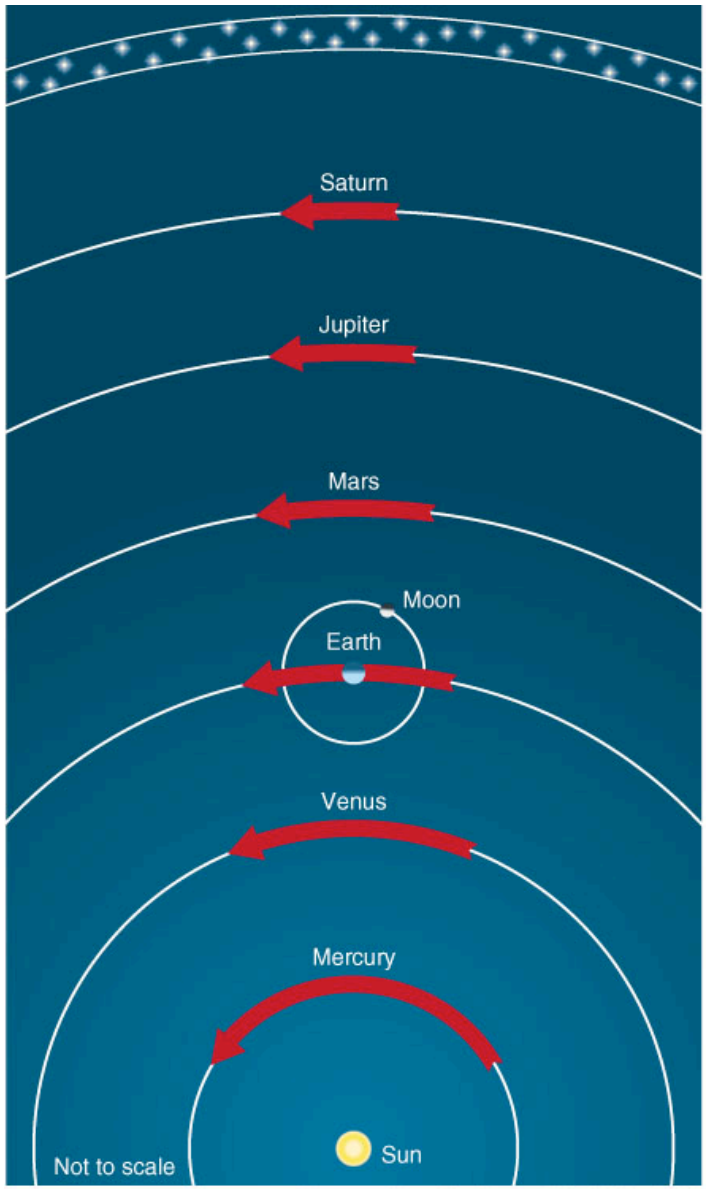
Basics of Kepler and Newton

Orbits of the planets, moons, …

Kepler's Laws, as derived by Newton.

- Kepler's Laws
- Universal Law of Gravity
- Three Laws of Motion
- Deriving Kepler's Laws

Recall: The Copernican Model

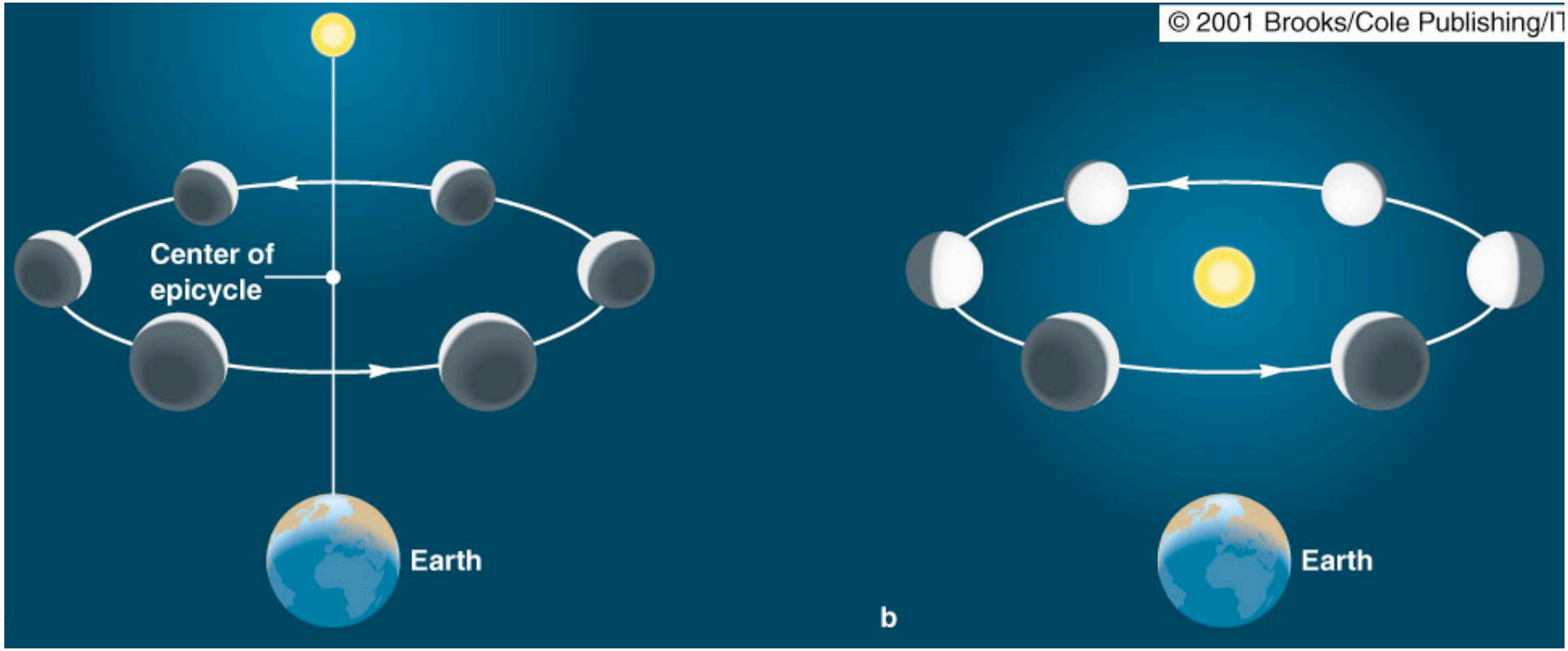


- Postulated planets orbit Sun, not Earth
- Worked out correct order of planets from Sun
- Realized planets near Sun move fastest
- Accurately measured distances of planets from Sun, and orbital periods

