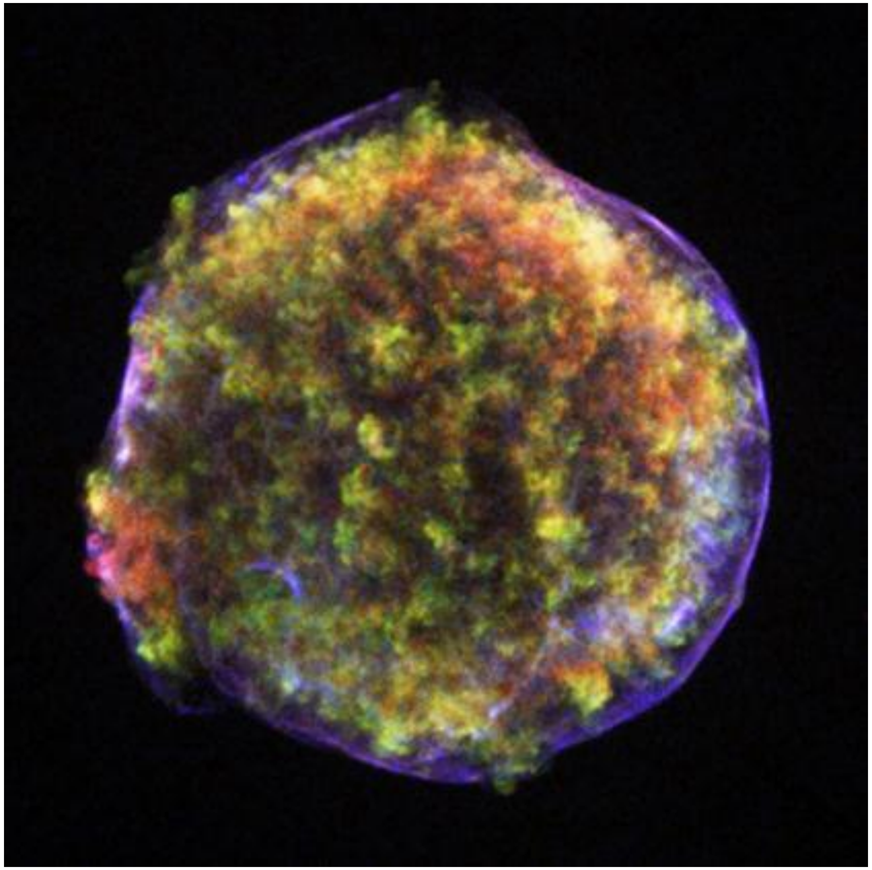
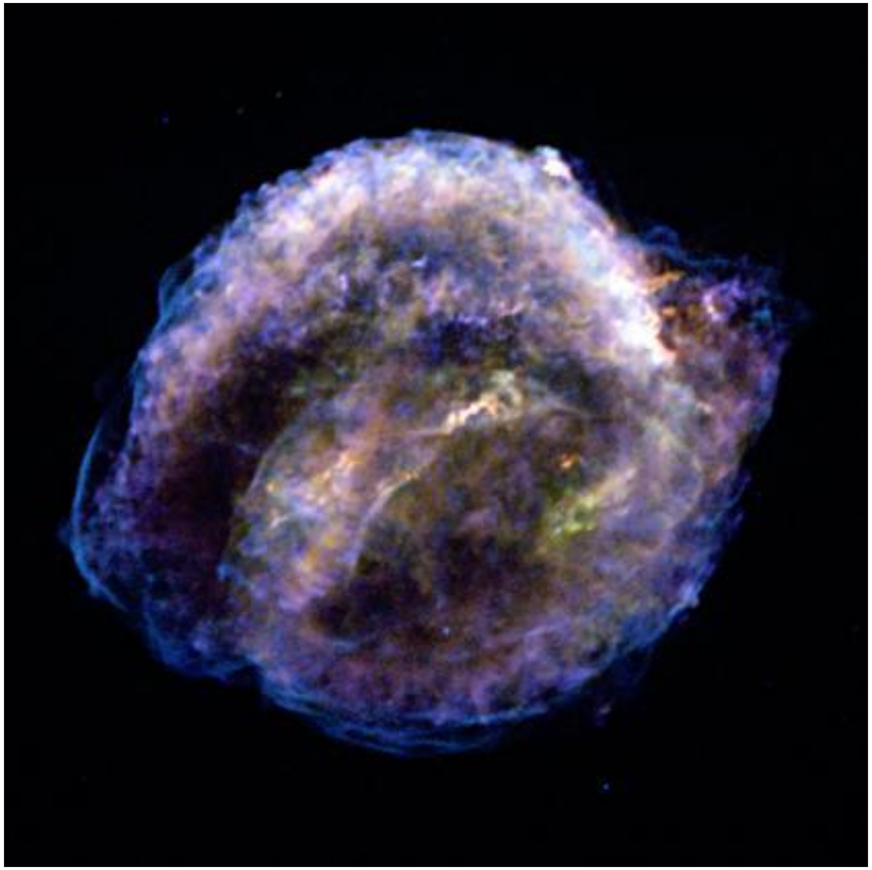
Chapter 2: Emergence of Modern Astronomy



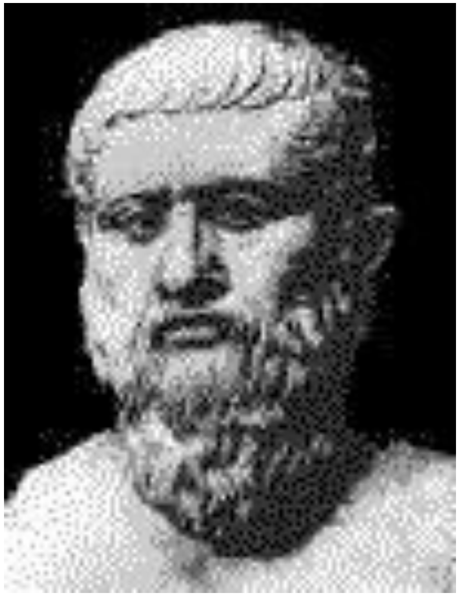


Greek innovations to thinking

- 1 - Explain nature using reason, not supernatural explanations
- 2 - Use mathematics to support ideas
- 3 - Reasoning must agree with observations
- Use these 3 fundamentals to form a *model* of nature – a conceptual representation used to explain and predict an observed event.
- Greeks formed many models to explain astronomy and some still exist today.

