Astr 2310 Thurs. Feb. 4, 2016

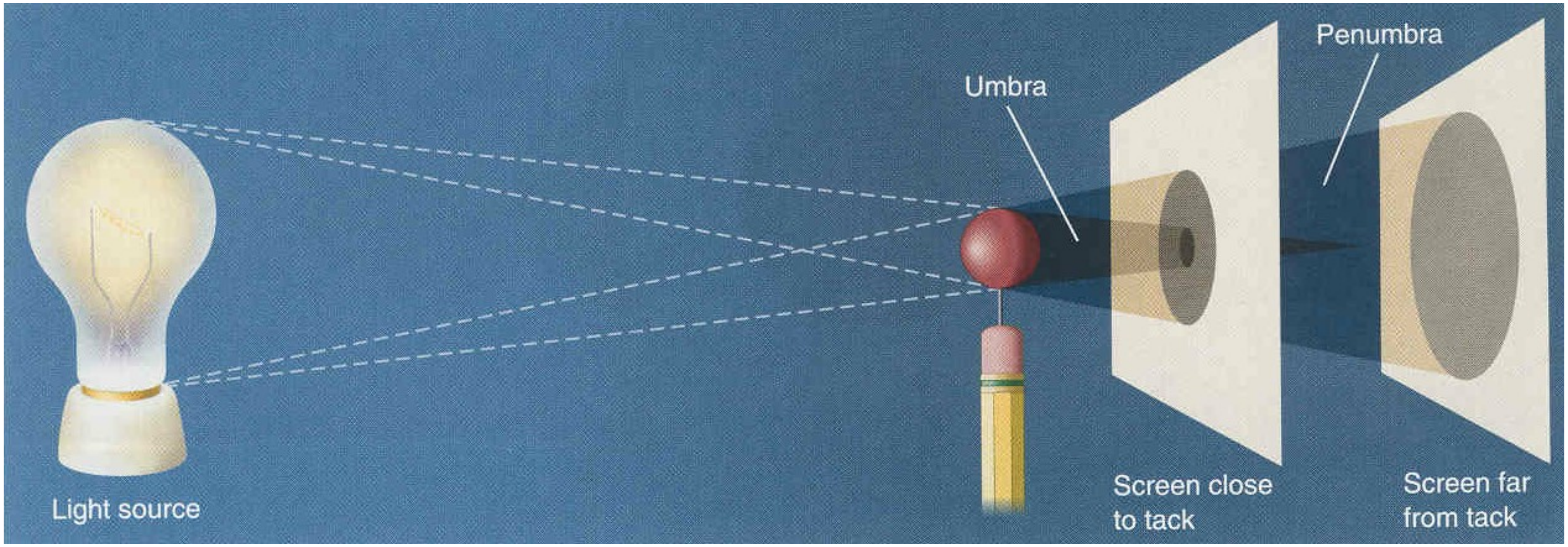
Today's Topics

- **Ancient Astronomy**
  - Babylonians and early culture
  - Greeks
  - Aristarchus
  - Hipparcos
  - Ptolemy
- **Origin of Modern Astronomy and Celestial Mechanics**
  - Copernicus
  - Tyco Brahe
  - Kepler
  - Galileo
  - Newton

Homework this Week

- A2310 HW #1
- Due Tuesday Feb. 9
- Ryden & Peterson: Ch. 1: #2, #3, #4, #6, #8
- Plus the following:
- Compute the approximate Sideral Times:
  - a) midnight on June 20,
  - b) 3 am on Sept. 20,
  - c) 8 pm on Nov. 1,
  - d) 6 am on March 20

Shadows and Eclipses



From our text: Horizons, by Seeds

Both the Earth and the Moon will cast shadows. If the Sun, Earth, and Moon are all lined up, then the shadow from one can fall on the other.

Because the Earth is ~4 times bigger, it will cast a shadow 4 times bigger.

Umbra — **Portion of shadow where it is completely dark.**

(for a person in the shadow, the light bulb would be completely blocked out)

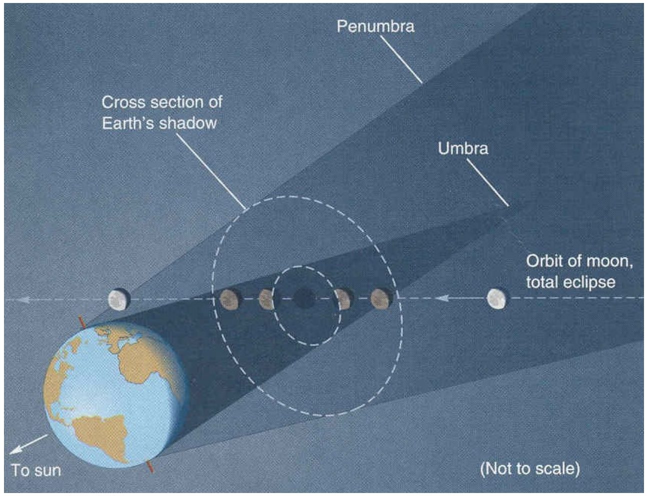
Penumbra — **Portion of shadow where it is only partially dark.**