Telescopic observations of the phases of Venus confirm the heliocentric model

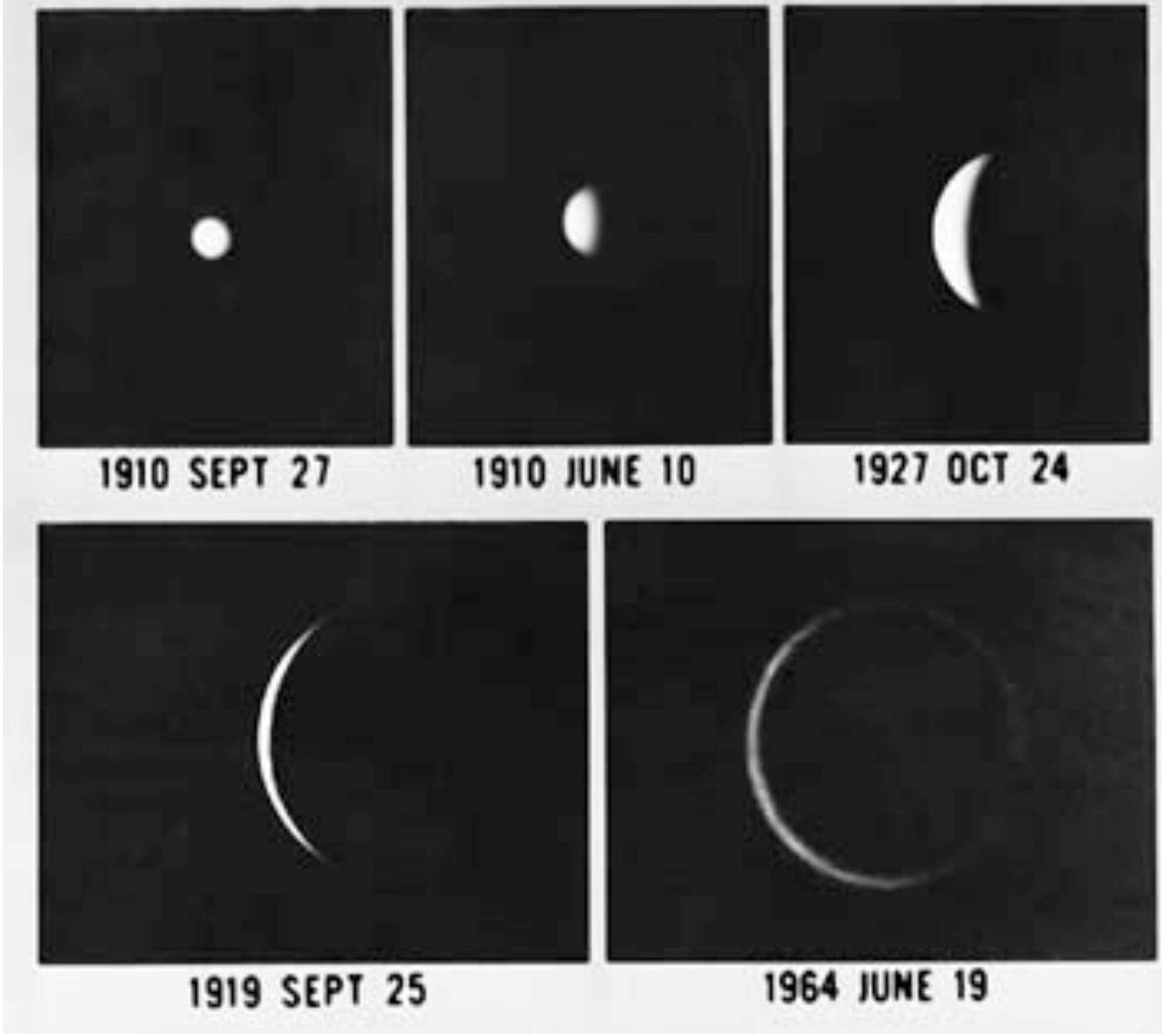
Geocentric

Heliocentric



Always crescent

Full range of phases


1910 SEPT 27
1910 JUNE 10
1927 OCT 24
1919 SEPT 25
1964 JUNE 19

Tycho Brahe (b.1546)

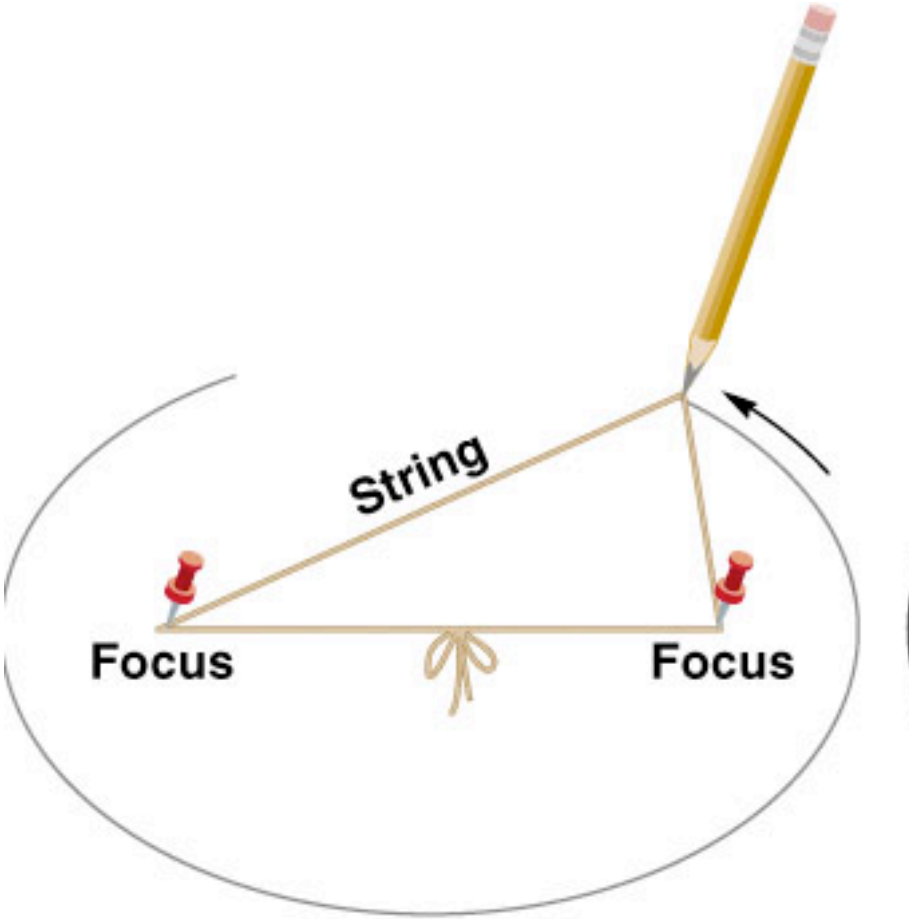
Collected most accurate observations of planetary motions to date. Found Copernican model still did not agree with data.

Kepler (b.1571)

Hired as an assistant by Tycho to interpret observations of planetary motion.