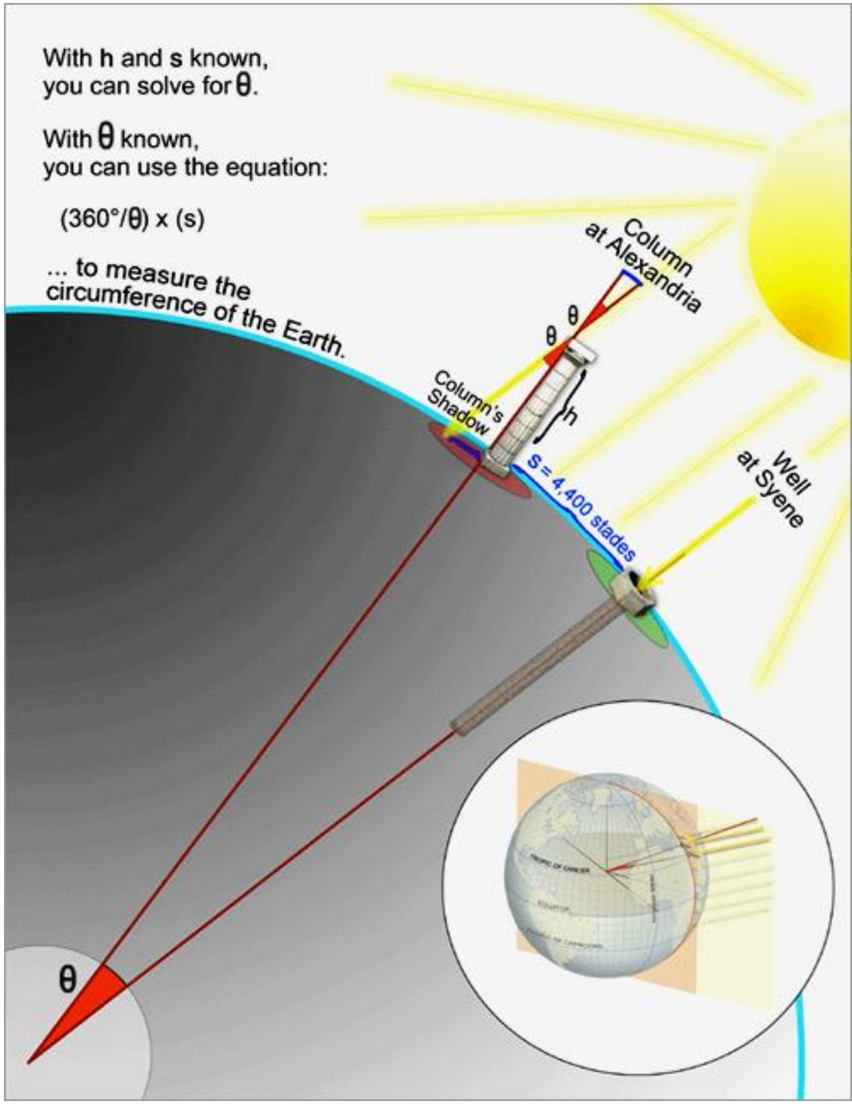
Early Greeks

- Pythagoras (500 B.C.) – Earth is a sphere – 3D
- Plato (428 – 348 B.C.) all heavenly objects move in perfect circles on perfect spheres
- Eudoxus (400 – 347 B.C.) Sun, Moon and planets on nested spheres surrounding Earth
- Aristotle (384 – 322 B.C.) Earth is the center due to gravity and heavens consisted of "lighter" things. Noted that certain stars are visible at certain latitudes
- Aristarchus (310 – 230 B.C.) Calculated relative sizes and distances to Moon & Sun, resulted in a heliocentric model



Eratosthenes (276-195 BC)

- Sun at zenith on solstice in Syene
  - Lat of Syene?
- Sun is south of zenith by 360°/50 = 7°12’
- Distance b/w cities, s = 1/50 of circumference (C)
- If s = 5,000 stades then C = 46,000 km (4x10^4 km)
- Also gives diameter of Earth since C = πD



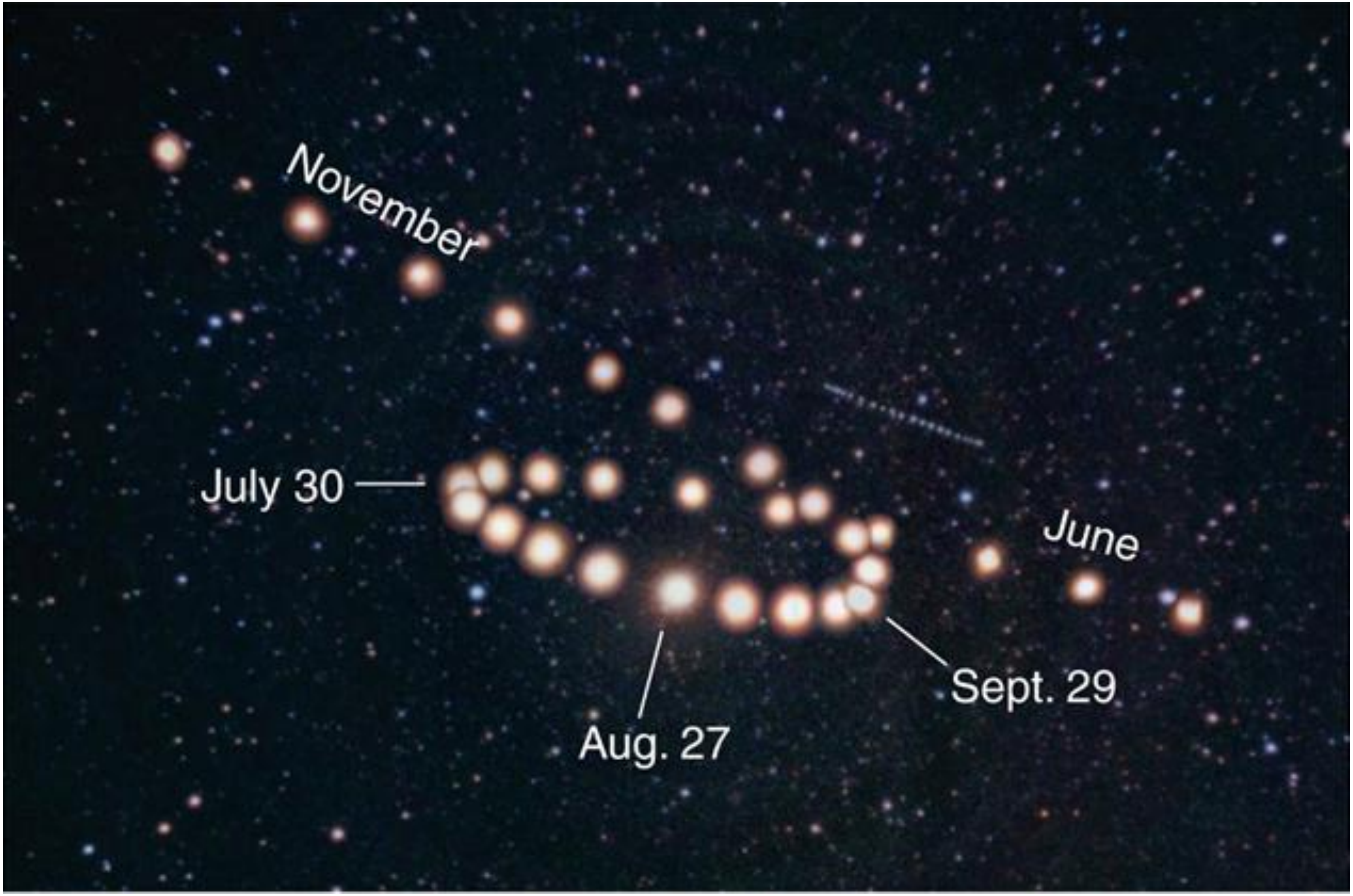
Hipparchus (190 – 120 B.C.)

- Created first star catalog
- Discovered precession of the equinoxes
- Established magnitude system on which current system is based
- Measured length of year and distance to Moon quite accurately (using parallax)
- ESA star mapping mission HIPPARCOS (1989-1993) – mapped >118,000 stars to milliarcsecond precision

Ptolemy

- Claudius Ptolemaeus (A.D. 100 – 170)
- Differed from previous models because it attempted to explain apparent retrograde motion (in addition to complex Sun and Moon motions)
- Ptolemaic model dominated astronomy for more than 14 centuries

Retrograde motion



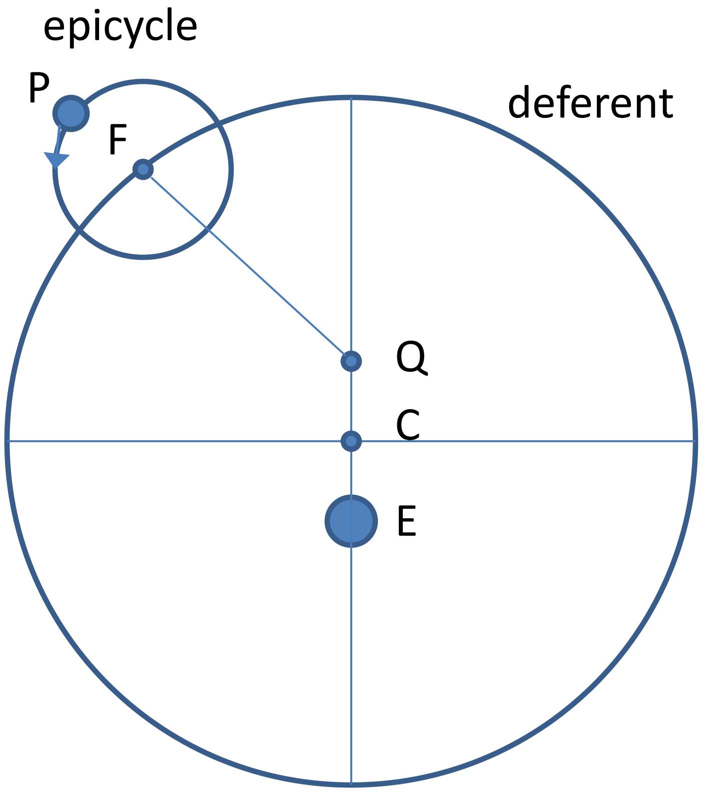
Ptolemaic model

- Assumptions
  - Geocentric
  - Perfect circular motion at constant speed
    - Uniform circular motion
  - Stars fixed to a rigid sphere
- Model had to provide enough parameters (flexibility) to be able to accurately predict motions
  - Not a good sign

Schema huius præmissæ diuisionis Sphærarum.

