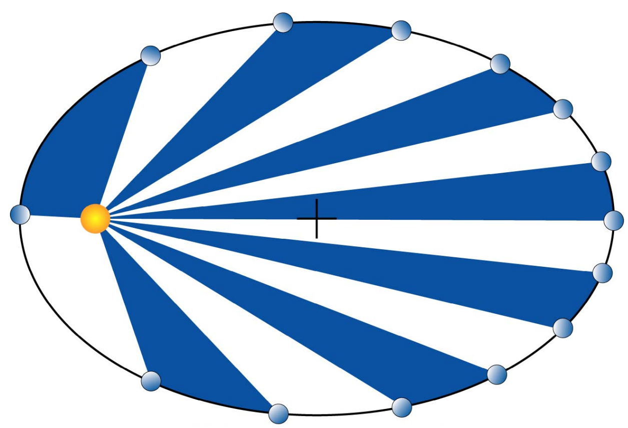
$$\frac{a^3}{P^2} = \text{constant}$$

Conic Sections

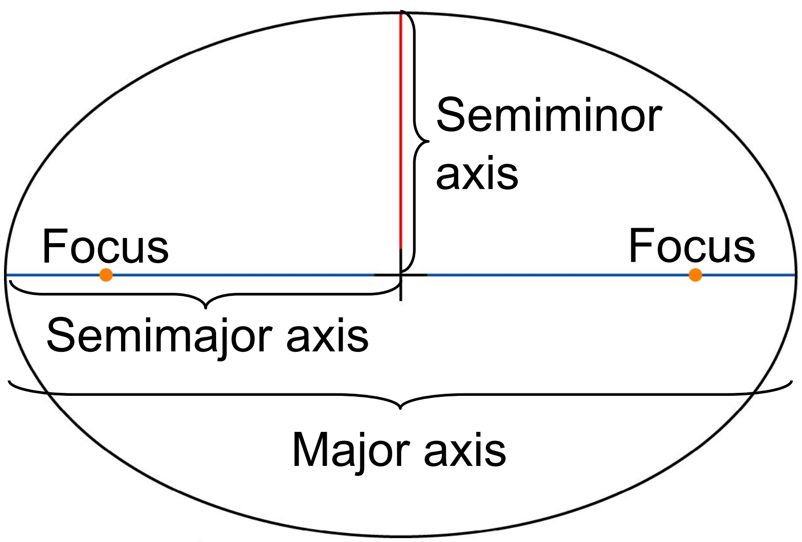


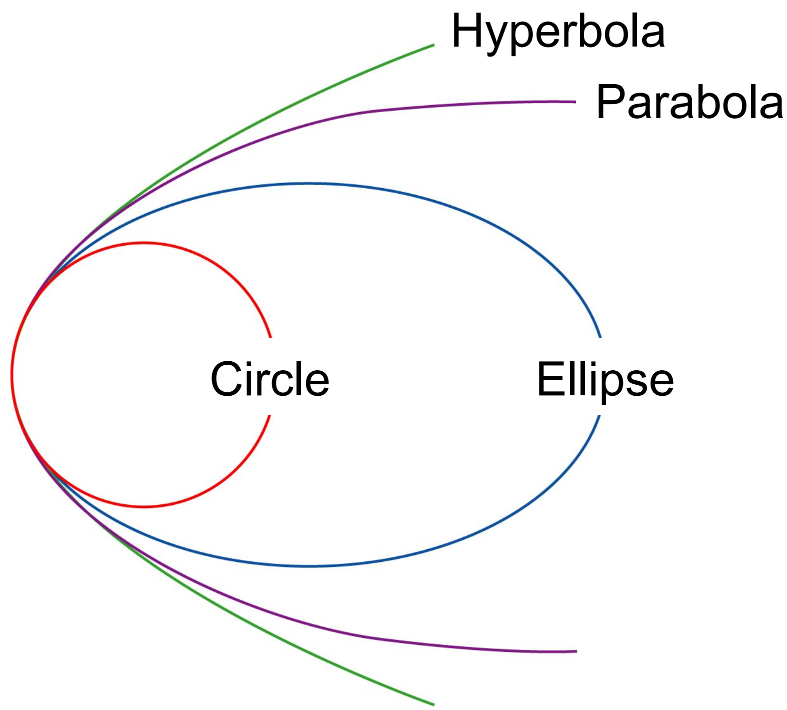
How to Draw an Ellipse





The Geometry of an Orbit





Checking Kepler's Third Law

We can check the third law using modern data. In this table, the semimajor axis *a* is given in astronomical units (AU), and the period *P* is given in years.

Planet	a	P	a^3	P^2	a^3/P^2
Mercury	0.387	0.241	0.058	0.058	1.0
Venus	0.723	0.615	0.378	0.378	1.0
Earth	1.0	1.0	1.0	1.0	1.0
Mars	1.523	1.88	3.53	3.53	1.0
Jupiter	5.20	11.86	140.6	140.7	1.0
Saturn	9.54	29.46	868.3	867.9	1.0

The Earth's orbit defines our system of units, so the quantity a^3/P^2 is equal to 1.0 for all the planets. Thus if we measure a in AU and P in years, we have

$$a^3 = P^2,$$

which implies that

$$a = \sqrt[3]{P^2} \quad \text{and} \quad P = \sqrt{a^3}.$$

Summary of Kepler's Laws

Kepler's laws give a complete* description of planetary motion.

The three laws work together like this:

1. Law 1 tells us the shape of the planet's orbit.
2. Law 3 tells us how long the planet takes to complete one orbit.
3. Law 2 tells us how fast the planet moves at each point in its orbit.

*well…almost. Except for:

- gravitational pull of the planets on each other
- general relativistic effects,
- etc…

<u>But</u> these are small effects,
certainly <u>too small</u> to be seen in ancient measurements.

Conceptual Breakthroughs

Comment 1

It may not seem like a big deal now, when we are accustomed to scientific (and religious and political and social) doubters and innovators, but:

It required a huge leap of imagination for Kepler to abandon circular orbits and conceive of elliptical orbits.

Almost the whole world had believed only in circular orbits for 2000 years.

Conceptual blindness is still a problem in modern science.

Comment 2

Kepler's laws are the beginning of mathematical laws of nature.

They are critically important steps in the development of modern science.

Ninety-Nine Years that Changed Astronomy