Kepler's Three Laws

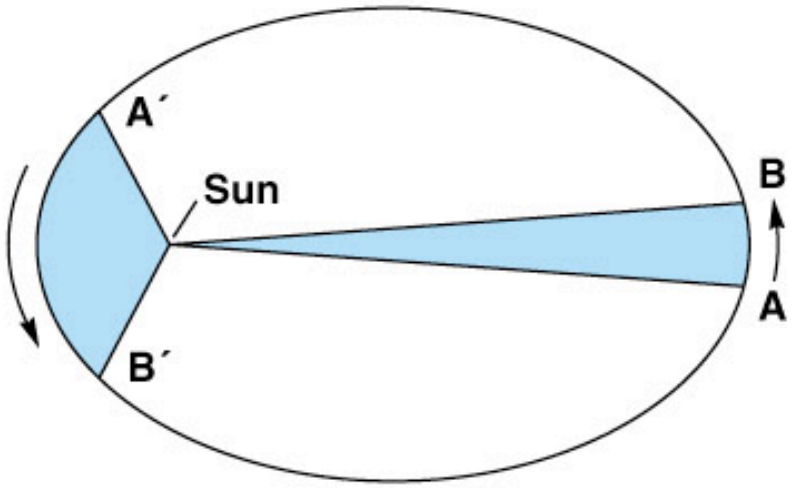
I. Orbits of planets are ellipses with sun at one focus



a

Kepler's Three Laws

II Line from planet to sun sweeps out equal areas in equal intervals of time



b

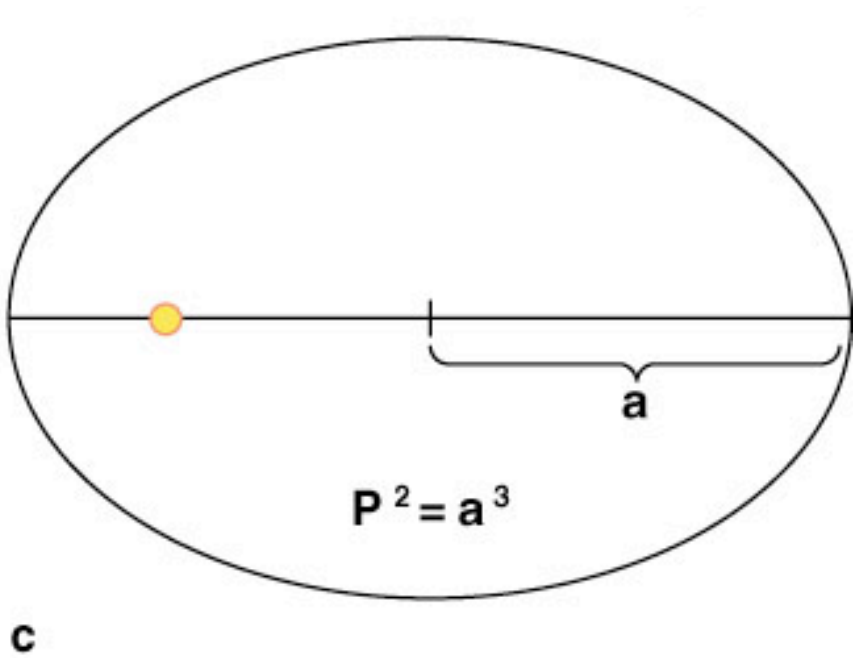
Kepler's Three Laws

III Planet's orbital period squared is proportional to its average distance from sun cubed:

$$P^2 = a^3$$

P is period in years

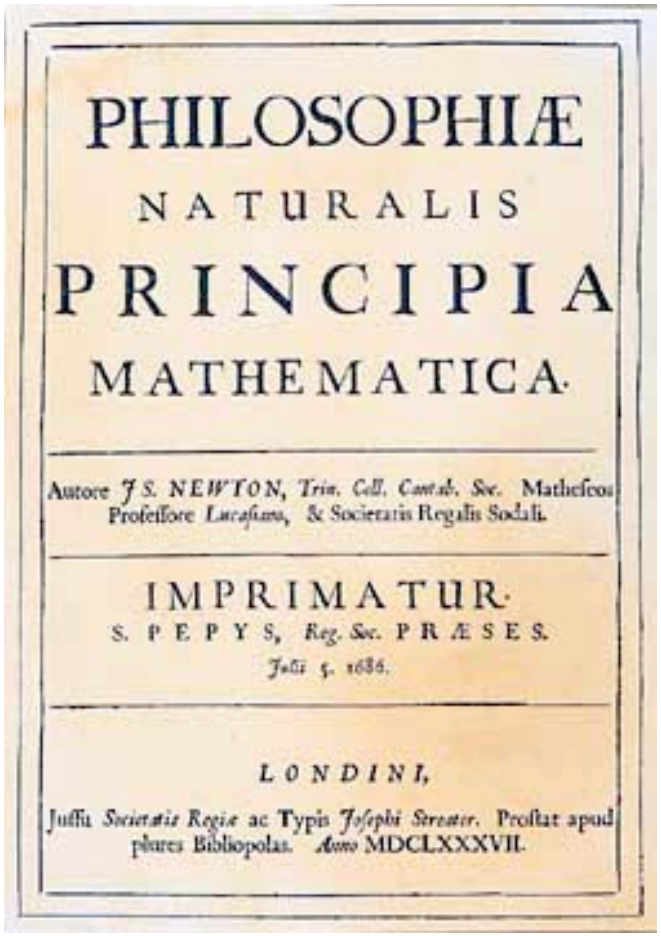
a is average distance in AU



c

Newton (b.1642)

Mathematician and physicist. Developed Laws of mechanics and gravity, and invented calculus, to explain planetary motion



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,
Justu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Newton's Laws of Motion

I An object

at *rest* continues so or

in *uniform motion* continues so

unless acted upon by some (net) *force*

The momentum of an object remains constant unless it experiences an external force

Principle of Inertia

Newton's Laws of Motion

II A body's *change* of motion is proportional to the force acting on it, and in the direction of the force.

$$\mathbf{F} = m\mathbf{a} = m(d\mathbf{v}/dt) = (d\mathbf{p}/dt)$$

Where m is mass of body, and $\boldsymbol{a}$ its acceleration (any change in speed **or** direction), $\boldsymbol{v}$ is velocity, $\boldsymbol{p}$ is momentum, $m\boldsymbol{v}$

Newton's Laws of Motion

III When a body exerts a force on a 2nd body, the 2nd body exerts an equal but oppositely directed force on the 1st body

Action – Reaction

$\mathbf{F}_{12}=-\mathbf{F}_{21}$

Laws applied to planetary motion

- First law says there must be a force acting on the planets
- Newton realized that force must be *gravity*, that inverse-square-law forces lead to elliptical orbits

Gravity

- Same force that causes an apple to fall to Earth causes the Moon to orbit the Earth
- Law of Gravity: gravitational force between two masses M and m separated by distance R is

$$F = -G M m / R^2$$

G is a constant number (6.67×10^{-11} Nm^2/kg^2 = 6.67×10^{-8} (cgs))