Ptolemaic model

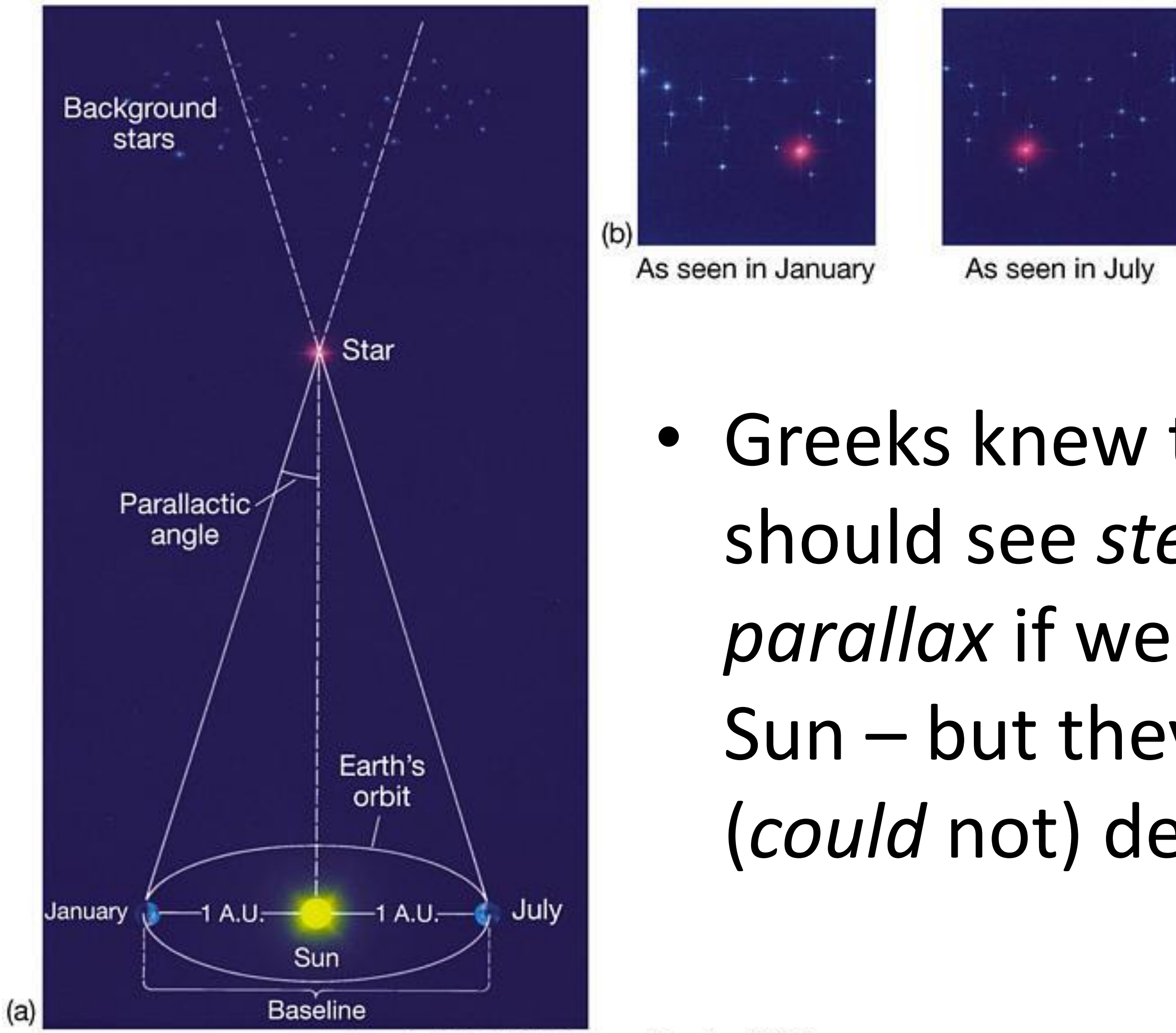
- Earth at **eccentric** (E) slightly removed from center (C) of **deferent**
- Planet travels around F on **epicycle**.
  - Takes care of retrograde
- F travels around deferent tied to **equant** (Q)
  - Increases precision
- Really toying with "perfect" circular motion



Why did the ancient Greeks reject the notion that the Earth orbits the sun?

- It ran contrary to their senses
- If the Earth moved, then there should be a "great wind" as we moved through the air.

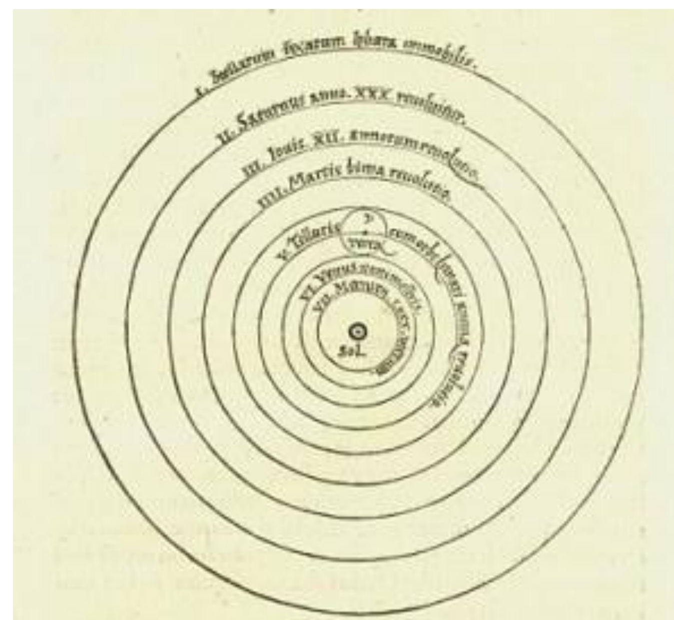
Why did the ancient Greeks reject the notion that the Earth orbits the sun?



- Greeks knew that we should see *stellar parallax* if we orbited the Sun – but they did not (*could* not) detect it.

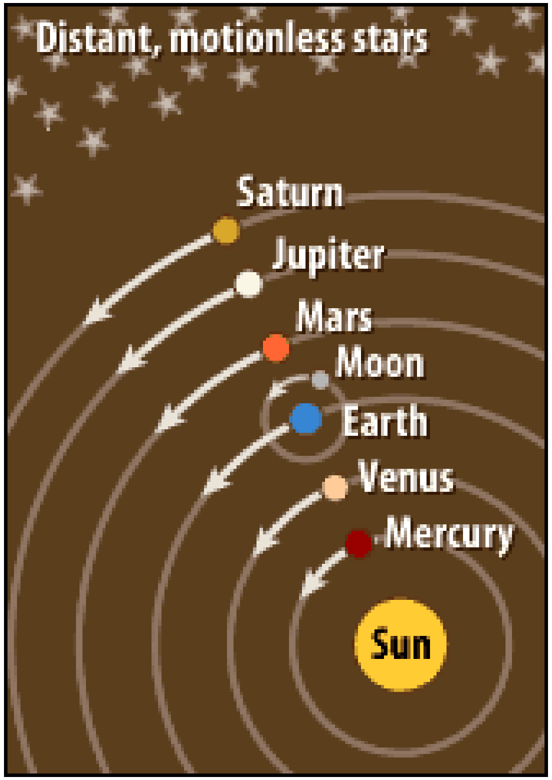
The Copernican Revolution

- Nicholas Copernicus (1473 – 1543)
- He thought Ptolemy’s model was contrived
- Yet he believed in circular motion
- HELIOCENTRIC!!!!
- His ideas were published just before he died
- Retained epicycles
- Better model (more simplistic) but still not elegant

