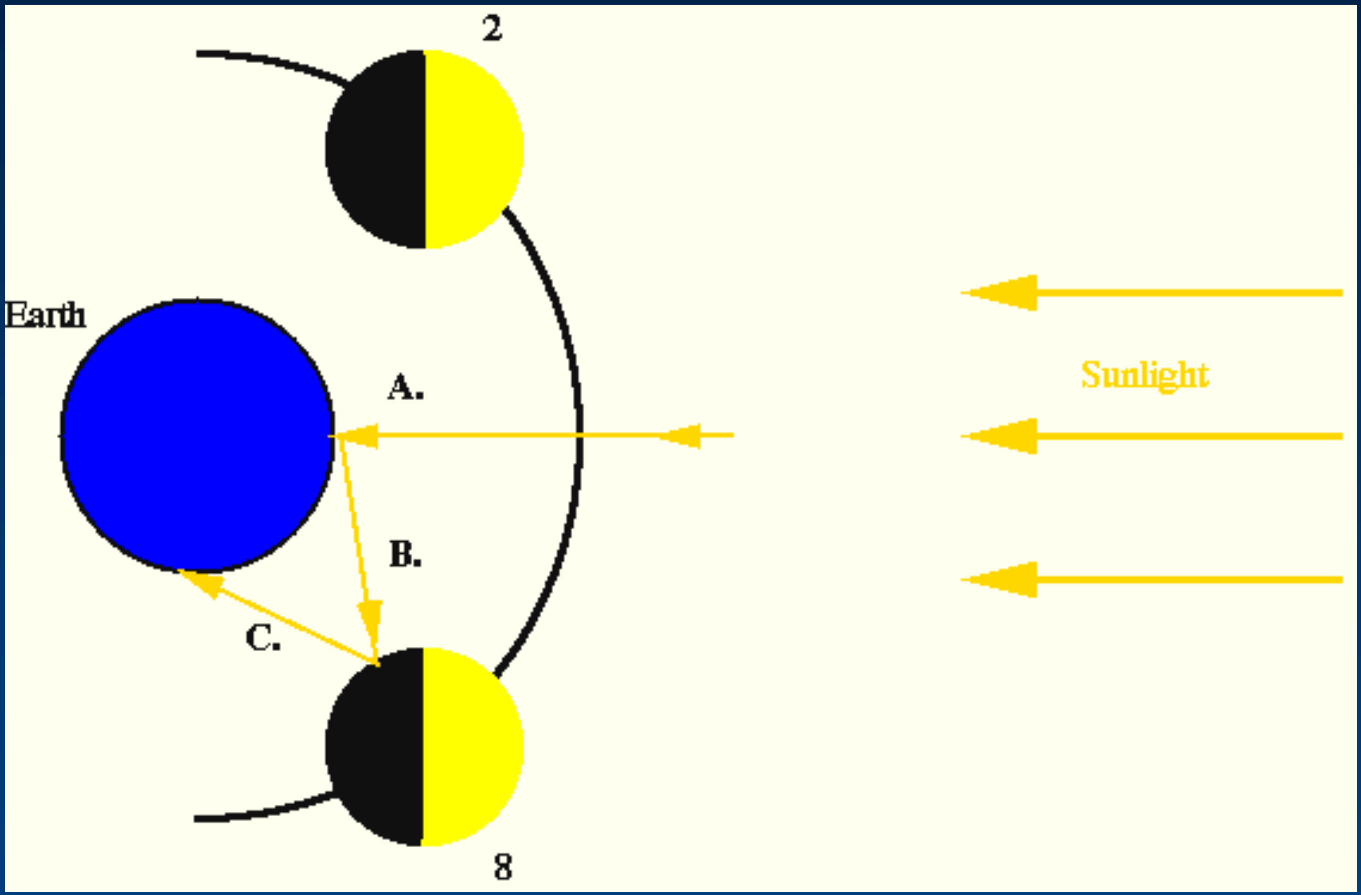
"Earthshine"

Earthshine is reflected light



Only seen in crescent phases because:

a) Only small part of the Moon is directly illuminated by the Sun

b) The Moon is in the right position to reflect back light to the Earth.

Gravitation Part I.

Ptolemy, Copernicus, Galileo, and Kepler

Celestial motions

- The stars:
  - Uniform daily motion about the celestial poles (rising and setting).
- The Sun:
  - Daily motion around the celestial poles.
  - Eastward drift along the ecliptic over a year, a little faster in January, slower in July.
- The Moon:
  - Daily motion around the celestial poles.
  - Eastward motion near the ecliptic over a month.

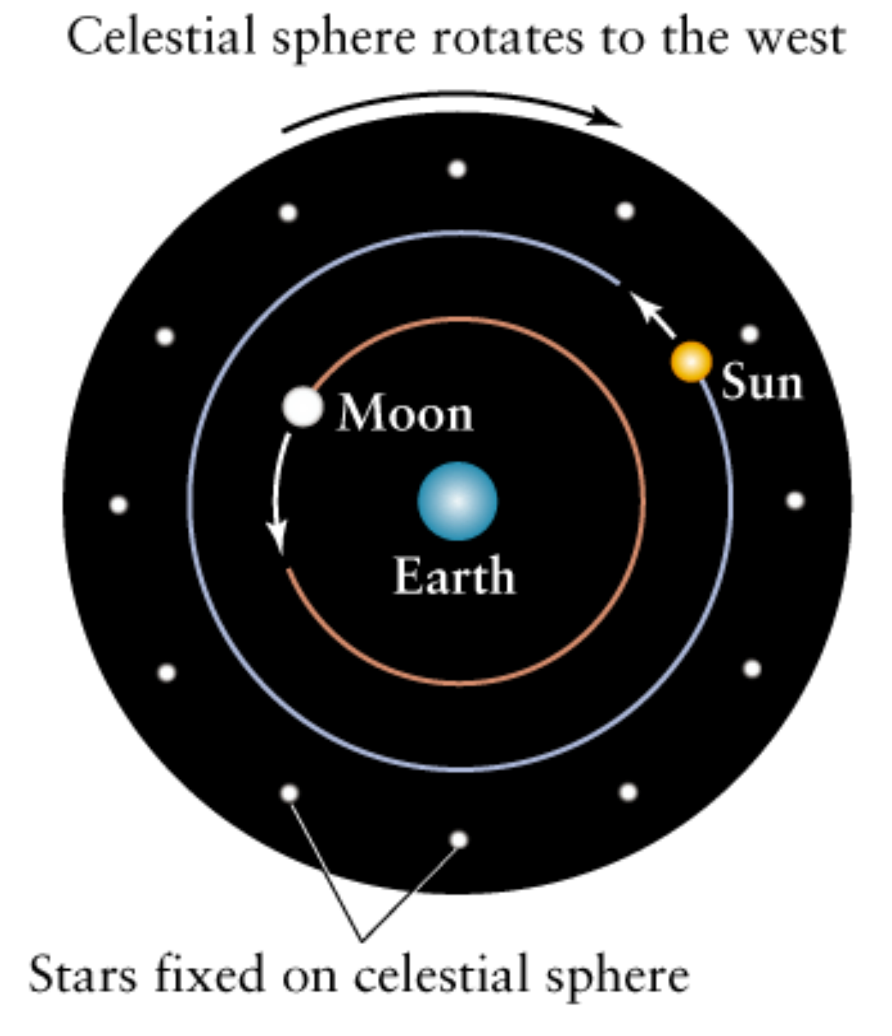
Celestial motions – cont.

- The planets:
  - Daily motions around celestial poles.
  - Generally eastward motion near the ecliptic at different speeds for each planet.
  - Occasional westward "retrograde" motions.
  - Planets change in brightness and angular size.

Any successful description of the Solar System must explain all these facts!

The appearance of the celestial sphere gives the impression that the Earth is the "center of the Universe", and everything moves around us.

This was the accepted model passed down from Greek scholars, and other cultures, and is known as the "geocentric“ model.



b The Greek geocentric cosmogony

"Geocentric Model" of the Solar System

Ancient Greek astronomers knew of Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn.

Aristotle vs. Aristarchus (3rd century B.C.):

Aristotle: Sun, Moon, Planets and Stars rotate around fixed Earth.

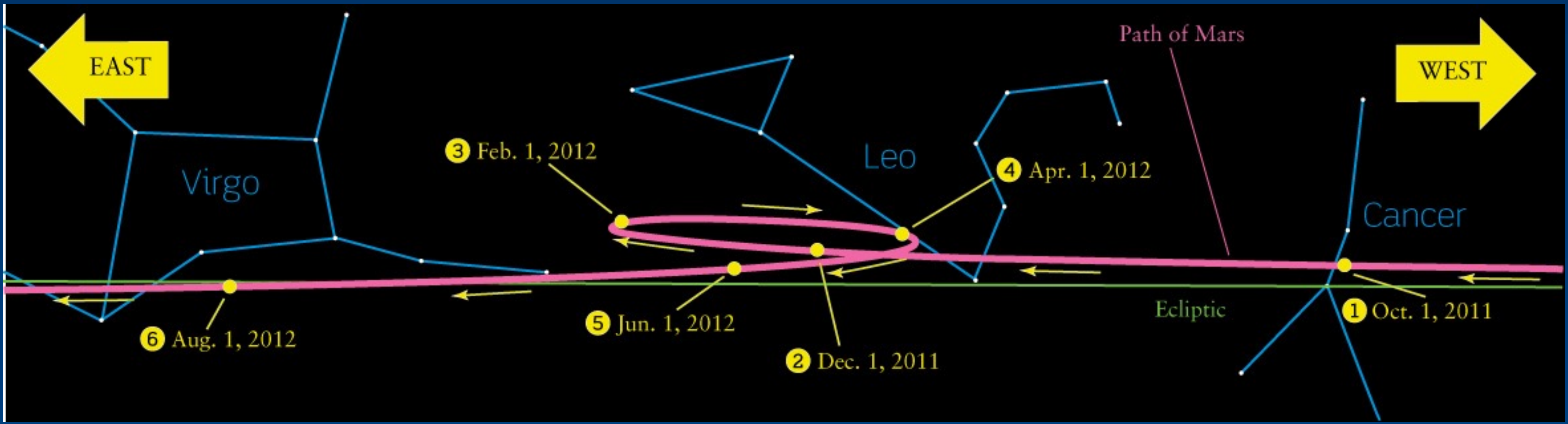
Aristarchus: Used geometry of eclipses to show Sun bigger than Earth (and Moon smaller), so guessed that Earth orbits the Sun. Also guessed Earth spins on its axis once a day => apparent motion of stars.

Aristotle: But there's no wind or parallax.

Aristarchus: Yes, sir

Difficulty with Aristotle's "Geocentric" model: "Retrograde motion of the planets".

The planets move across the celestial sphere near the ecliptic, but sometimes they stop, go backwards for a while, then continue on as normal! This is *retrograde motion*.