Kepler's Laws explained

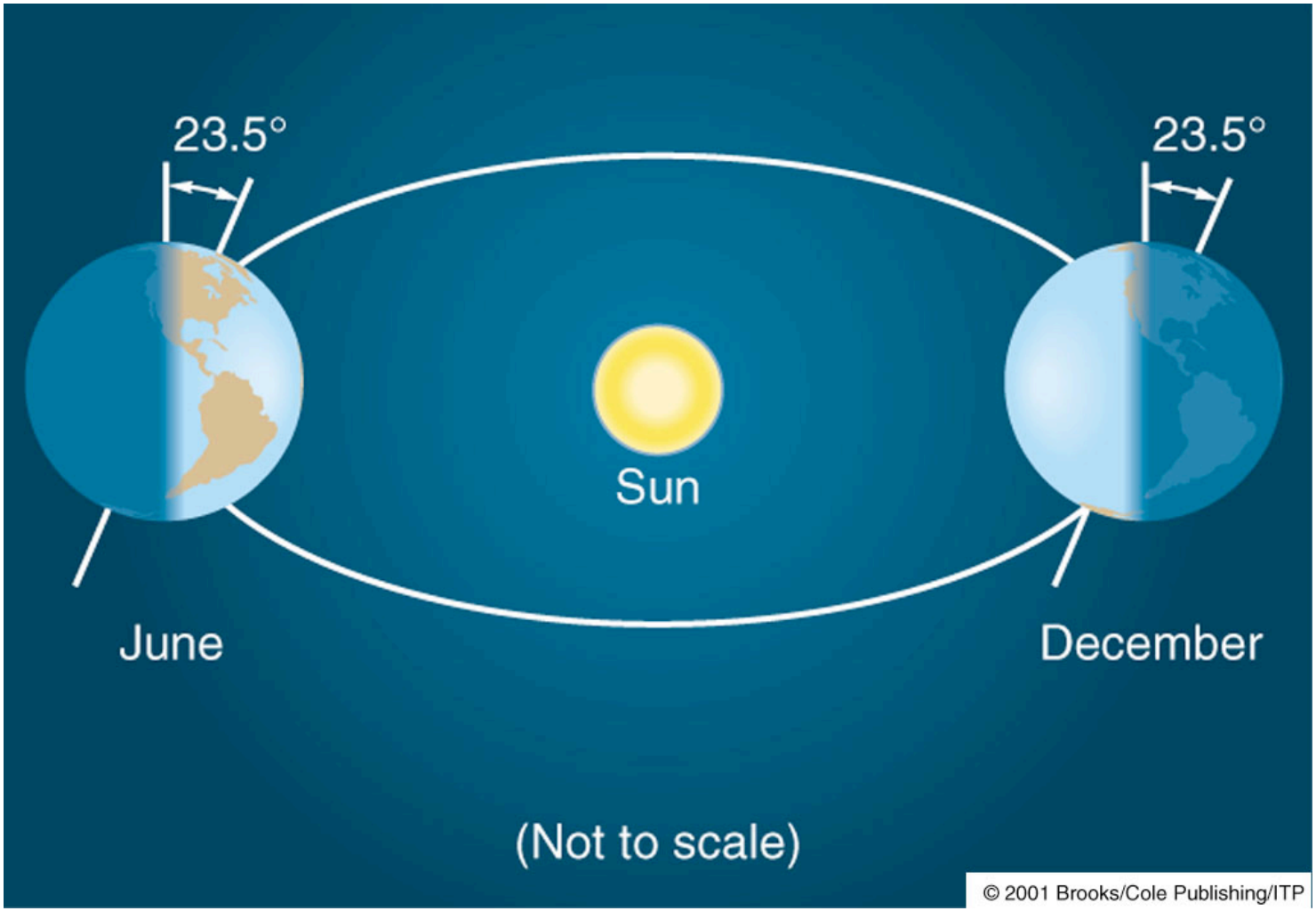
- Using only Laws of Mechanics and Gravity (and *the calculus*), Newton could derive Kepler's three laws.
- Kepler *discovered* them, but Newton *understood* them.