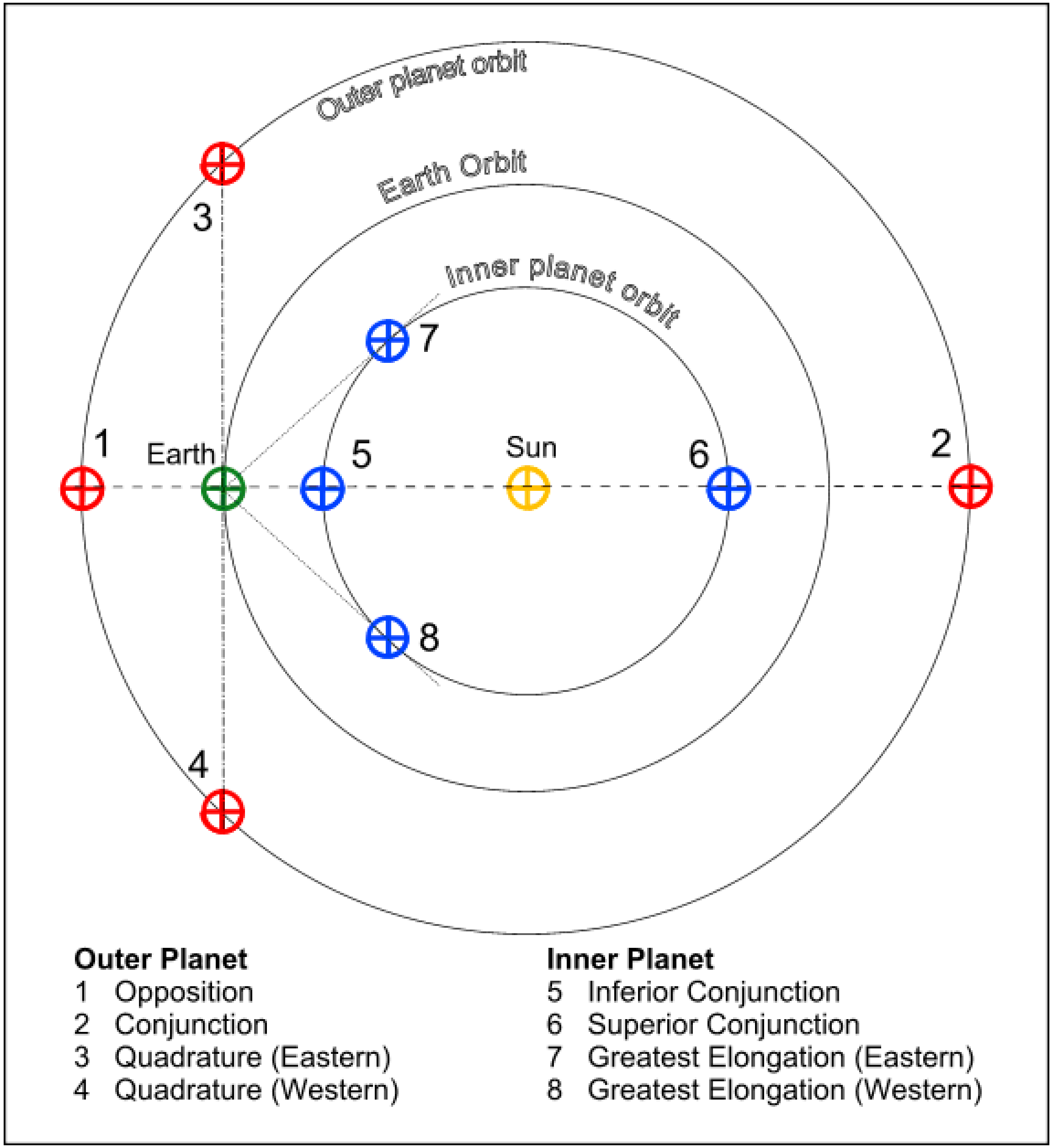


Planetary data

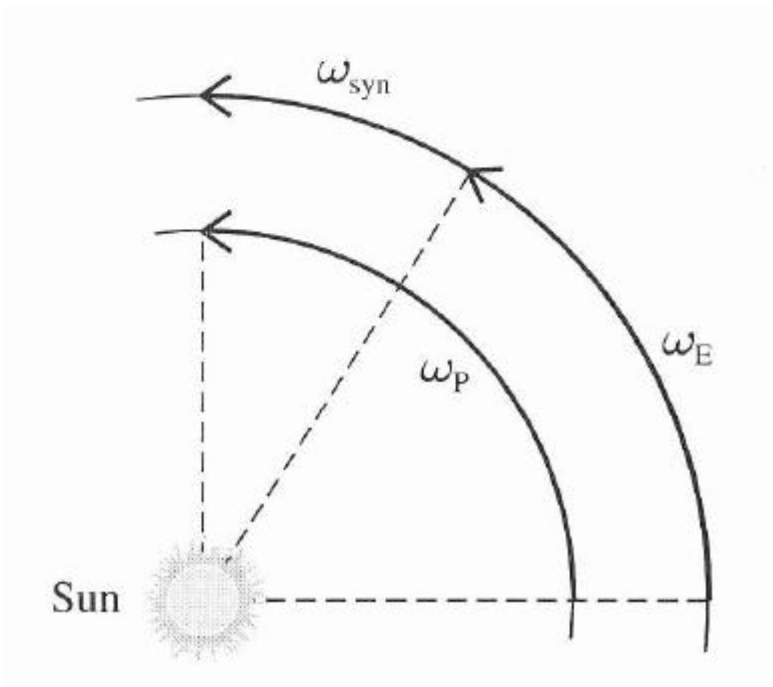
- Copernican (heliocentric) model allows calculation of sidereal period and size of orbits for planets
- Types of planets
  - **Inferior**
    - Closer to Sun than Earth
  - **Superior**
    - Orbits outside Earth's

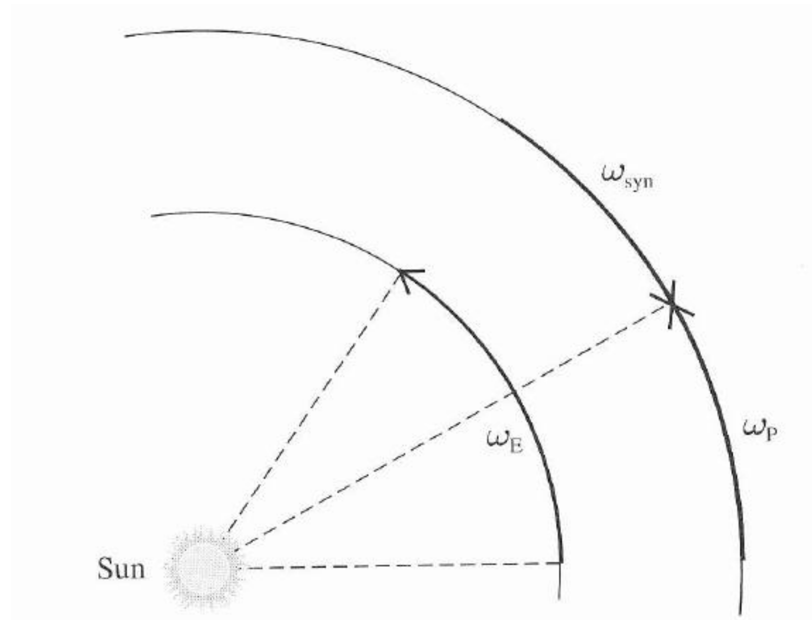


Planetary configurations



How to calculate sidereal period?



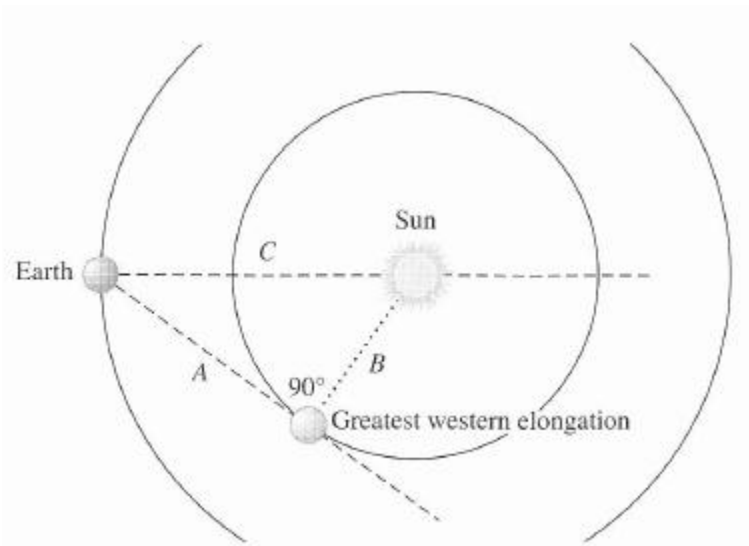


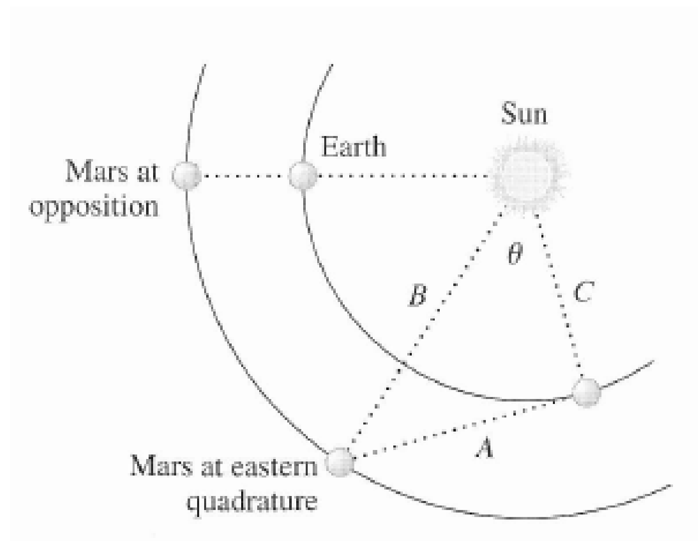
$$\vec{\omega}_P = \vec{\omega}_E + \vec{\omega}_{syn} \quad \rightarrow \quad \frac{1}{P_P} = \frac{1}{P_E} + \frac{1}{P_{syn}}$$

Measure synodic period (position relative to Sun) then calculate sidereal period (change sign for superior planets)

How to calculate orbital distances?