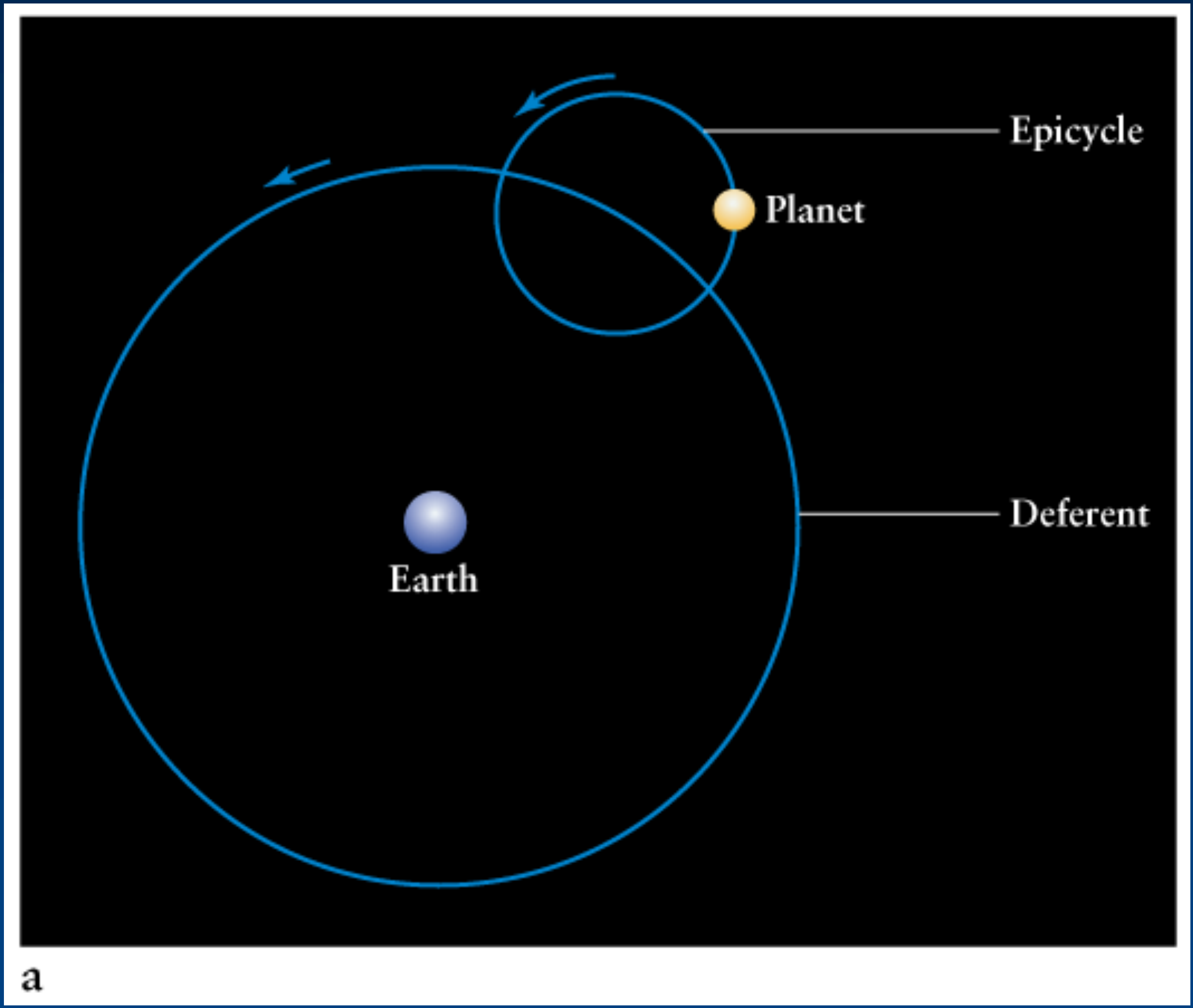
Path of Mars in 2011 - 2012.

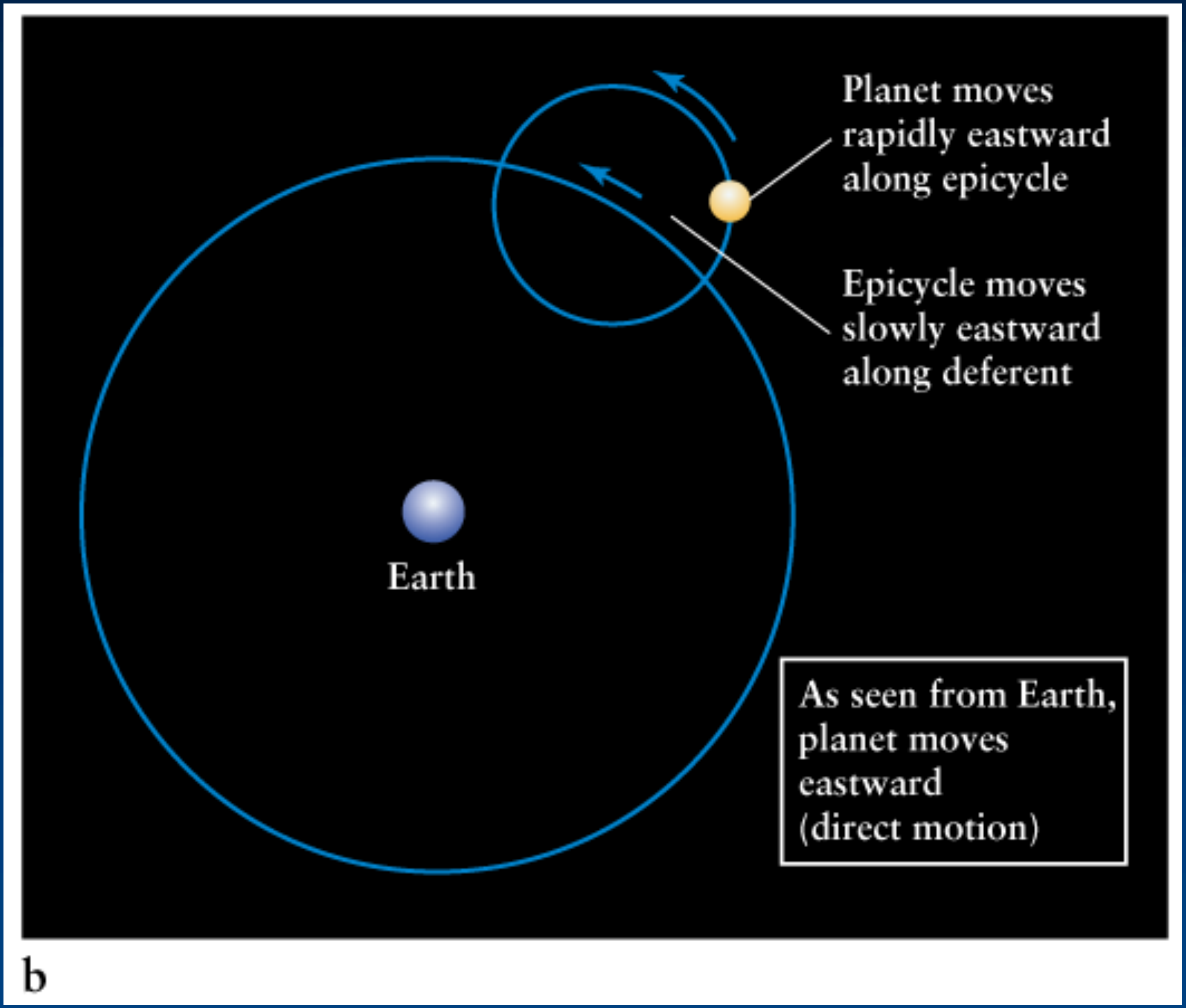
The motion of the planets is not so straightforward!

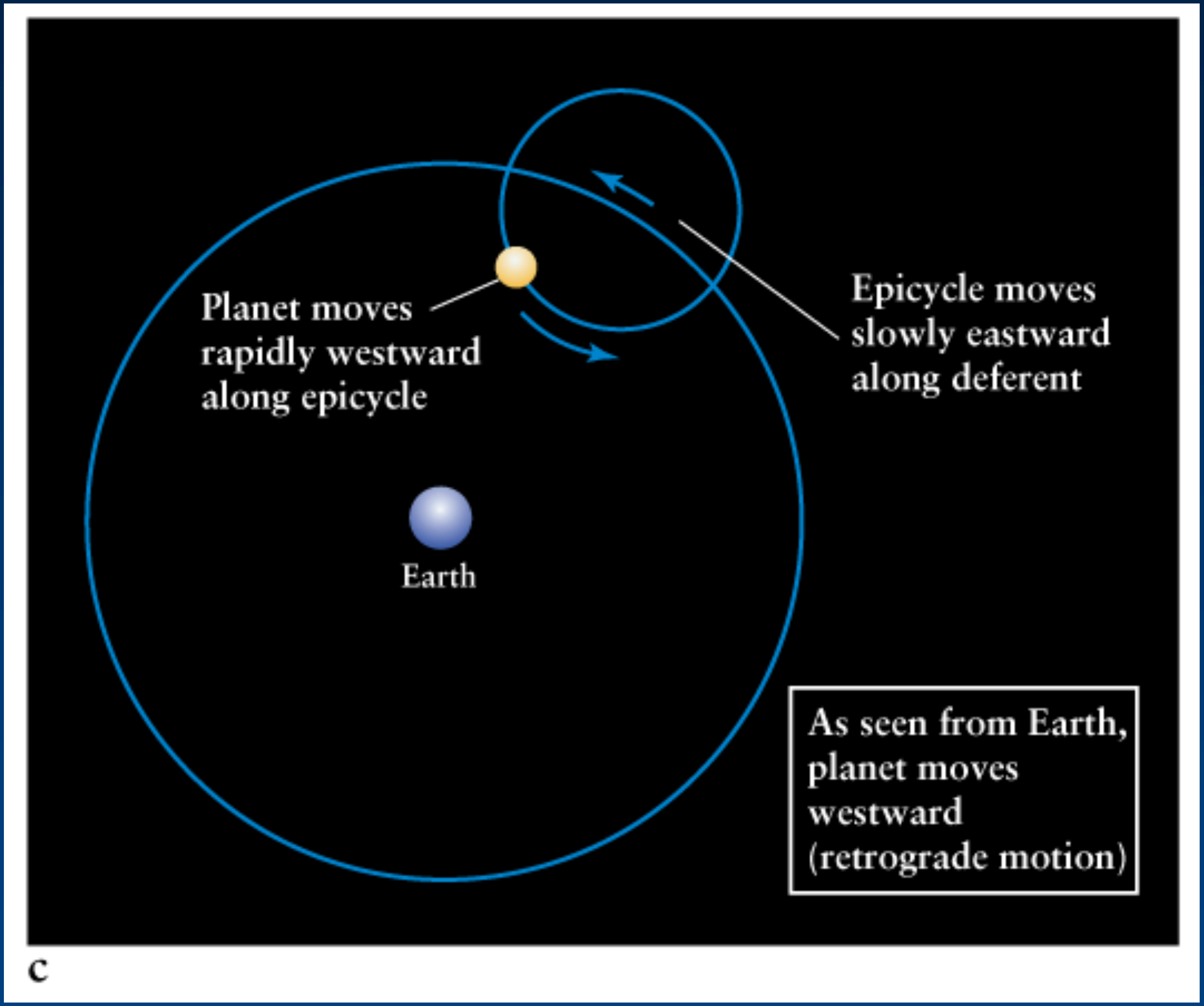
The accepted geocentric model, fine-tuned in the second century A.D., was called the *Ptolemaic system*.