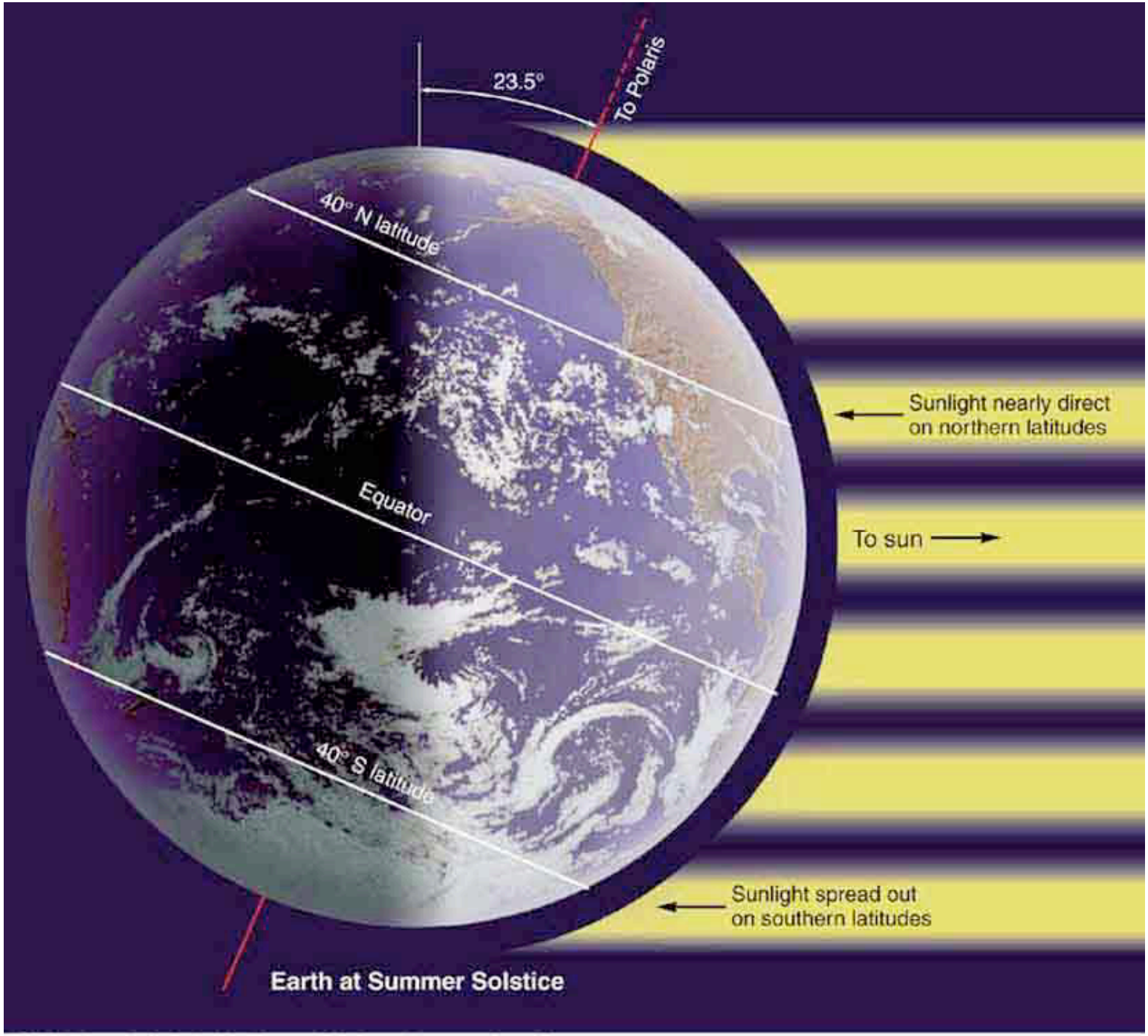
Earth-Moon Orbital and Dynamical System

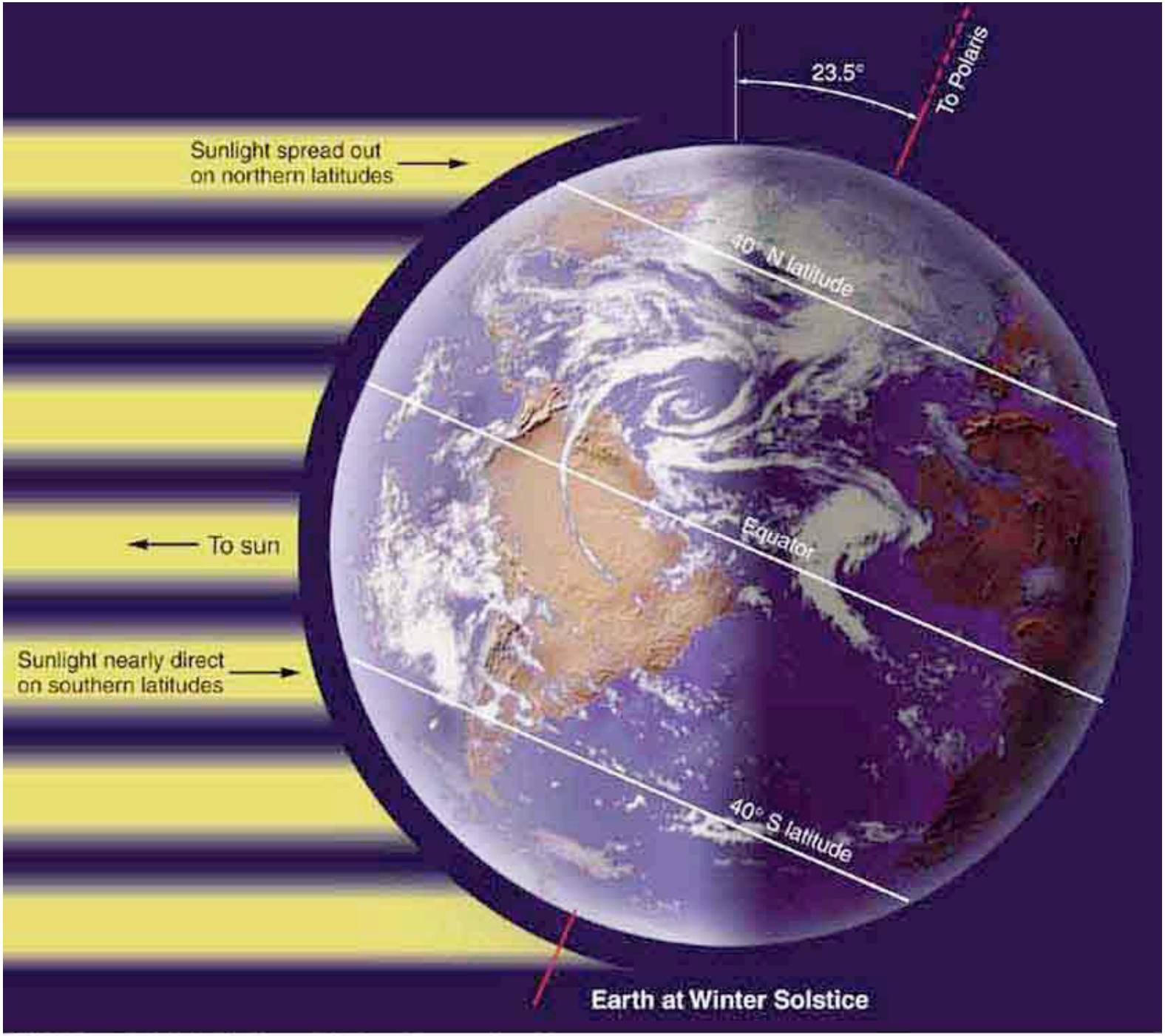
The Earth: basic facts.

- Average distance from Sun = 1 AU
- Perihelion = 0.983 AU
- Aphelion = 1.017 AU – pretty low e
- Orbital period = 1 year (by definition)
- Tilt of axis = 23.5 degrees
- Rotation period = 23 hr, 56 min
- Temperature range 200-350 K
- Teeming with life

Seasons: Due to Tilt of Earth's Axis



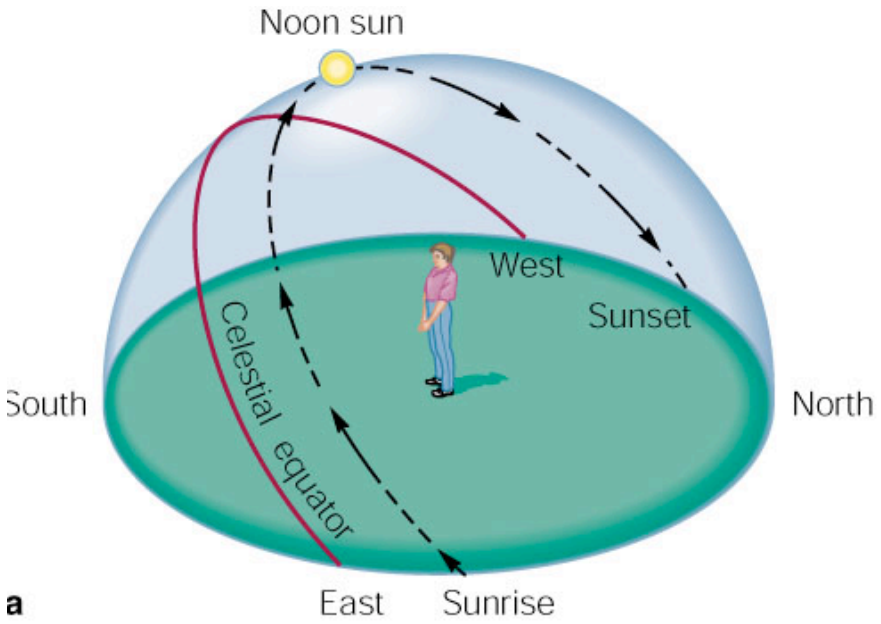




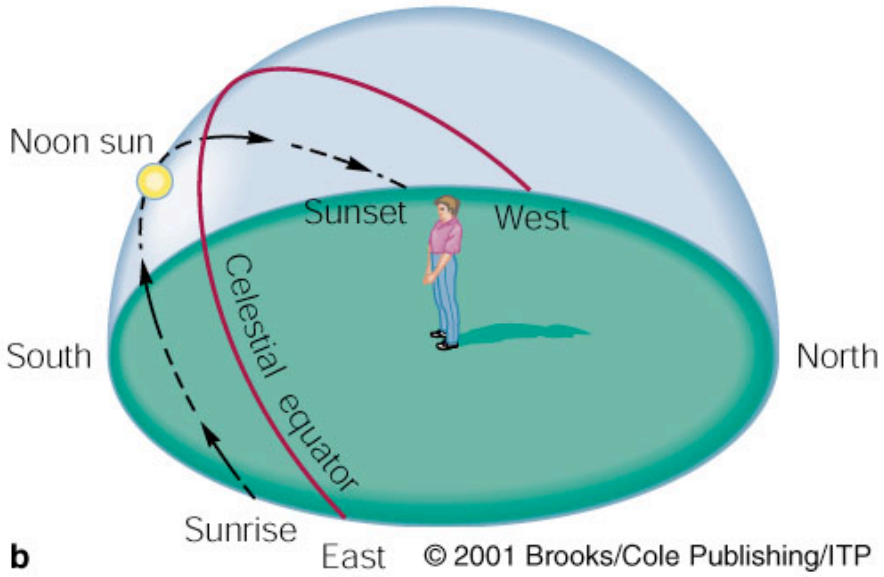
Why does the tilt cause seasons?