- Can be relative given *C* = 1 AU (Earth's average distance)





Inferior planets: *C* given, measure θ
$B = C \sin \theta$

Superior planets: *C* given, Can't measure θ
$B = C / \cos \theta$
Need another equation
$\theta = (\omega_E - \omega_P)\tau$
τ is time between opposition and quadrature

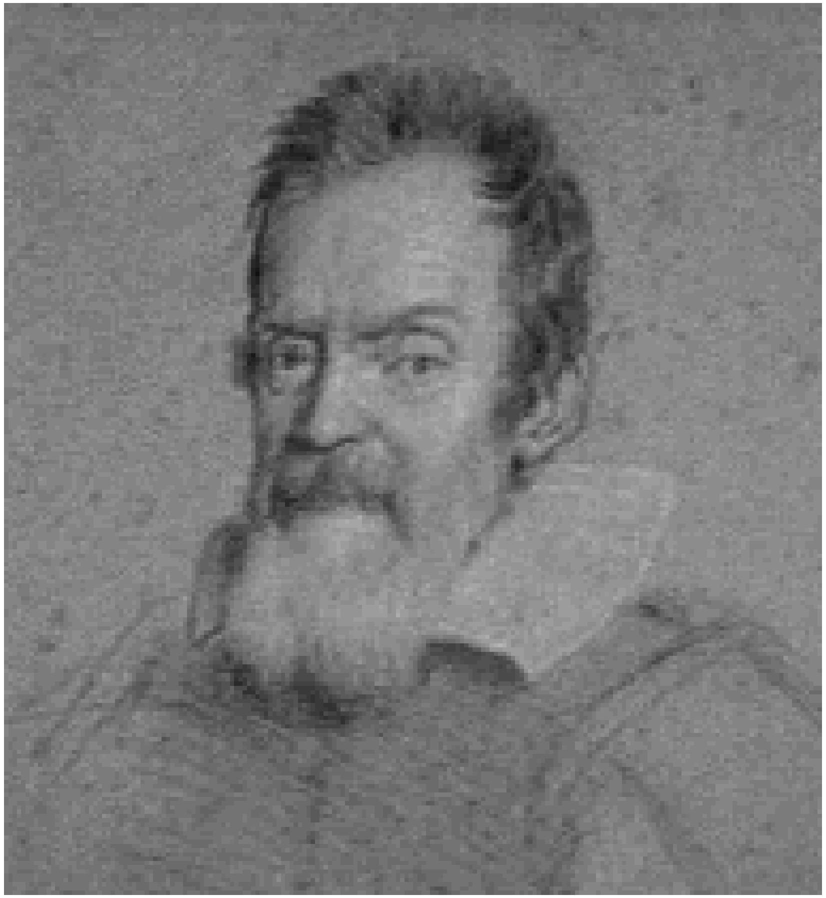
TABLE 2.1 Planetary Orbits

Planet[a]	Sidereal Period (years)	Orbital Radius (AU)
Mercury	0.2408	0.3871
Venus	0.6152	0.7233
Earth	1.000	1.000
Mars	1.881	1.524
Ceres	4.599	2.766
Jupiter	11.863	5.203
Saturn	29.447	9.537
Uranus	84.017	19.189
Neptune	164.79	30.070
Pluto	247.92	39.482
Haumea	283.28	43.133
Makemake	306.17	45.426
Eris	559.55	67.903

a. Dwarf planets in italics.

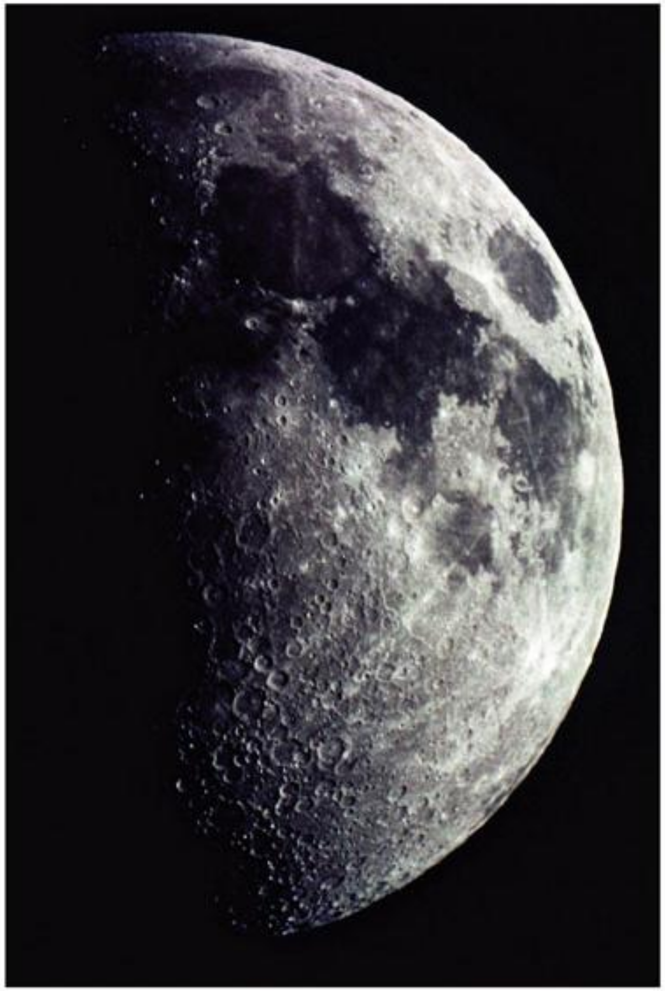
Galileo Galilei (1564-1642)

- First man to point a telescope at the sky
- wanted to connect physics on earth with the heavens
- *Dialogue Concerning the Two Chief World Systems*



This book got him in trouble with the Church

Galileo's Observations



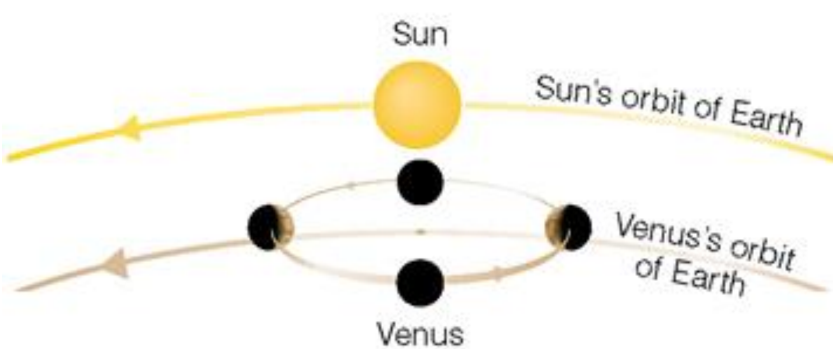
- Galileo saw shadows cast by the mountains on the Moon.
- He observed craters.
- The Moon had a landscape; it was a "place", not a perfect heavenly body.
- Also saw "inperfect" sunspots

Galileo’s Observations

- Galileo discovered that Jupiter had four moons of its own.
- Jupiter was the center of its own system.
- Heavenly bodies existed which did not orbit the Earth.