(for a person in the shadow, the light bulb would be partially blocked out)

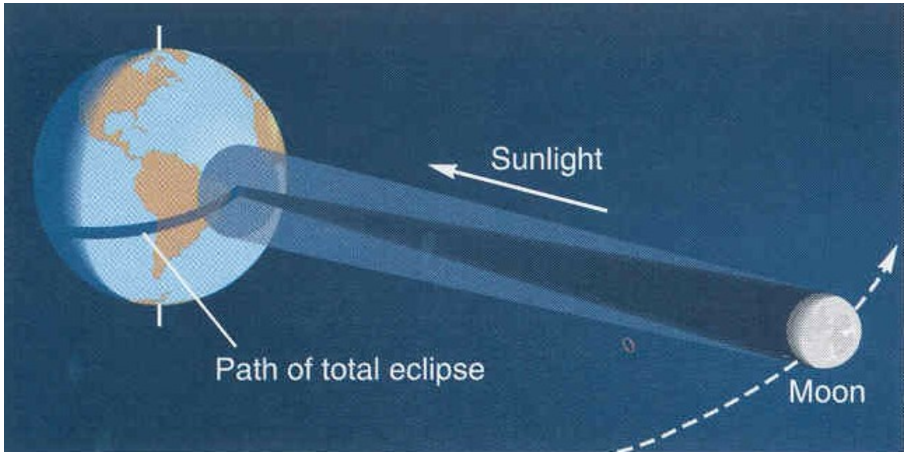
(To remember the names, think of "ultimate" and "penultimate")

Types of eclipses

Lunar Eclipse



Solar Eclipse



From our text: Horizons, by Seeds

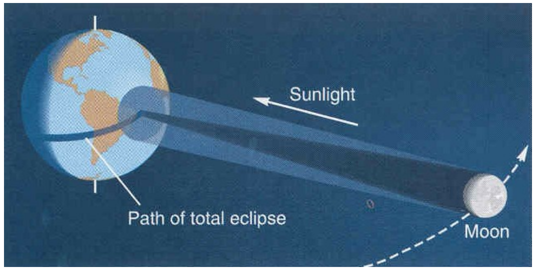
We view the illuminated object and watch it go dark.

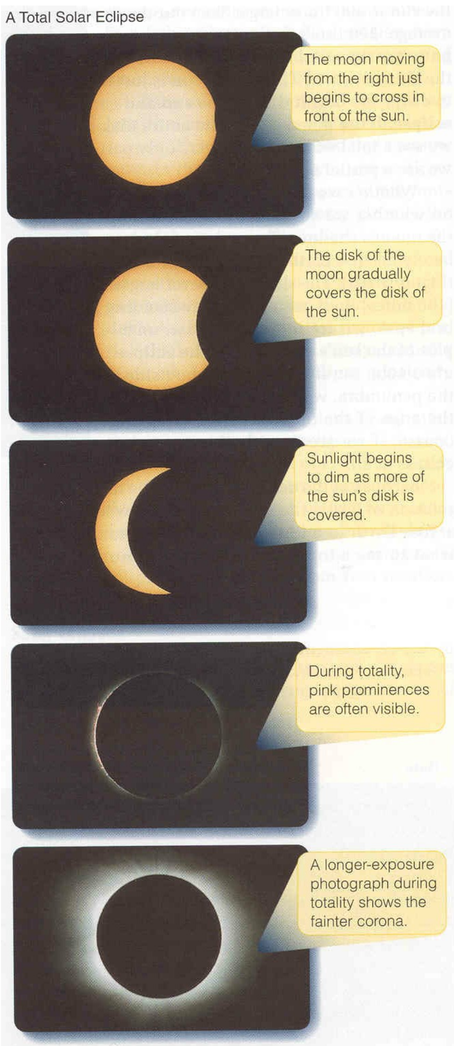
Everyone on one side of the Earth can see the Moon – so a given lunar eclipse is visible to many people.

We view the illuminating object (the Sun) and see it blocked out.

Only a few people are in the right place to be in the shadow.

It is "coincidence" that the umbra just barely reaches earth.