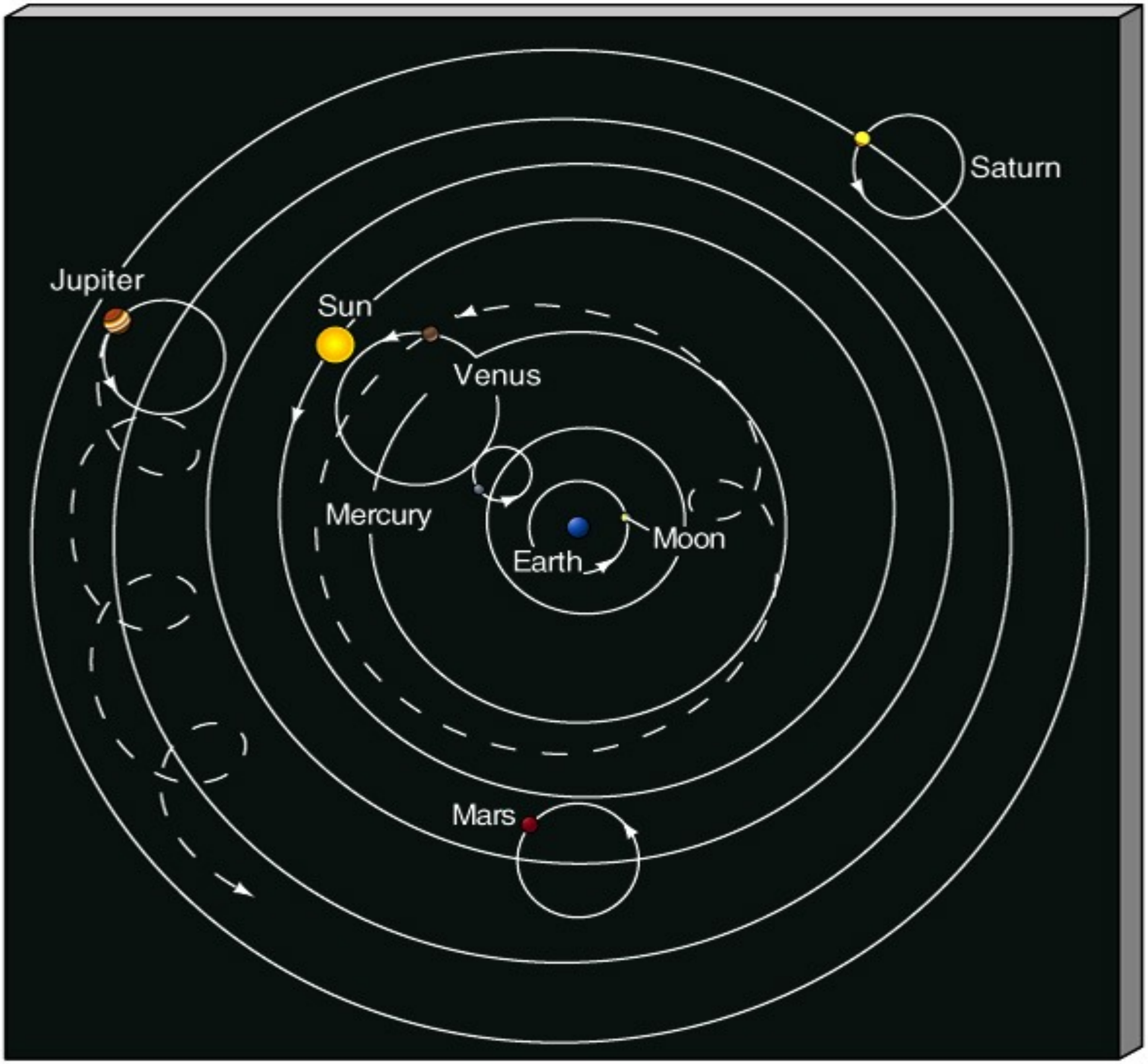
It required complex circles-on-circles to explain retrograde motion.

Ptolemaic system required “deferents” and “epicycles” to explain planetary motion.




Planet moves
rapidly eastward
along epicycle
Epicycle moves
slowly eastward
along deferent
Earth
As seen from Earth,
planet moves
eastward
(direct motion)
b


Planet moves
rapidly westward
along epicycle
Epicycle moves
slowly eastward
along deferent
Earth
As seen from Earth,
planet moves
westward
(retrograde motion)
c

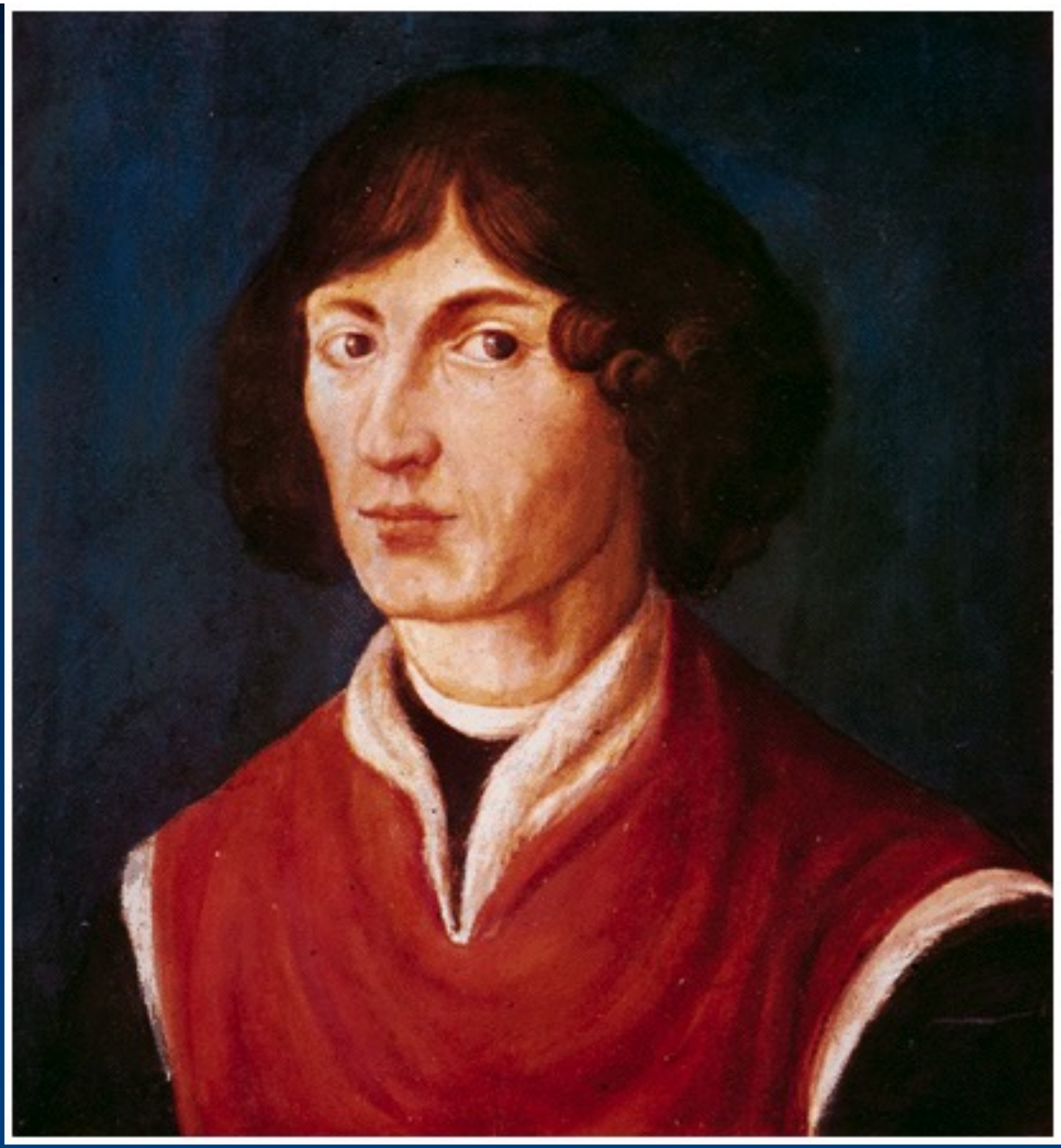

Saturn
Jupiter
Sun
Venus
Mercury
Moon
Earth
Mars

Ptolemaic system could explain the motions and could predict them, but was messy, and got messier as observations improved.

System was used for over a thousand years
(even taught in "Astro 101" at Harvard in its early days!).

"If the Lord Almighty had consulted me before embarking upon the Creation, I should have recommended something simpler.“

Alfonso X El Sabio "The Wise", of Castile (1221-1284) upon being instructed in the Ptolemaic system.

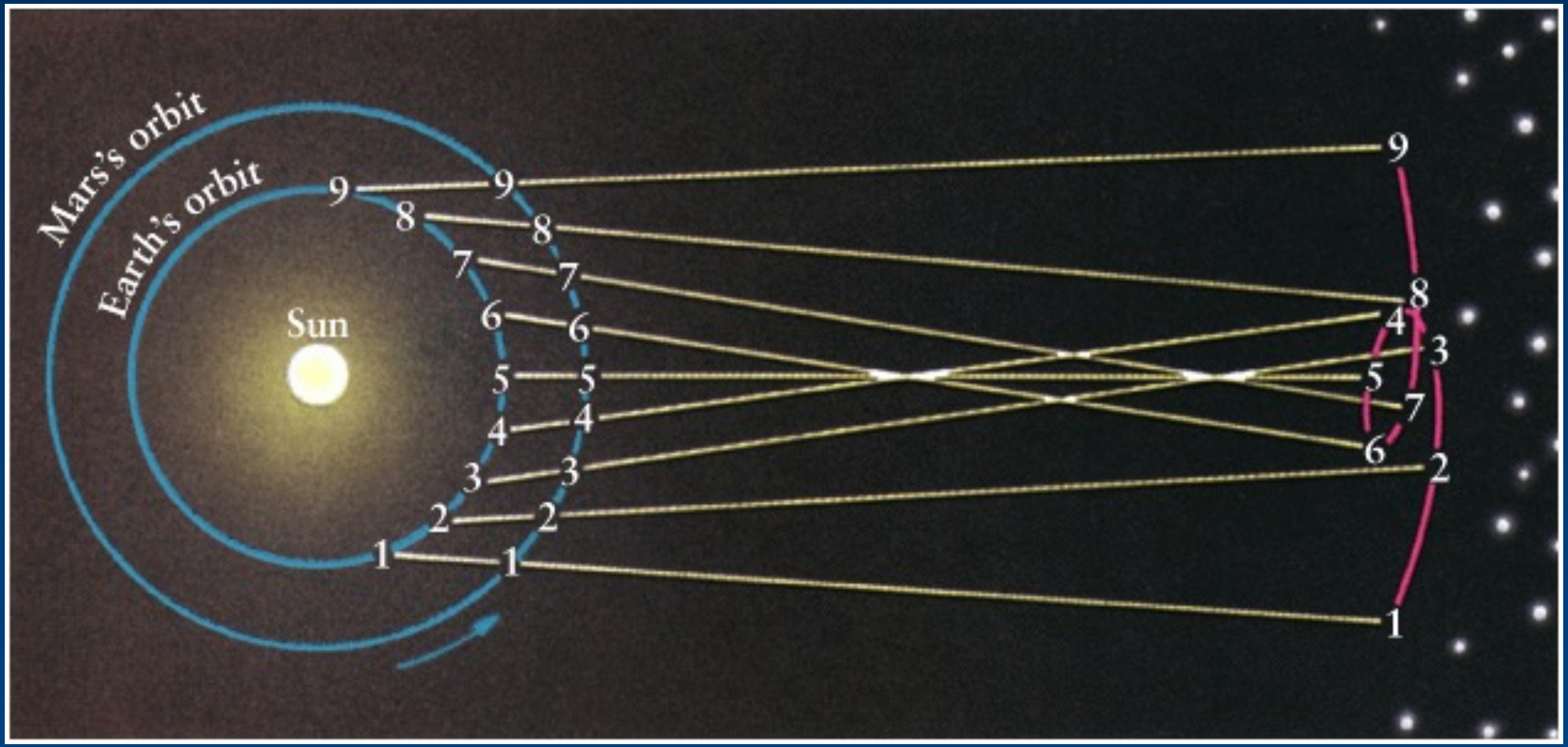


Nicolaus Copernicus (1473 – 1543) developed the first comprehensive heliocentric (= Sun-centered) model.

Copernicus' heliocentric model:

- All planets, Earth included, revolve around the Sun.
- Planets farther from Sun take longer to complete orbit. Orbits are circular.
- Orbits of Earth and planets are nearly in the same plane.
- The Earth rotates on its axis once a day. This explains diurnal motions.
- Simple!