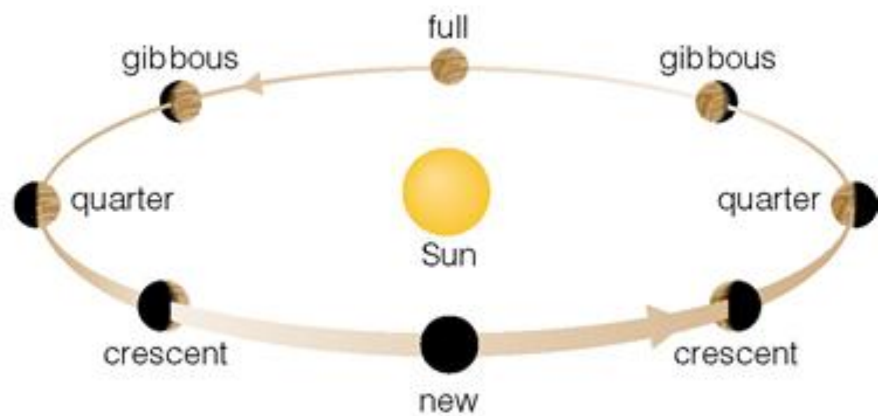
Galileo's observation of the phases of Venus was the final evidence which buried the geocentric model.

Geocentric



No gibbous or full phases

Heliocentric

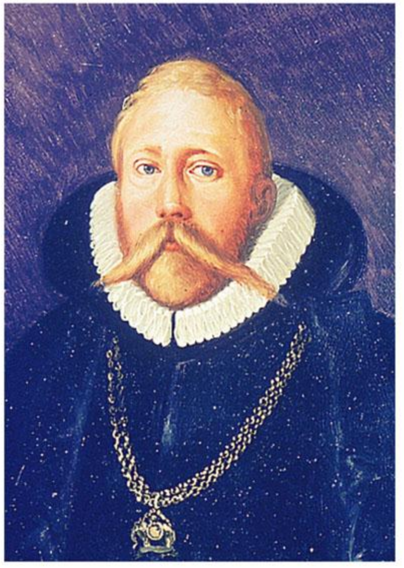


All phases are seen (with appropriate sizes)

Galileo observed **all** phases

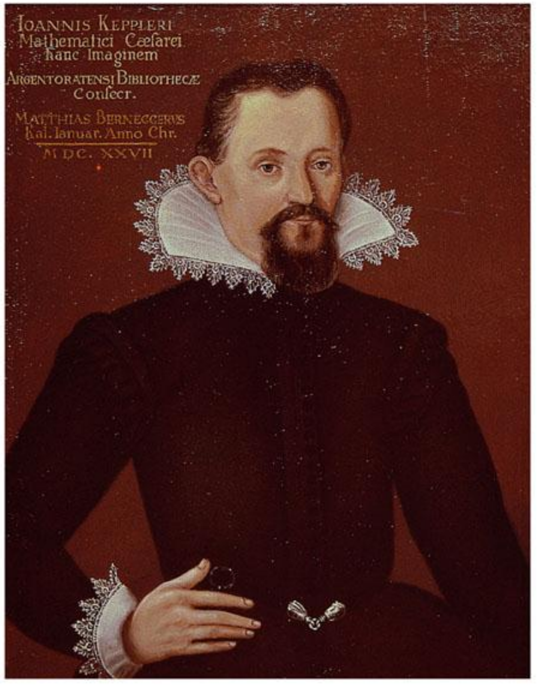
Tycho Brahe (1546-1601)

- Greatest observer of his day
- Charted accurate positions of planets
- Compiled most accurate set of naked eye observations ever made
- Observed a nova in 1572
- Heliocentric but Earth didn't move – no parallax



Johannes Kepler (1571-1630)

- Great theorist of his day
- Worked for Tycho
- Trusted accuracy of Tycho's measurements
- The first to abandon the idea of perfect circles



Kepler’s Laws

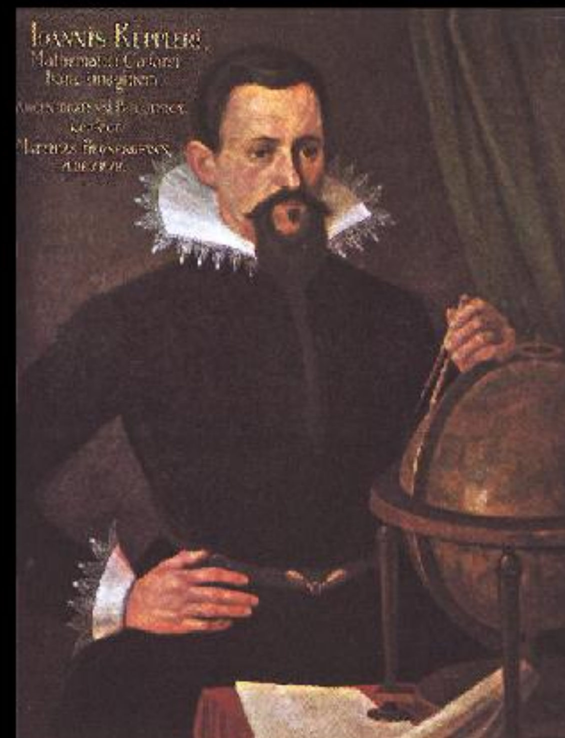
Kepler's Laws

Introduction Norton AstroTours

Reference U SN 10^n

In the sixteenth century, the nature of the orbits of the planets was debated along with the geocentric and heliocentric models of the solar system.

Johannes Kepler was a German mathematician who initially sought to prove that the planets orbited the Sun and that their orbits were perfect circles.