- Tilt causes the sun to remain lower in the sky in winter
  - When the sun is low in the sky, less heat is supplied per unit area of Earth's surface
- Tilt causes winter days to be much shorter than summer days
  - The shorter the day, the less heating by the Sun

Summer, Winter Path of Sun



Summer



Winter

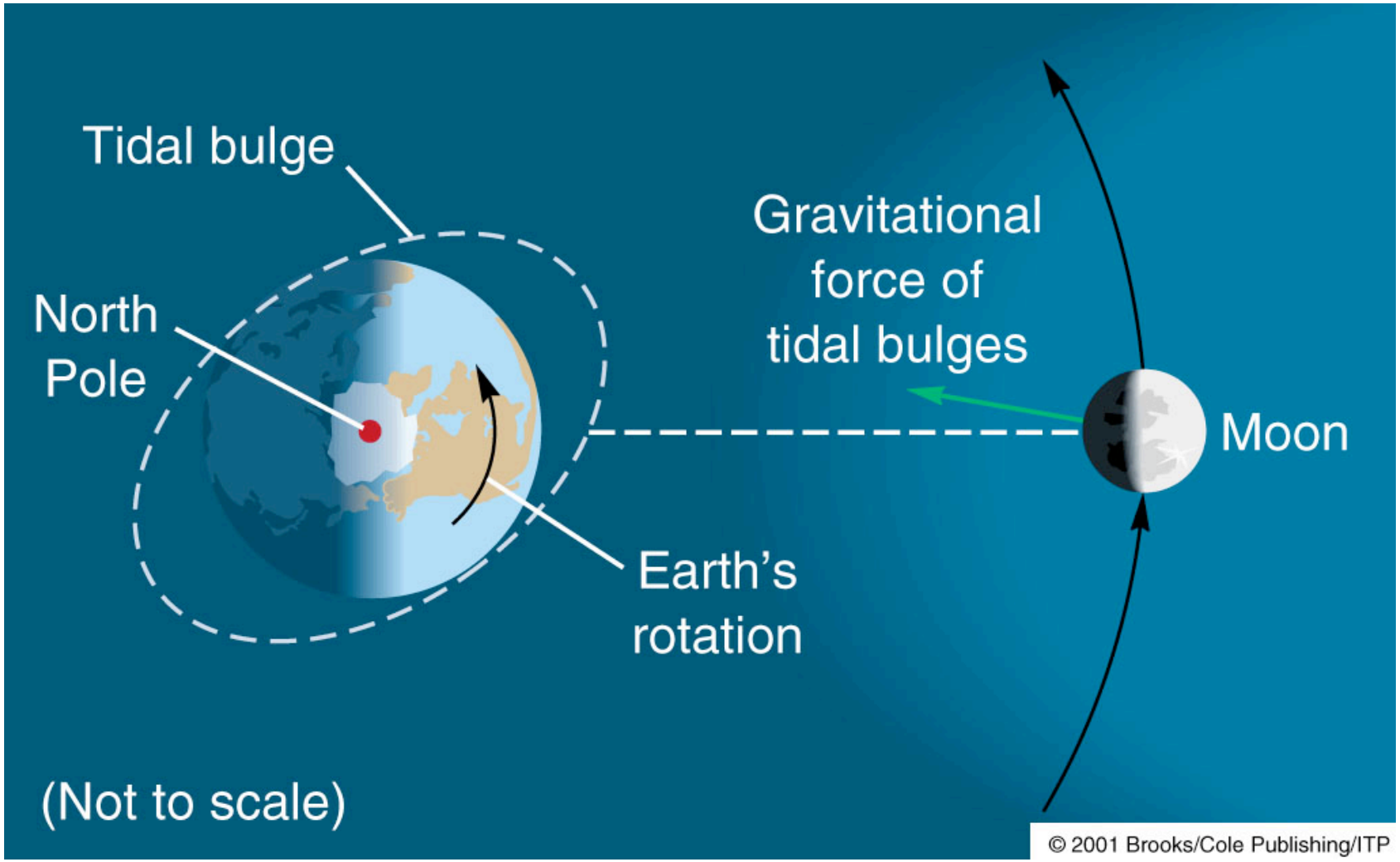
Cause of the Seasons

- Entirely due to *tilt* of Earth's rotation axis
  - It does NOT occur because the Earth is closer to the sun in Summer !
  - Orbital ellipticity has very little to do with seasons !
  - Eccentricity can account for only couple of % change in irradiation – too little to explain seasons

Tides

Gravitational pull of moon and Sun stretches Earth, and produces tidal bulges.

Tidal bulge leads Moon



Effects of tides

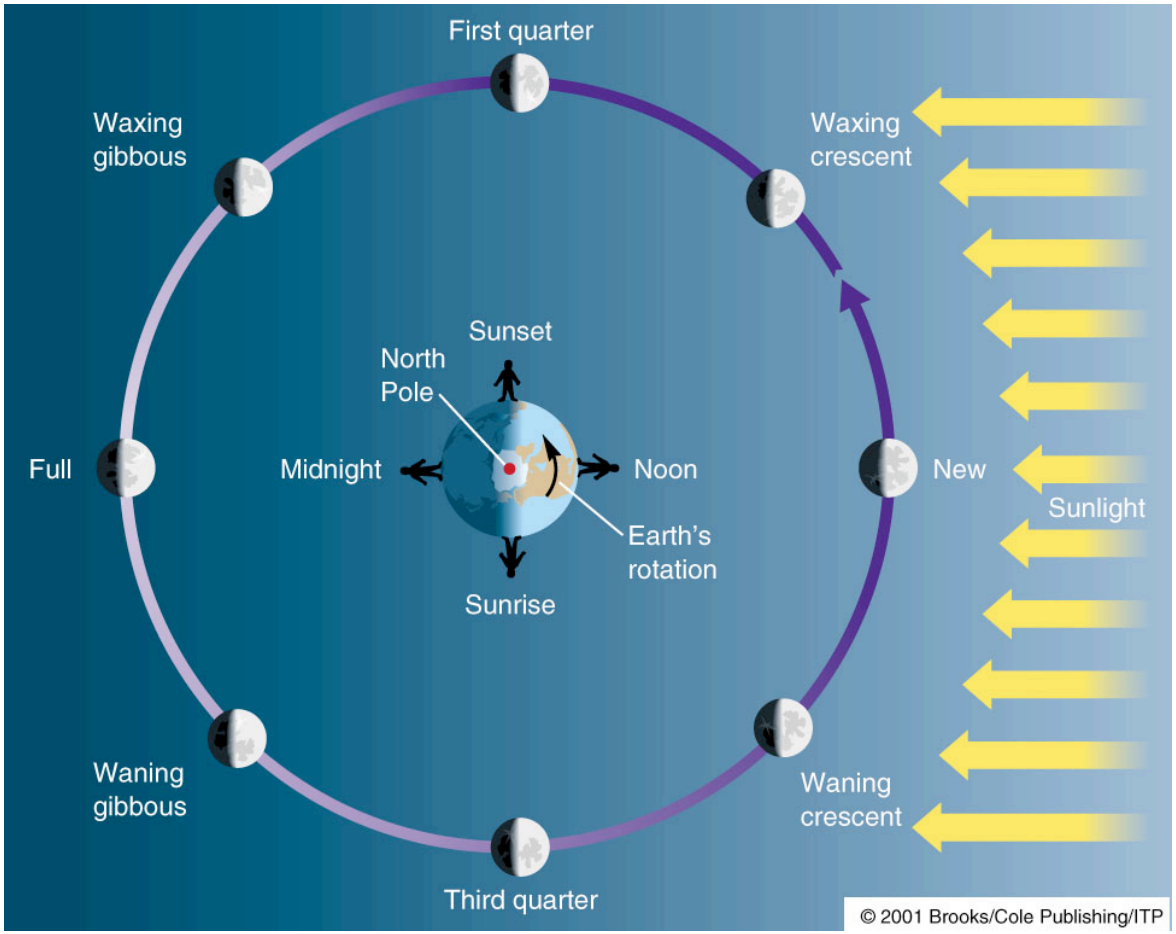
- Keeps Moon in ***synchronous rotation*** → Moon always has same side facing Earth
- Increases orbital angular momentum of Moon
  - Increases Earth-Moon distance by 4 cm/year
  - Moon's orbital period also increasing
- Slows rotation of Earth
  - Day was much shorter in past
  - Day will be much longer in future
  - Eventually, one side of Earth will be locked towards Moon, with a day lasting 50 present Earth days