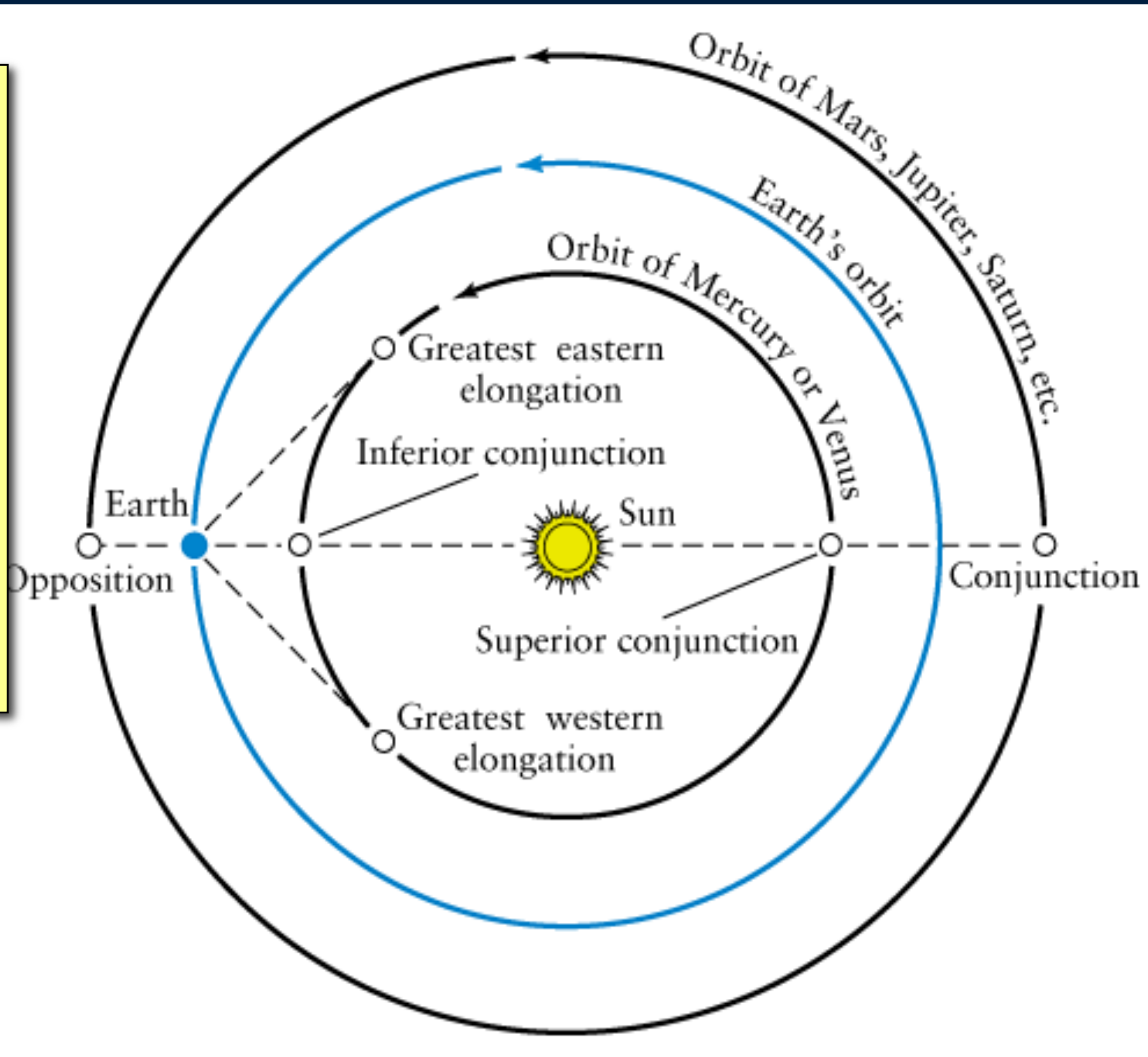
Retrograde motion is explained! The inner planet (Earth) moves faster than the outer one (Mars), creating the apparent motion.



Copernicus noticed Mercury and Venus are never far in angle from the Sun. They are the ***inferior*** planets, which have orbits smaller than Earth's.

The others are the ***superior*** planets, with orbits larger than Earth's.

Stars much further away – no apparent motion except due to Earth’s rotation.

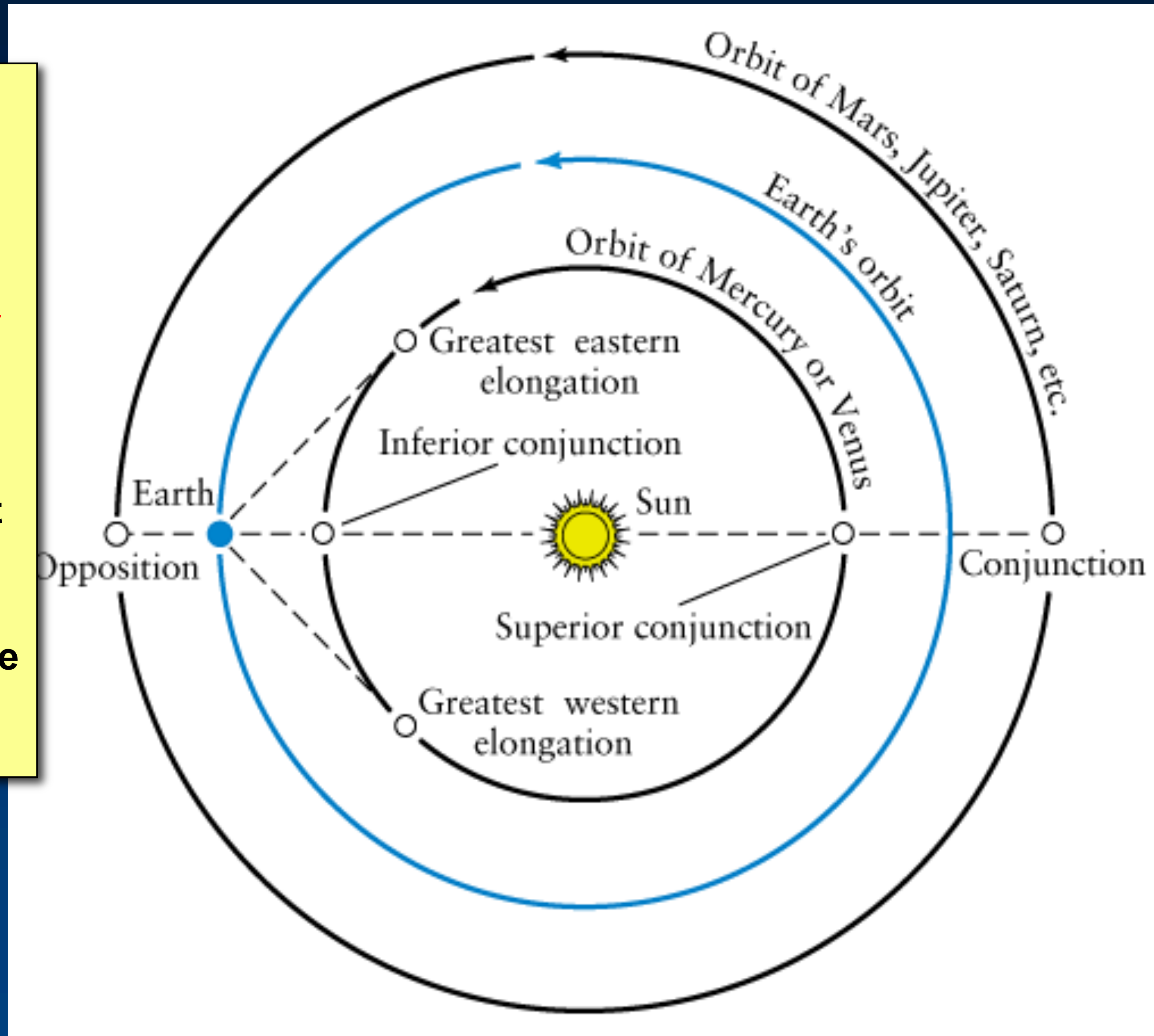


The angle between the Sun and a planet viewed from Earth is the planet's *elongation*.

When a planet is at *inferior conjunction*, it is between us and the Sun.

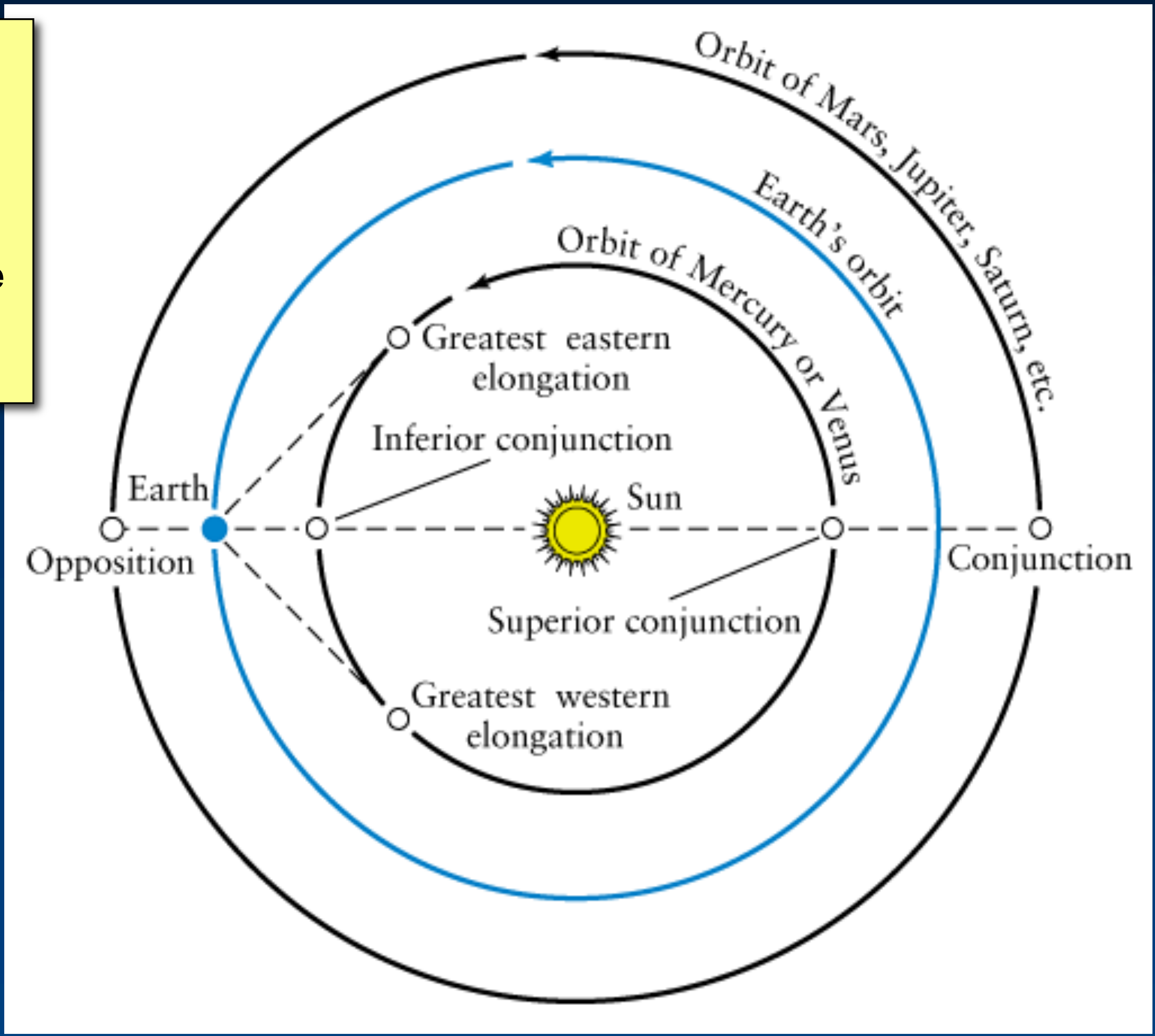
Q: which planets can be at inferior conjunction?

At *superior conjunction*, the inferior planet is on the opposite side of the Sun.