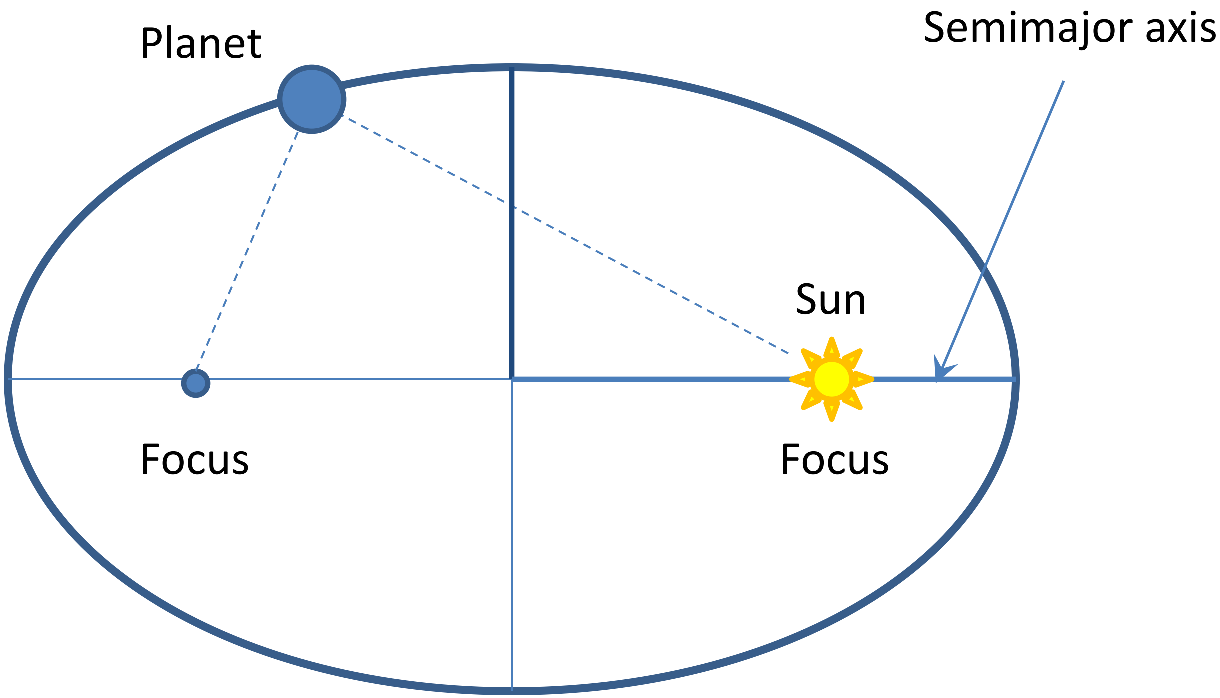


Johannes Kepler

Section 1 of 3

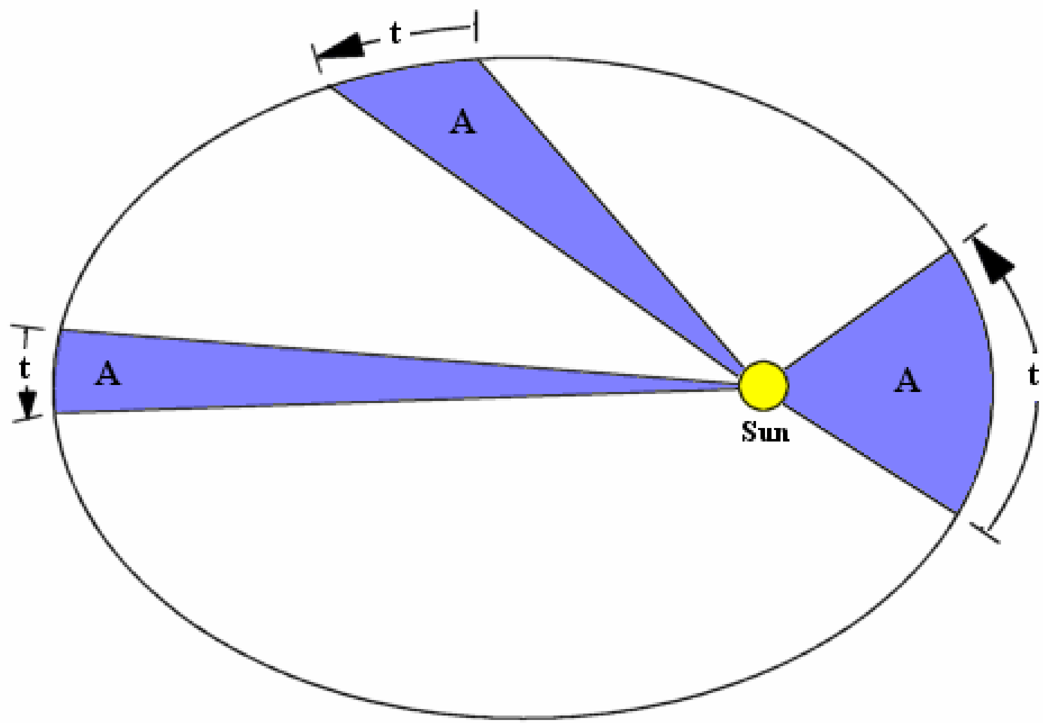
Kepler's laws of planetary motion

- 1^{st} Law
  - Planets travel on elliptical orbits with the Sun at one focus



Kepler's laws of planetary motion

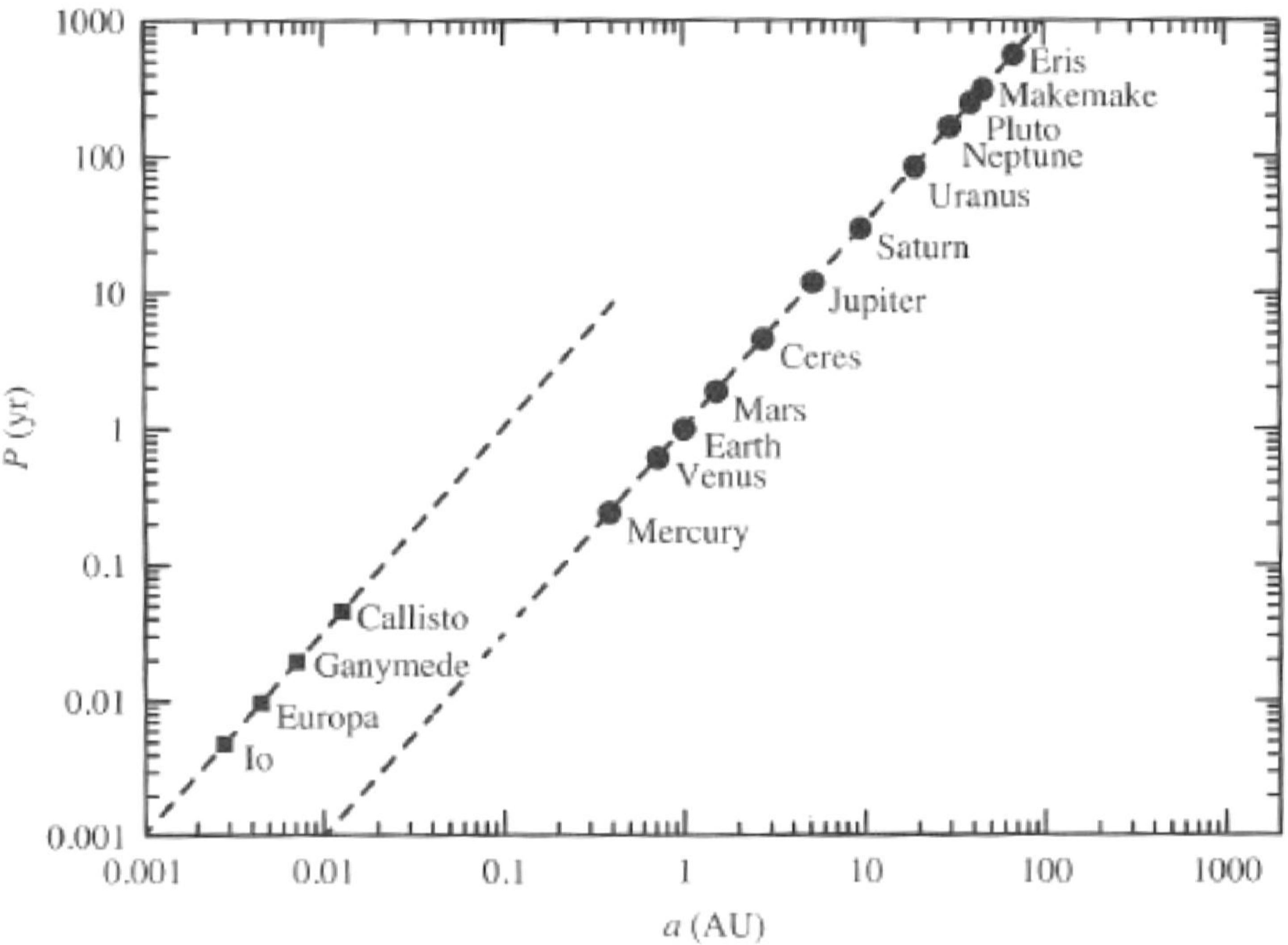
- 2^{nd} Law
  - Planetary orbits sweep out equal areas in equal time
    - i.e. planets move faster when they're close (perhelion = closest) to the Sun and slower when they're farther away (aphelion = farthest)



Kepler's laws of planetary motion

- 3rd Law
  - $P^2 = a^3$ (P in years, a in AU)
- Newton's version of Kepler's 3rd Law… later
  - More generally:
    - $P^2 = K a^3$, where K is proportionality constant

Keplerian Orbits



Proof of Earth's Motion

- Rotation of Earth
  - Coriolis effect
- Revolution of Earth about Sun
  - Aberration of starlight
  - Parallax of nearby stars

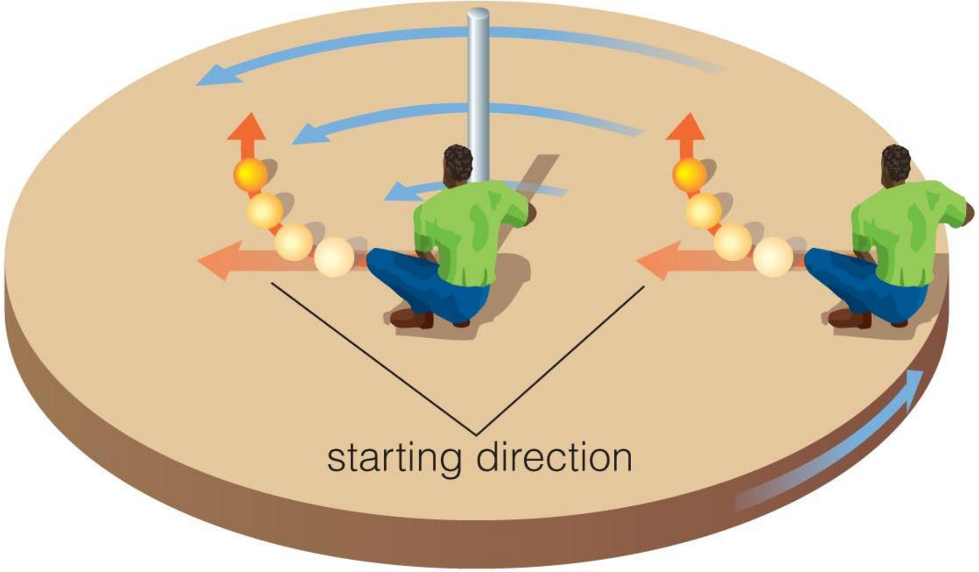
Acceleration in a rotating frame

- In a non-rotating frame, Newton's 2nd Law
  - $\vec{F} = m\vec{a} \rightarrow \vec{a} = \vec{F}/m$
- In a rotating frame
  - $\vec{a} = \frac{\vec{F}}{m} + 2(\vec{v} \times \vec{\omega}) - \vec{\omega} \times (\vec{\omega} \times \vec{r}) - \frac{d\vec{\omega}}{dt} \times \vec{r}$
  - External Forces
  - Coriolis Force
  - Centripetal Force
  - Euler Force
  - $\vec{a}, \vec{v}, \vec{r}$ measured in frame rotating at $\vec{\omega}$