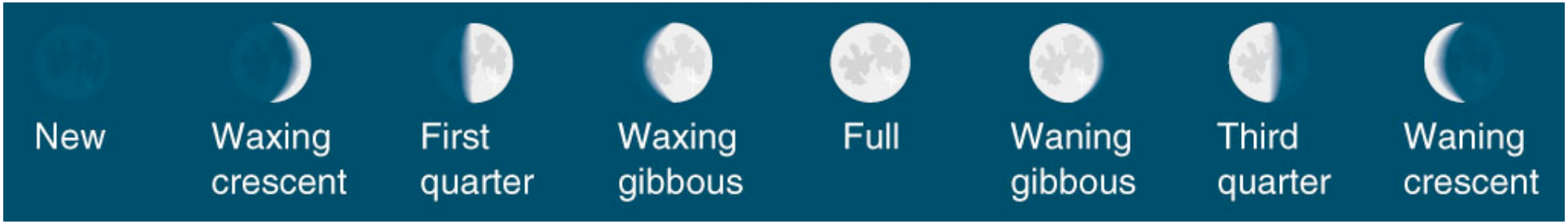
Tides exchange spin and orbital angular momenta of celestial bodies

Earth and Moon

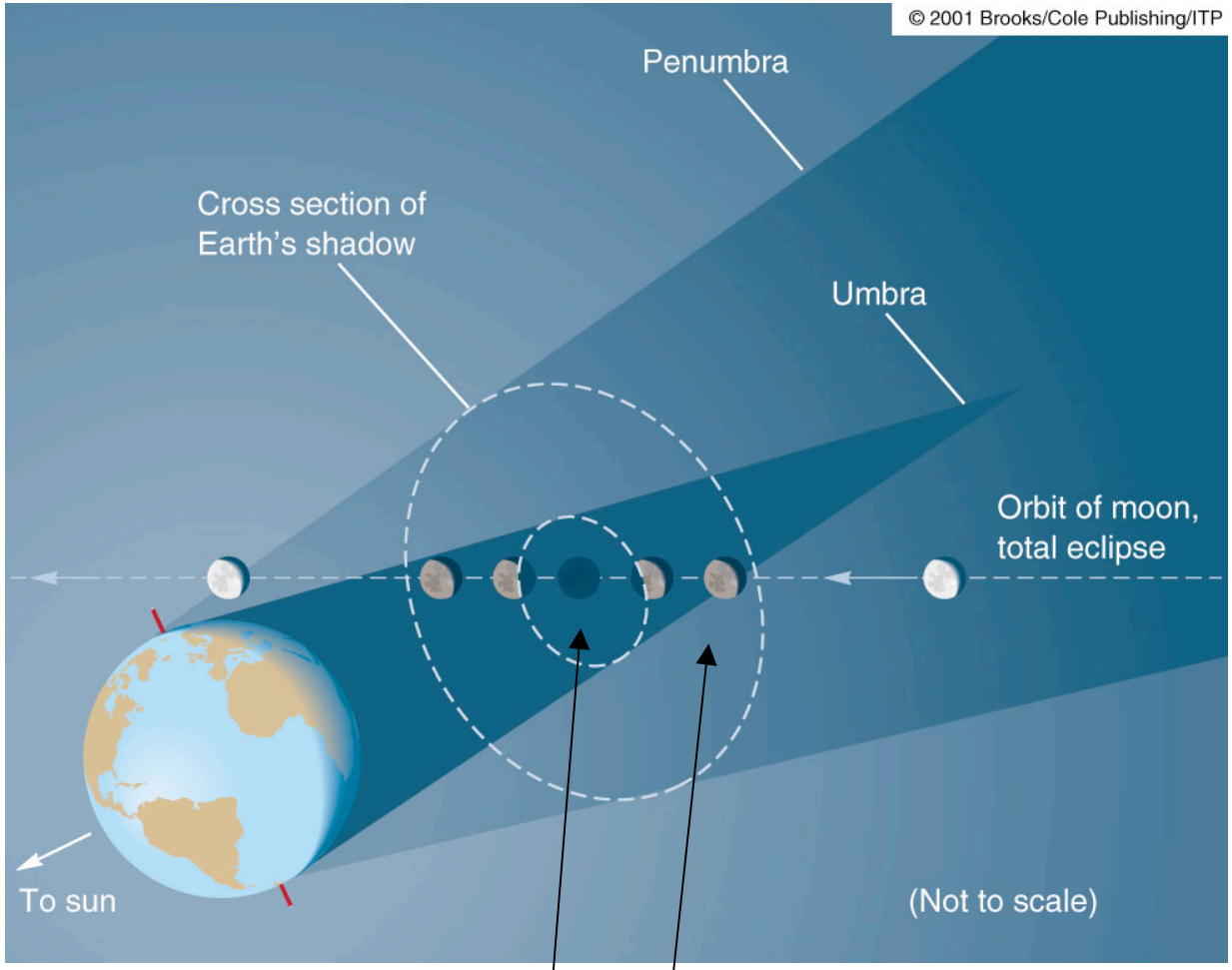
Phases of Moon

Each phase is visible only at certain times and certain directions in sky





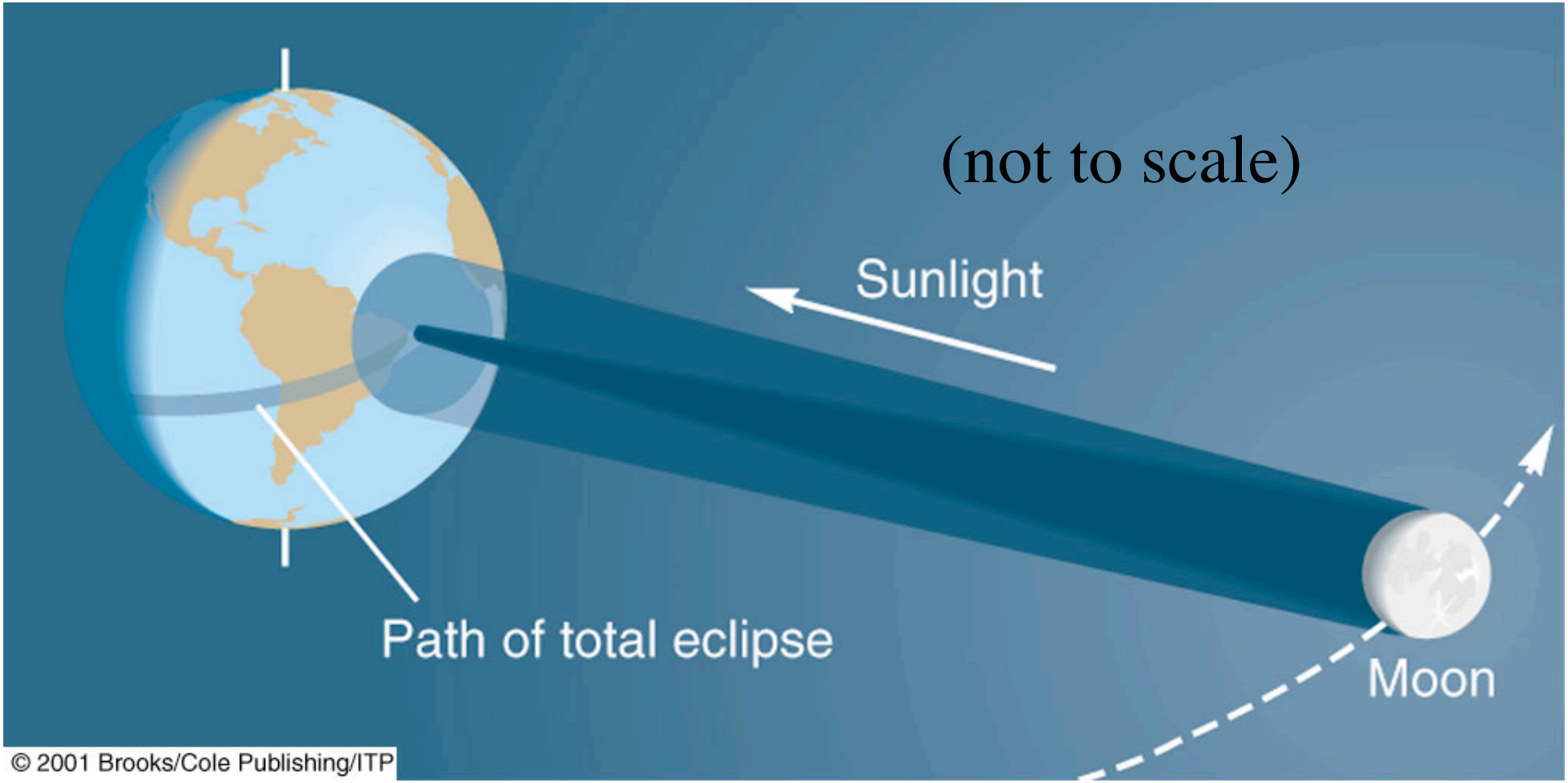
Lunar eclipse: ***Moon*** is shadowed by ***Earth***



In umbra, get total eclipse
In penumbra, get partial eclipse