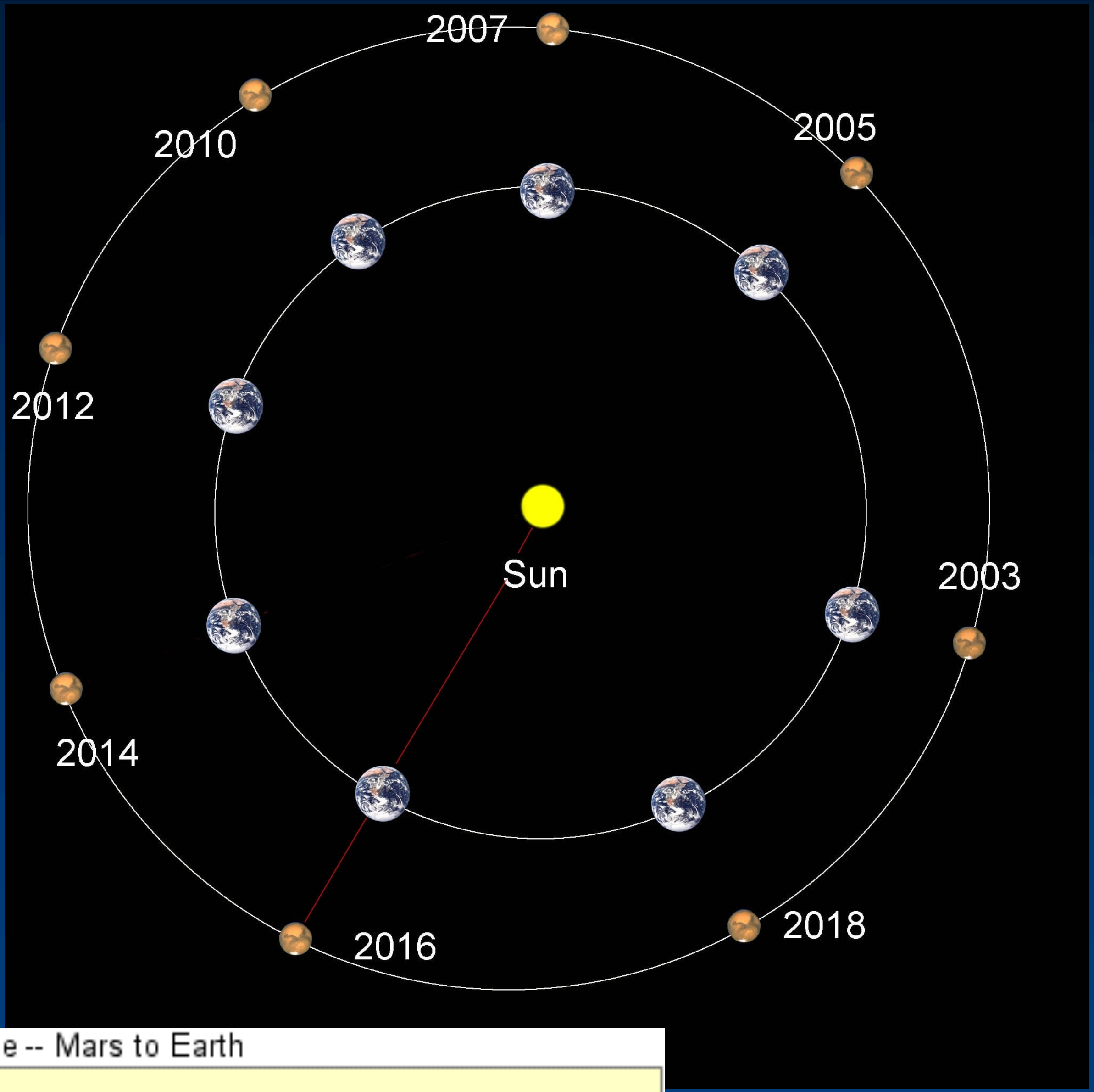
A superior planet at ***conjunction*** is behind the Sun.

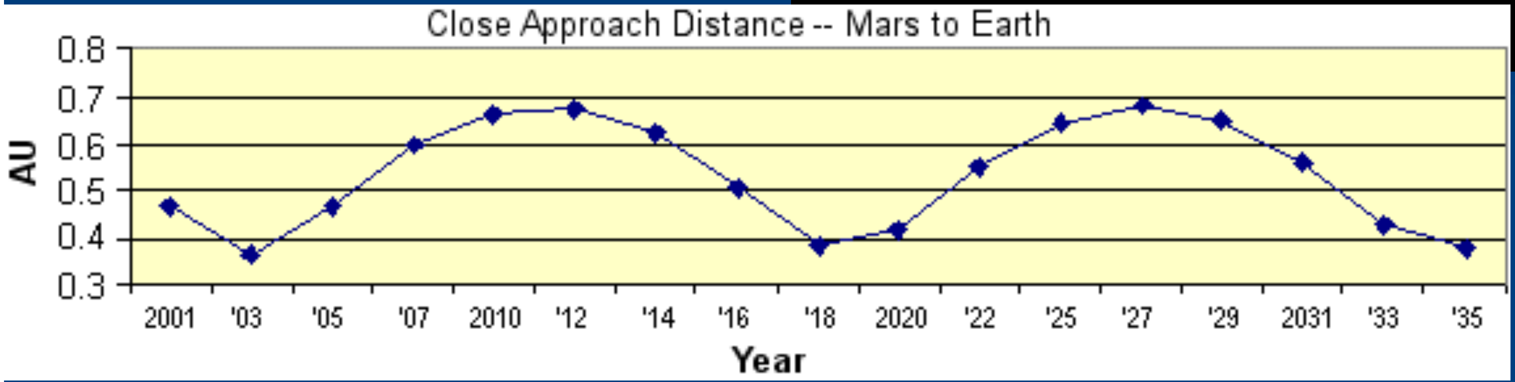
A planet at ***opposition*** is in the part of the sky opposite the Sun.



The motion of Mars and Earth around the Sun, 2003-2018.

The dates show when Mars is at opposition - these are the best times to observe Mars.





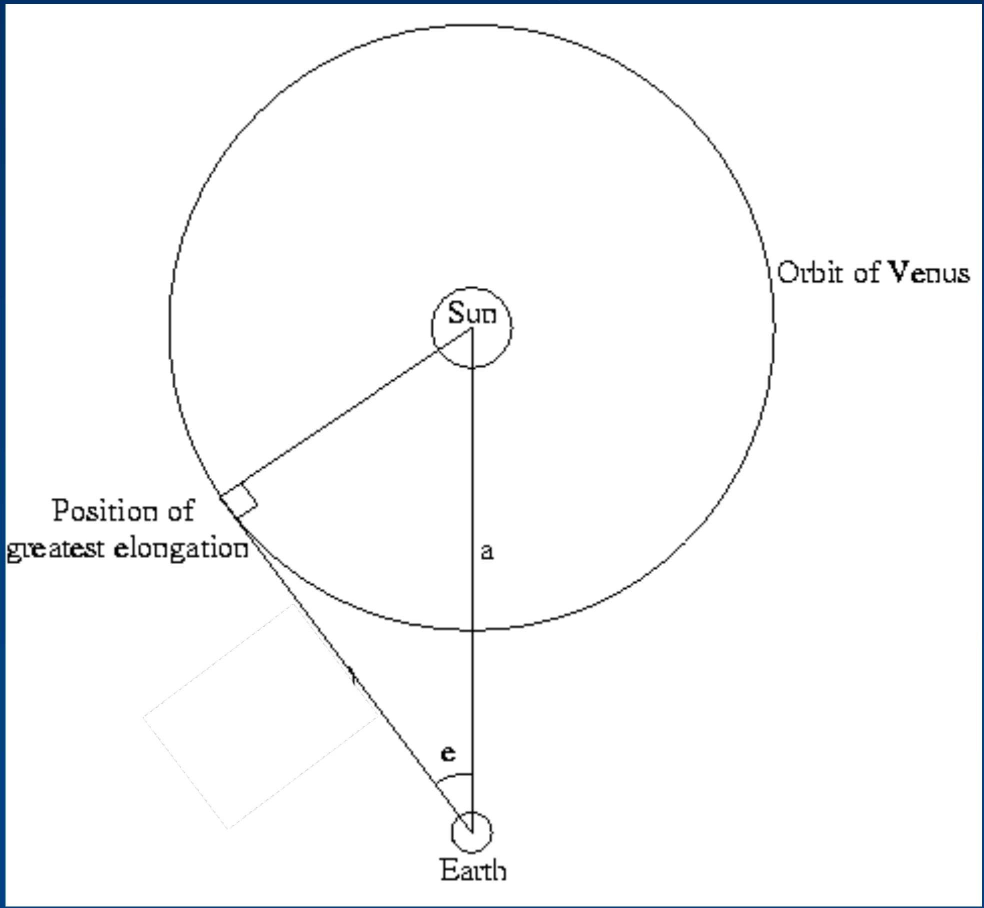
Copernicus could calculate the size of the orbits of the inferior planets relative to Earth's orbit

At greatest elongation, line of sight from Earth to Venus makes an angle of about $e = 46°$ to line of sight from Earth to Sun. And Venus is 24" in angular extent.

Worksheet #3: What is size of Venus orbit in terms of the Earth-Sun distance? And how big is Venus?

Copernicus could calculate the size of the orbits of the inferior planets relative to Earth’s orbit

At greatest elongation, line of sight from Earth to Venus makes an angle of about e = 46° to line of sight from Earth to Sun.



What is size of Venus orbit in terms of the Earth-Sun distance?

1AU = 1.496 x 10^11 m

De revolutionibus orbium coelestium

On the revolutions of the celestial spheres, 1543

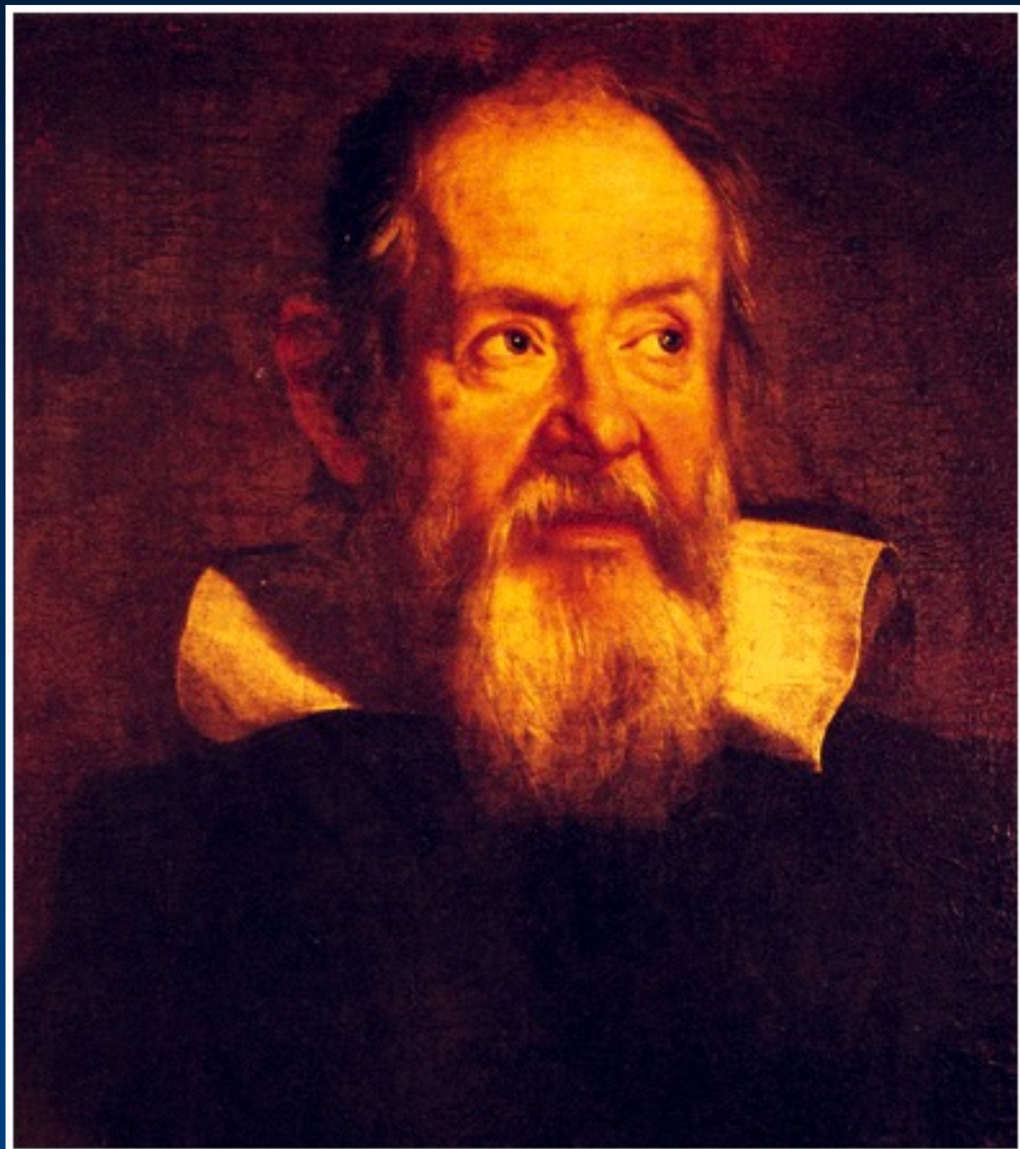
Not immediately accepted!