Centripetal acceleration

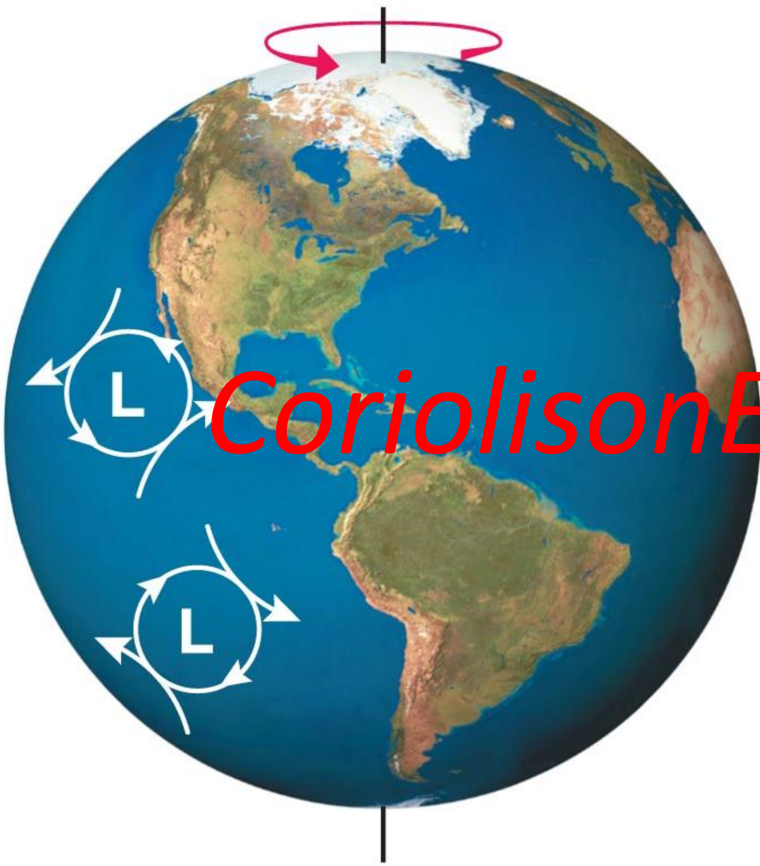
- $\vec{\omega} \times (\vec{\omega} \times \vec{r})$ toward center of rotation
- *Centrifugal* force is "fictitious" force seen in rotating frame – reactive force
  - Radially outward (opposite direction of centripetal force)
  - Makes planets oblate spheroids
  - Makes you weigh less at equator

Coriolis Effect



- Conservation of angular momentum causes a ball's apparent path on a spinning platform to change direction
- Earth's equator rotates faster than poles

Coriolis Effect on Earth

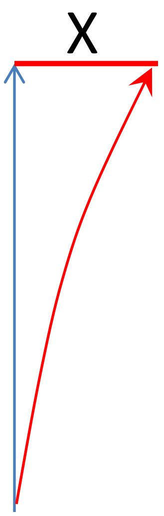


CoriolisonEarth.swf

- Air moving from pole to equator is going farther from axis and begins to lag Earth's rotation
- Air moving from equator to pole goes closer to axis and moves ahead of Earth's rotation
- Combination causes storms (low pressure regions) to swirl
  - Opposite directions in each hemisphere, CCW in the N, CW in the S

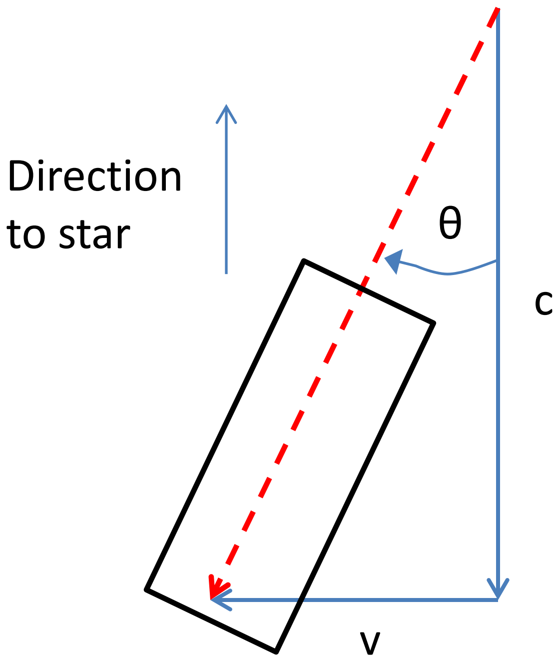
Coriolis Effect

- $2(\vec{v} \times \vec{\omega})$
- Again, a “fictitious” force that results from the non-inertial frame
- Perpendicular to direction of velocity
  - no effect at equator
  - Strongest effect near poles
- $x = v_x t + \frac{1}{2} a_x t^2$, where $a_x = a_{Cor}$
  - $v_x = 0$, a_{Cor} and t small $\rightarrow$ x small



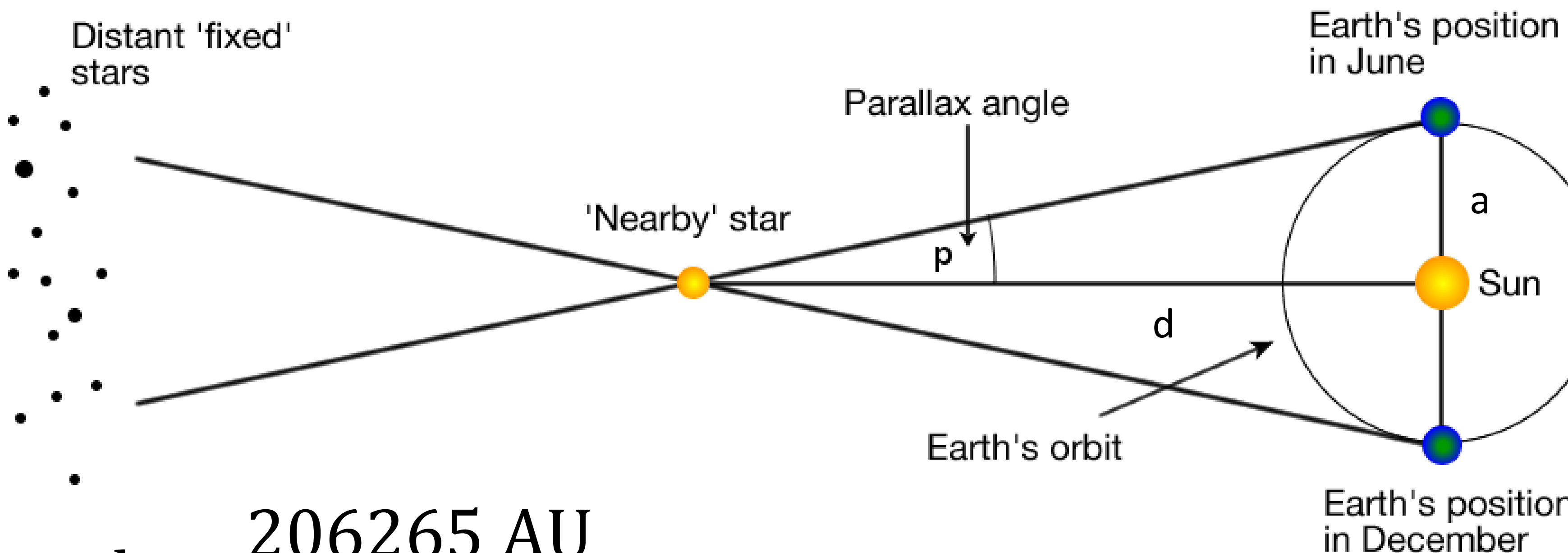
Revolution of Earth

- Aberration of starlight
  - Apparent positions of stars is offset toward direction of Earth's motion
- $\tan(\theta) = \frac{v}{c}, \theta \ll 1 \rightarrow$
  $\tan(\theta) \sim \sin(\theta) \sim \theta$



Revolution of Earth

- Stellar parallax (1838) $\tan(p) = \frac{a}{d} \rightarrow d = \frac{a}{p}$



- $d = \frac{206265\ \text{AU}}{p\ \text{(in arcseconds)}}$
- Hard to detect relative to aberration