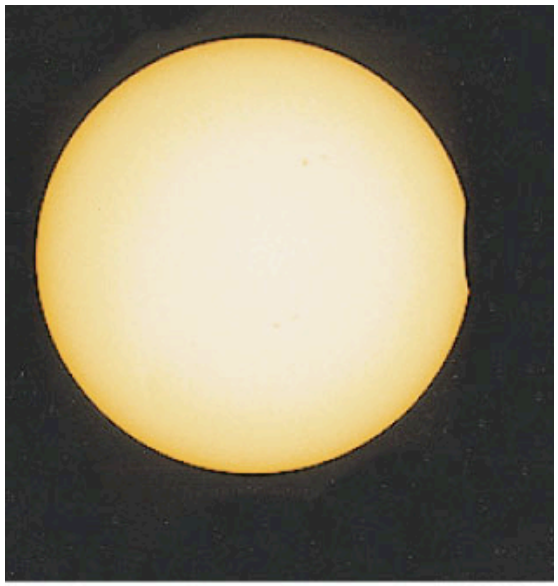
Solar Eclipses

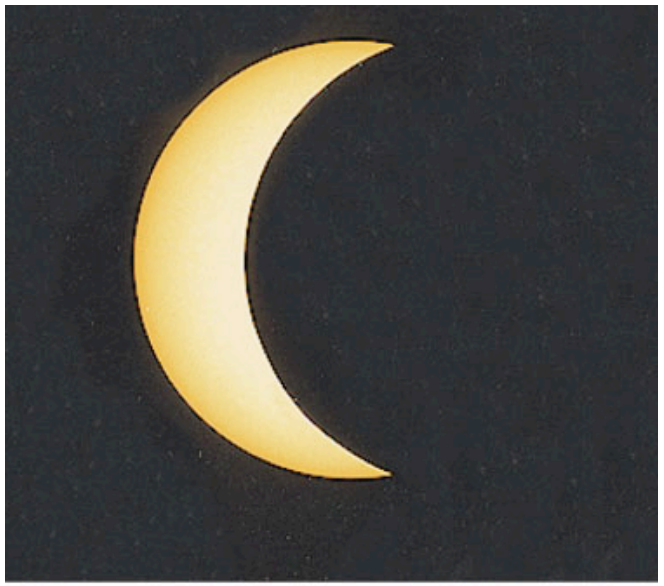
- Our view of ***Sun*** is blocked by ***Moon***
  - Only a small part of Earth sees solar eclipse

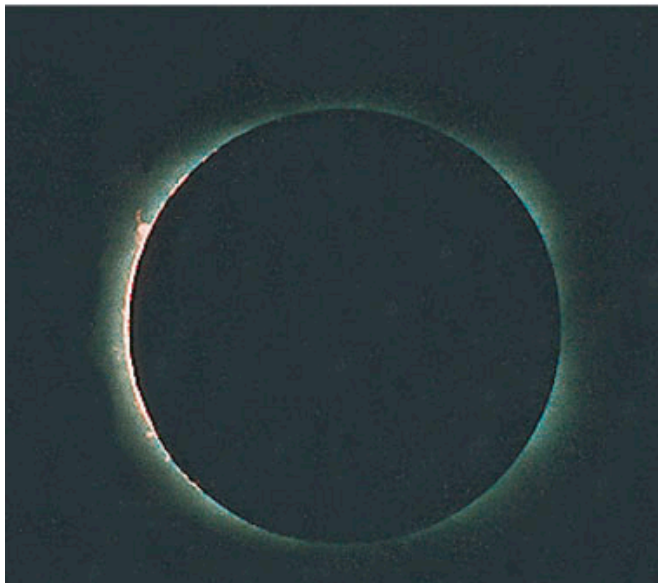


Solar eclipse sequence

Partial phase starts







Totality

Fortunate coincidence in angular sizes of sun and and moon allows us to see sun's atmosphere during total solar eclipse.