Wasn't significantly better than Ptolemaic system for calculating planetary positions, and still needed some epicycles (because he insisted on uniform circular motions – Kepler would later show this to be wrong).

Objections to Copernicus's model

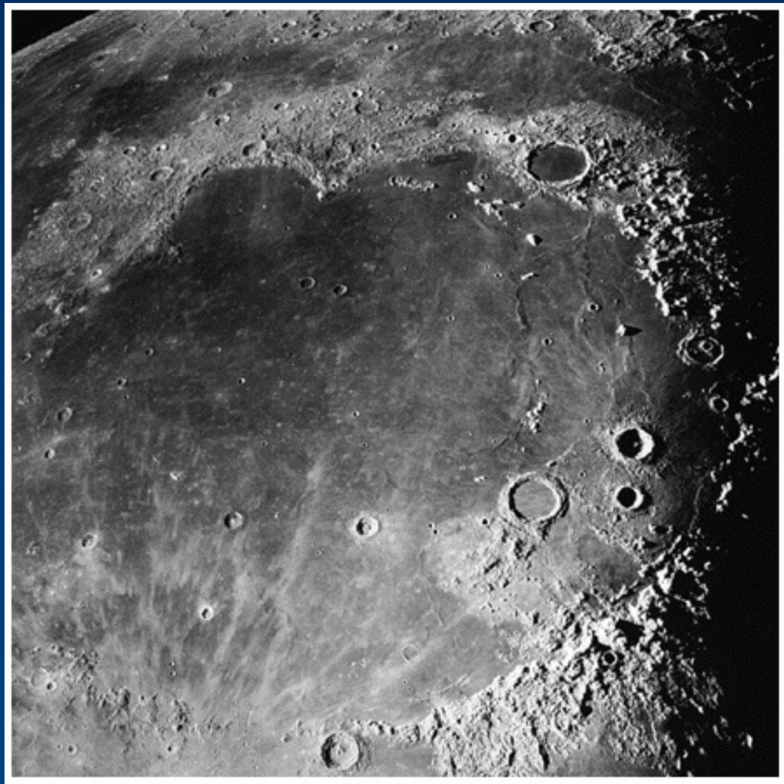
- Religious grounds (Earth not at center!)
- Motions required absurd speeds, rotational 1670 km/h = 0.5 km/s, orbital 30km/s
- No observational evidence of motion (stellar parallaxes)

Copernicus didn't publically advocate his model. But Galileo did, laying the path to its acceptance.



Galileo Galilei (1564 – 1642). Didn't invent the telescope (Dutch invention), but he was first to use it for astronomy.

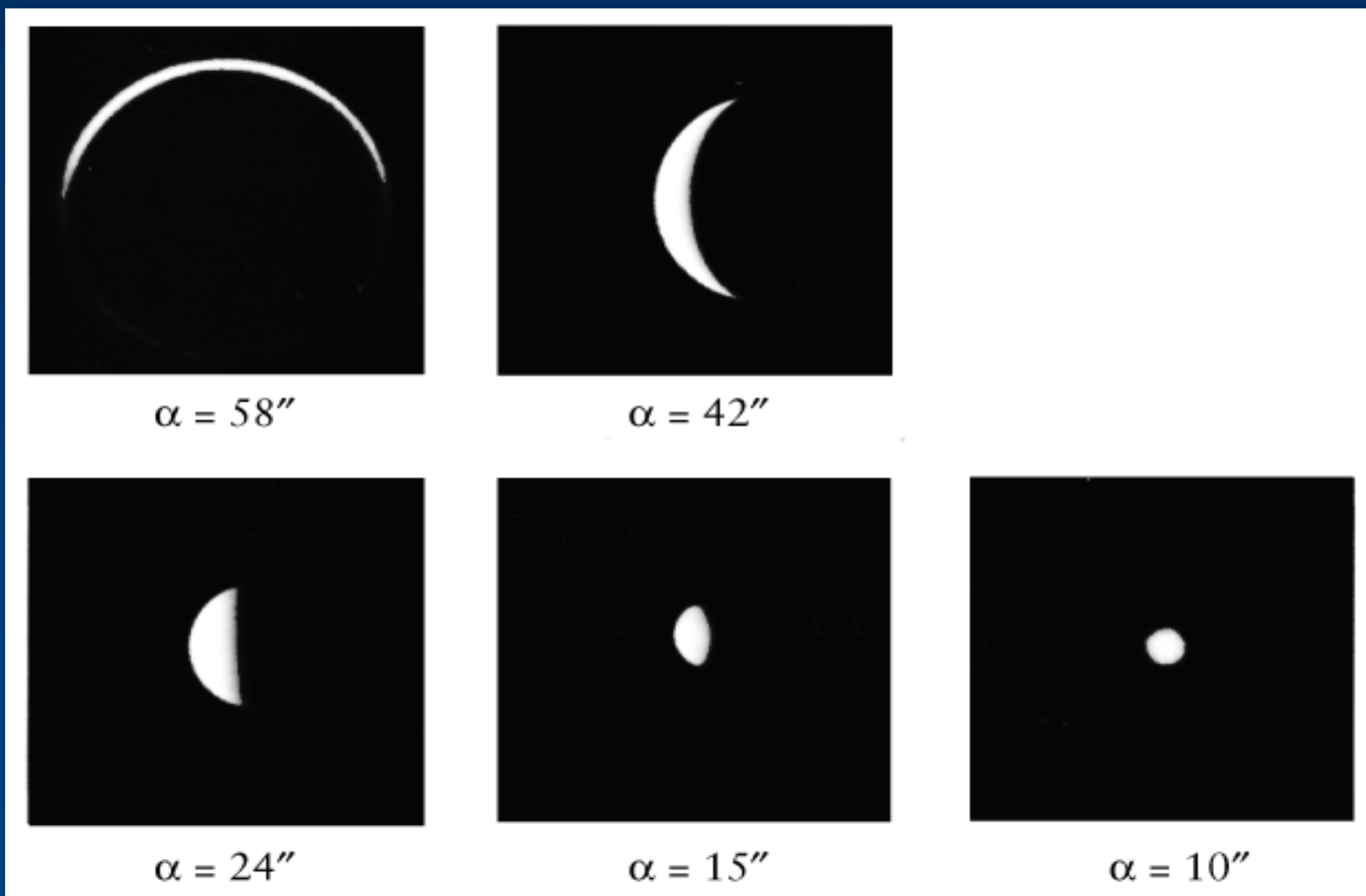
Galileo saw spots on the Sun.
Saw them rotate, inferred Sun does



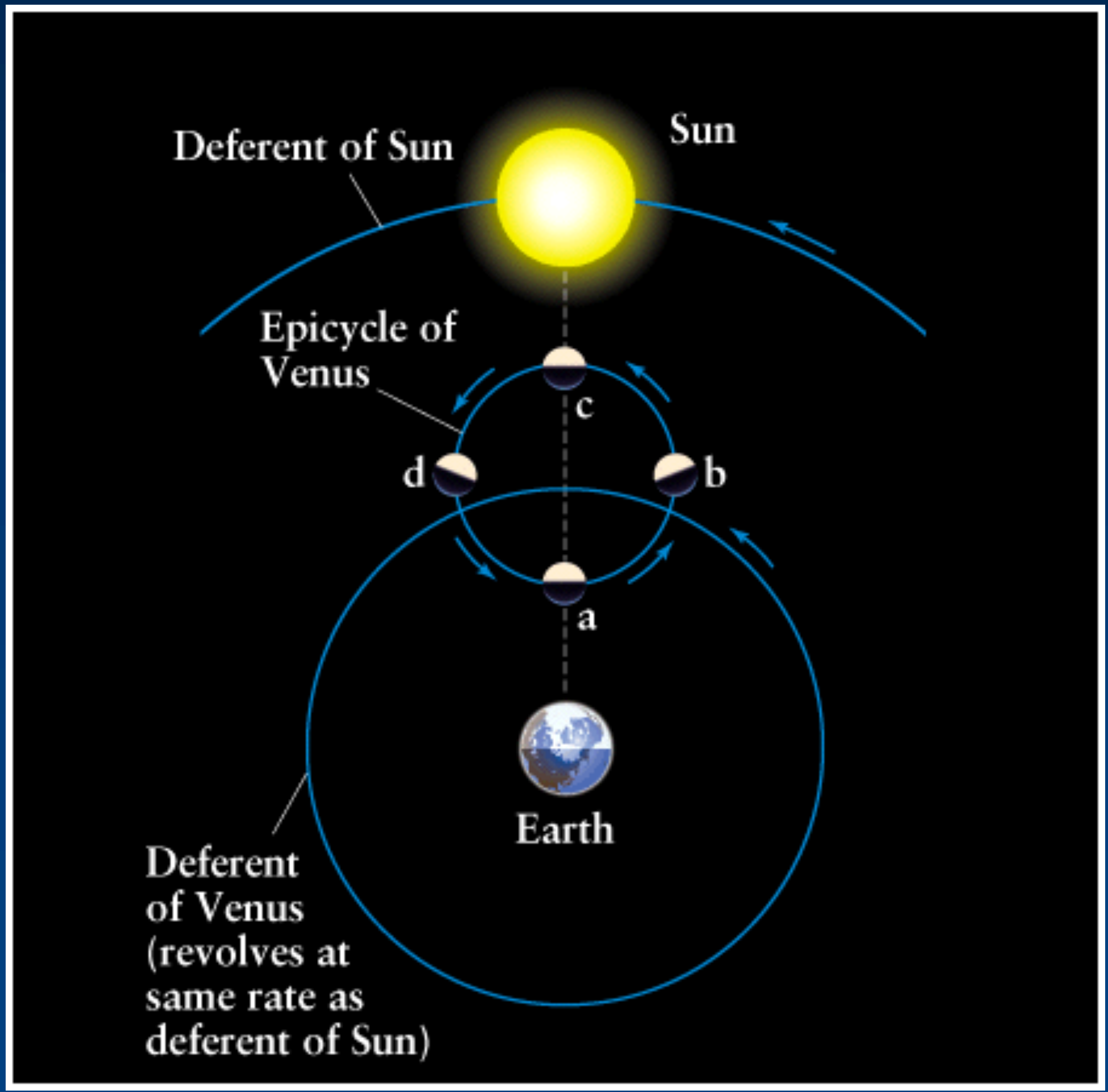
He also saw mountains and craters on the Moon

Galileo's other observations:

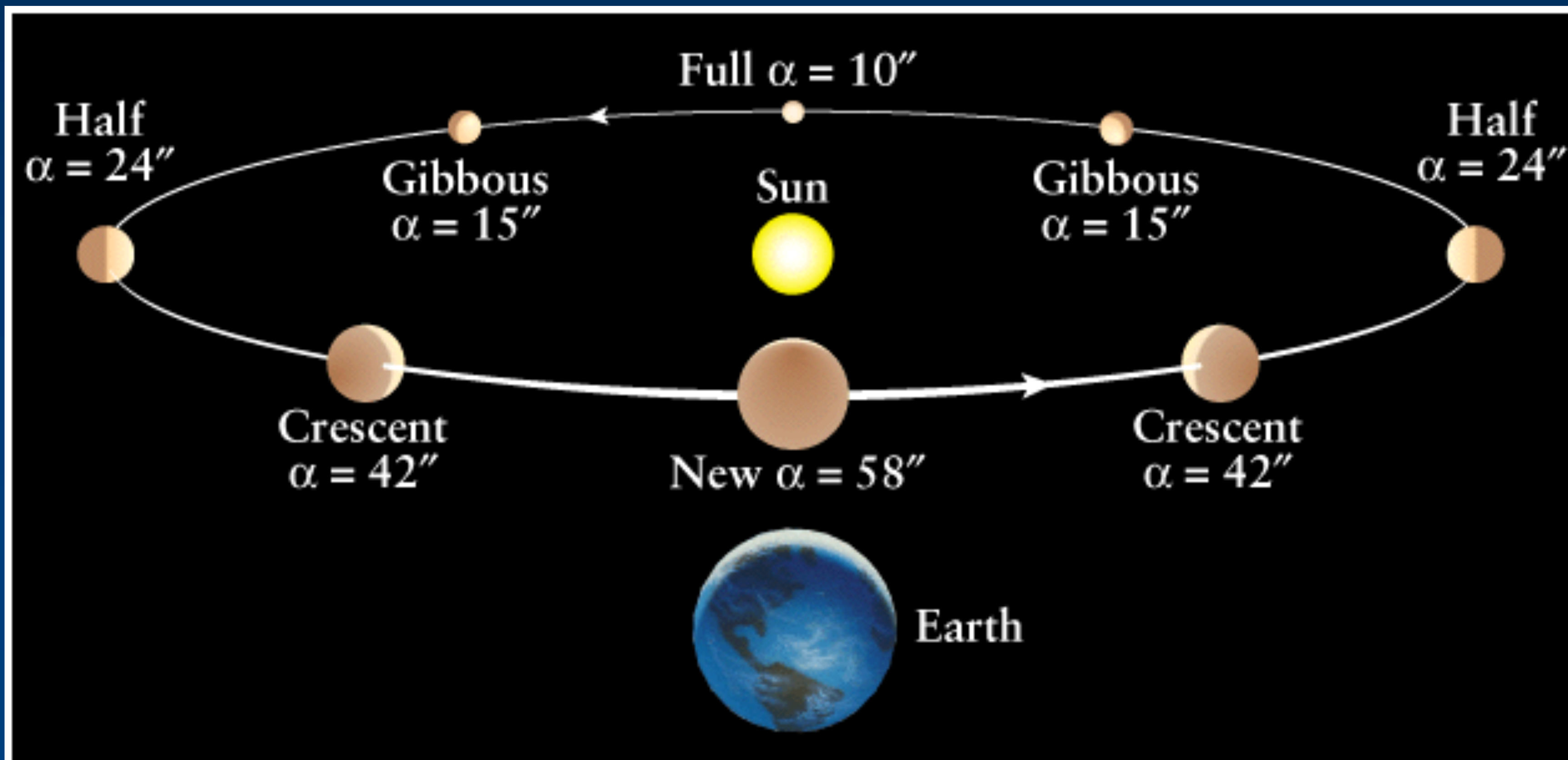
Venus goes through phases, and the angular size changes (these are related. The Ptolemaic model can't explain this.)



In the Ptolemaic model, Venus would always be less than half illuminated.



Phases are easy to understand in heliocentric picture. Note the relation between angular size and phase.



Galileo also discovered 4 bodies which clearly didn’t revolved around the Earth – the “Galilean satellites” of Jupiter.

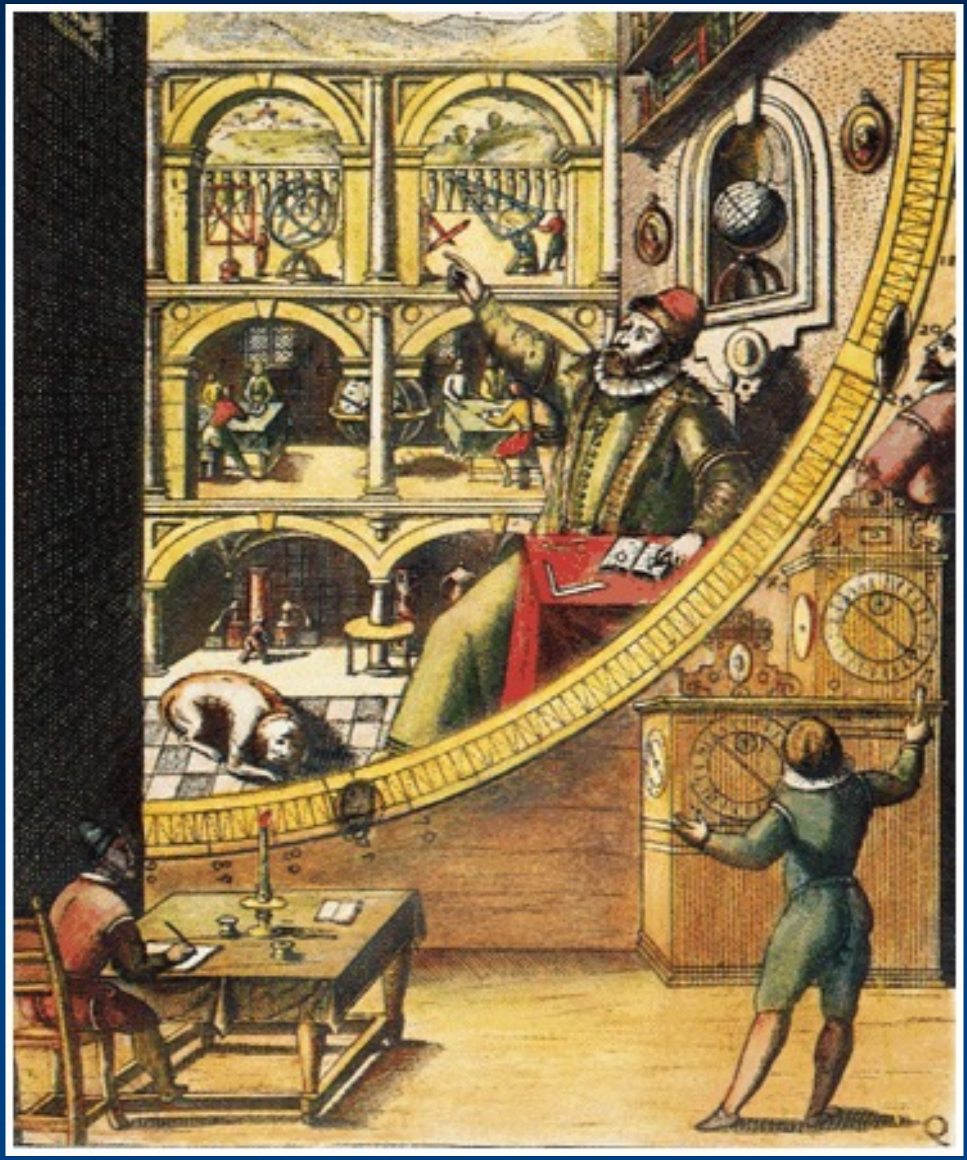
Impact of Galileo's observations

- Skeptics claimed that the telescope was lying…
- …but, many people got their own telescopes (including Kepler), they could see for themselves
- The Copernican system started to be taken seriously
- Galileo's ideas were declared heretical by the Church
- He was forced to recant his ideas, and spent his last years under house arrest (but his ideas were out anyway!)
- …But Copernican model still had inadequacies…

Tycho Brahe (1546-1601)

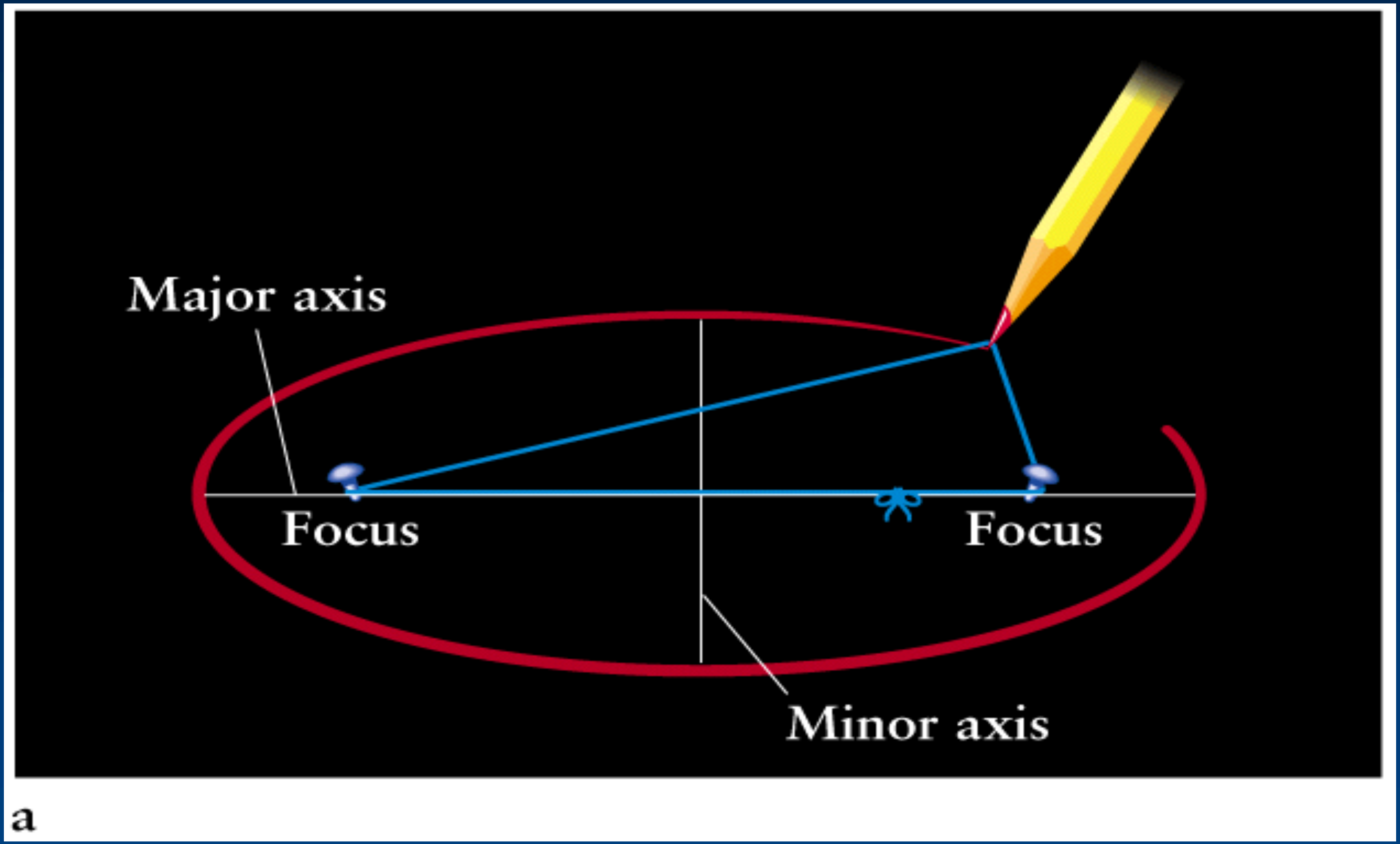
Made two huge contributions:

1. He made very careful observations of planetary positions over time,
2. He hired Johannes Kepler as his assistant.



Johannes Kepler (1571 – 1630) analyzed Tycho's accurate planetary position data.

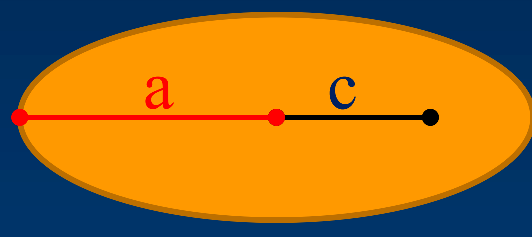
Kepler determined that planets move on elliptical orbits.

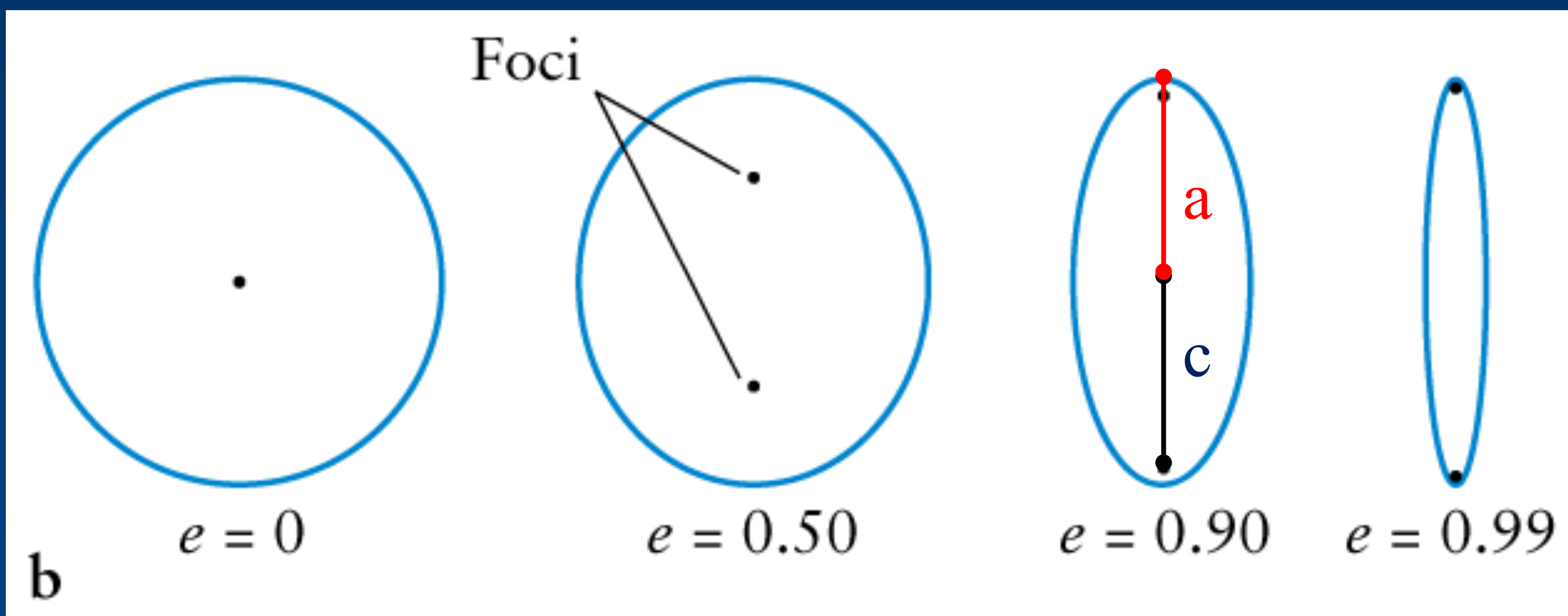


The *semimajor axis* of an ellipse is half of the major axis, and is usually denoted “a”.

The *eccentricity* of the ellipse measures how squashed it is. If the distance from the center of the ellipse to a focus is “c”, then

$$e = \frac{c}{a}$$





Eccentricity also relates major and minor axes: $b = a\sqrt{1-e^2}$

Kepler's first law: The orbit of a planet about the Sun is an ellipse with the Sun at one focus.

The semimajor axis of a planet's orbit is the average distance between the planet and the Sun.

Examples: planetary orbit with smallest eccentricity is Venus (e = 0.007). Largest is Mercury (e = 0.206). For Earth, e = 0.017.

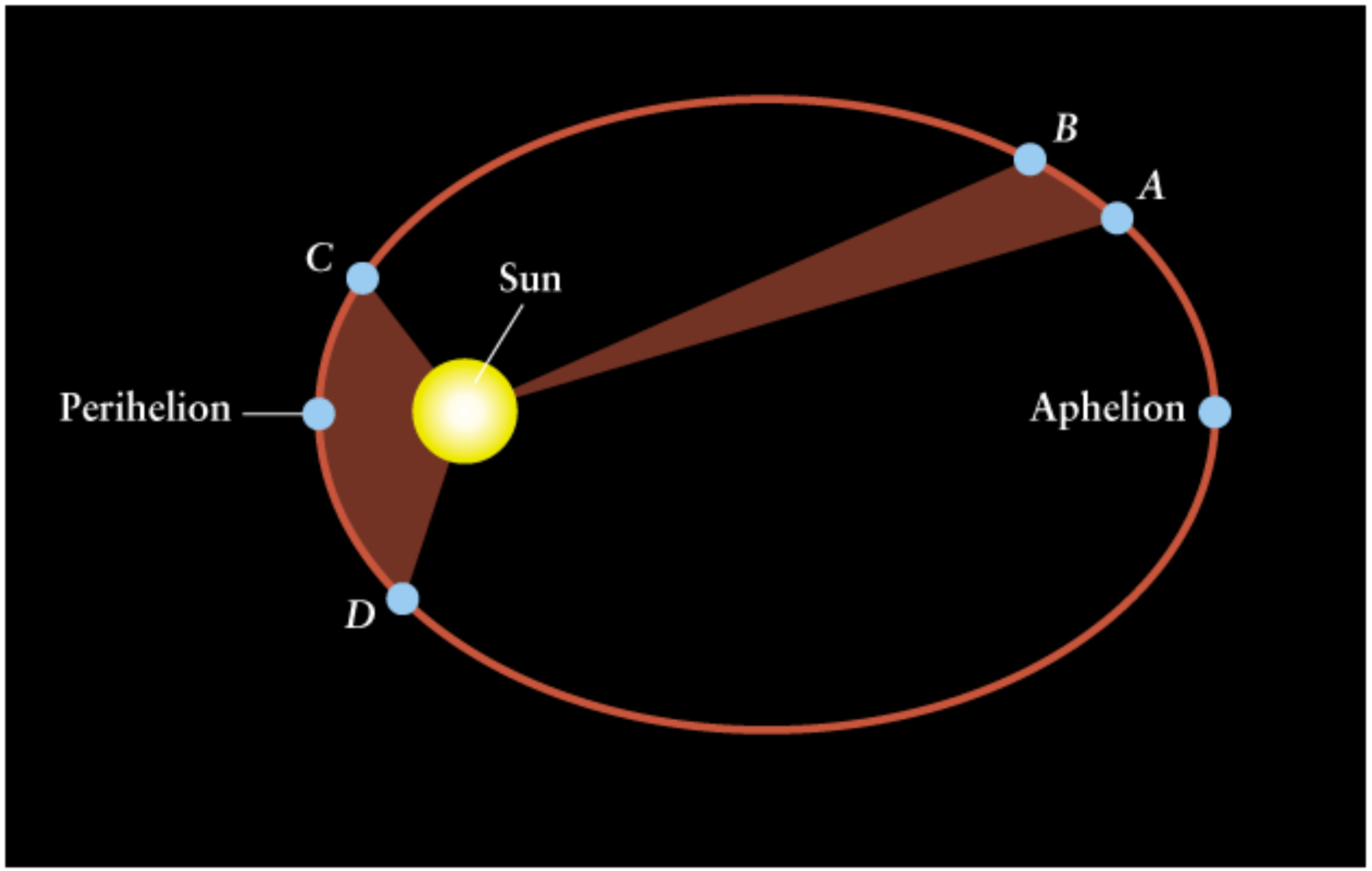
Knowing *a* and *e* specifies ellipse size and shape.

Kepler's second law: a line joining a planet and the Sun sweeps out equal areas in equal intervals of time.

In other words, a planet moves fastest when it is nearest the Sun, and slowest when it is farthest away from the Sun.

Perihelion = point in orbit closest to the Sun.

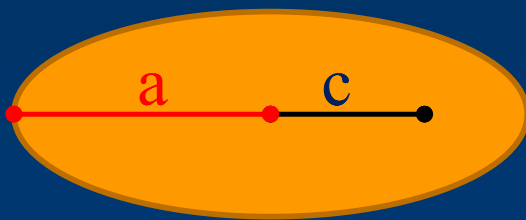
Aphelion = point in orbit farthest from the Sun.



Time it takes planet to go from point A to point B is the same as it takes to go from point C to point D.

(Advanced note: this law is a direct consequence of conservation of angular momentum) DEMO

We can calculate the distance from a planet to the Sun at perihelion and aphelion.



$D_{peri} = a – c = a – ae = a(1 - e)$

$D_{ap} = a + c = a + ae = a(1 + e)$

Kepler's third law: The square of the sidereal period of a planet is directly proportional to the cube of the semimajor axis of the orbit.

$\Rightarrow$ The larger the planet's orbit, the longer it takes the planet to go around the Sun.

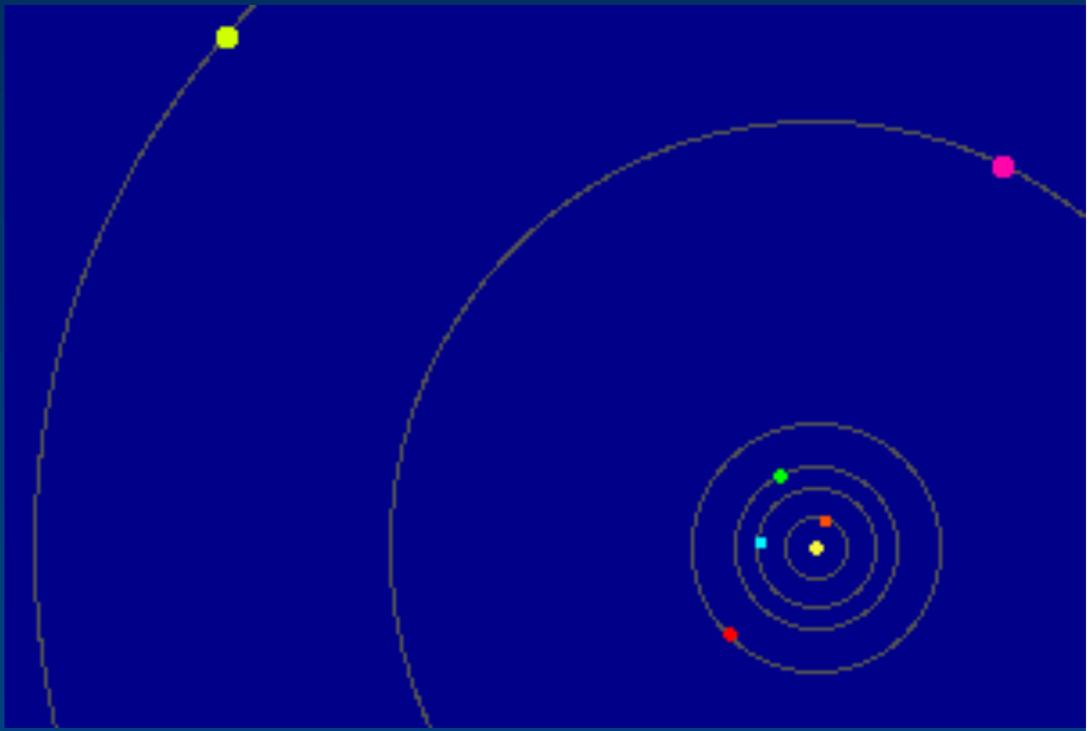
$\Rightarrow P^2 \propto a^3$

$\Rightarrow P^2 = a^{3,}$ when P is measured in years, and a is measured in AU

Example: For Earth, P = 1 year, a = 1 AU, so $P^2 = 1 = a^3$

More interesting example: For Venus, we know a = 0.72 AU What is P? $P^2 = a^3$, so

$P = \sqrt{a^3}$ = 0.61 years.



Kepler had no idea why these laws worked. That took Newton!

Solar System Orbits