From our text: Horizons, by Seeds

Solar eclipses

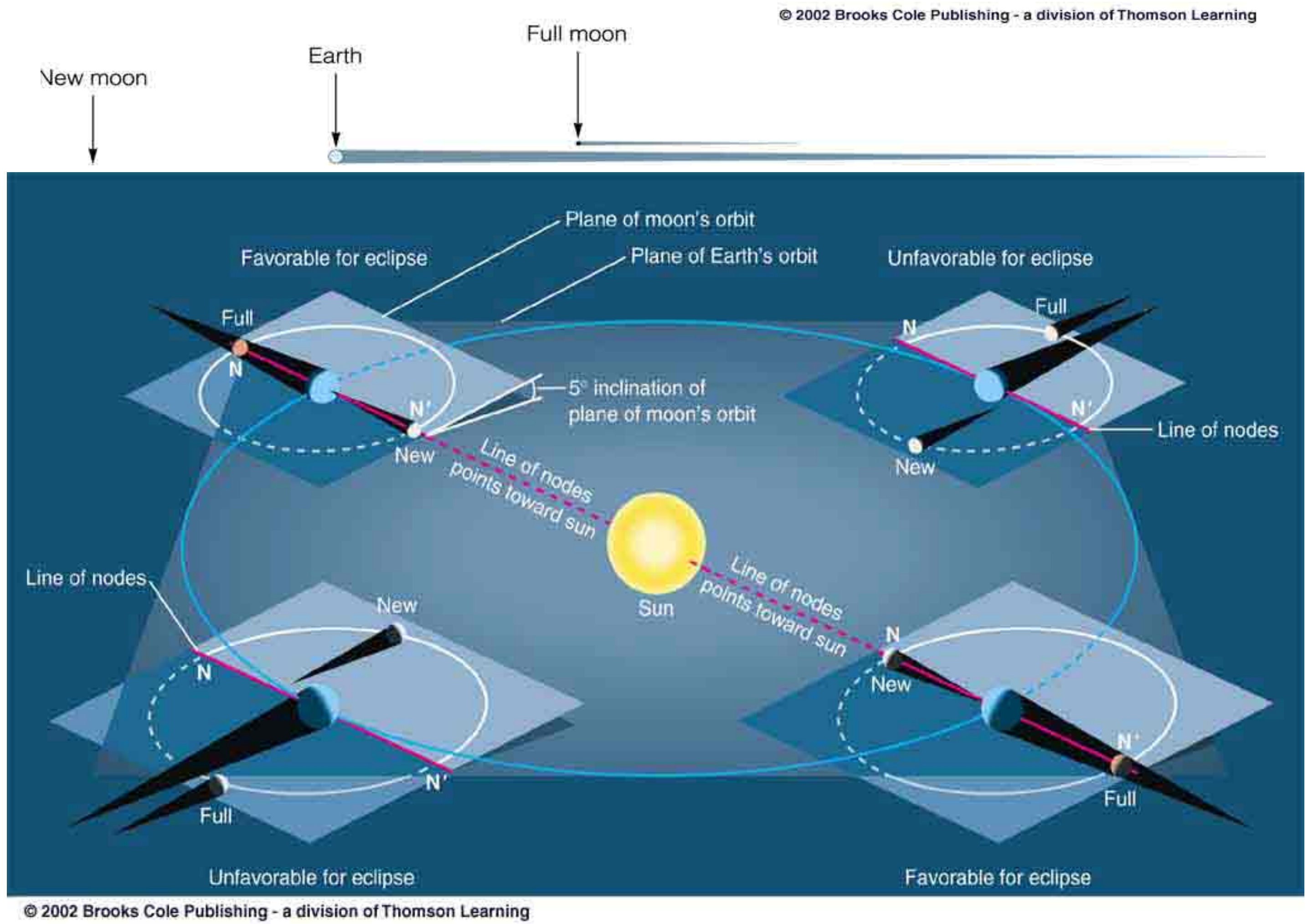
- If you are outside the penumbra you see the whole sun.
- If you are in the penumbra you see only part of the sun.
- If you are in the umbra you cannot see any of the sun.

- The fact that the moon is just barely big enough to block out the sun results from a coincidence:
    - The sun is 400 times bigger than the moon, but also almost exactly 400 times further away.
    - The orbit of the moon is elliptical.
        - At perigee it can block out the full sun
        - At apogee it isn't quite big enough, giving an annular eclipse.

Eclipse Facts

- **Longest possible total eclipse is only 7.5 minutes. Average is only 2-3 minutes.**
- **Shadow sweeps across Earth @ 1000 mph!**
- **Birds will go to roost in a total eclipse. The temperature noticeably drops.**
- **Totally predictable (even in ancient times, e.g., the Saros Cycle, eclipse pattern repeats every 6585.3 days or 18 years, 11 1/3 days – due to precessional period of Moon's orbit).**

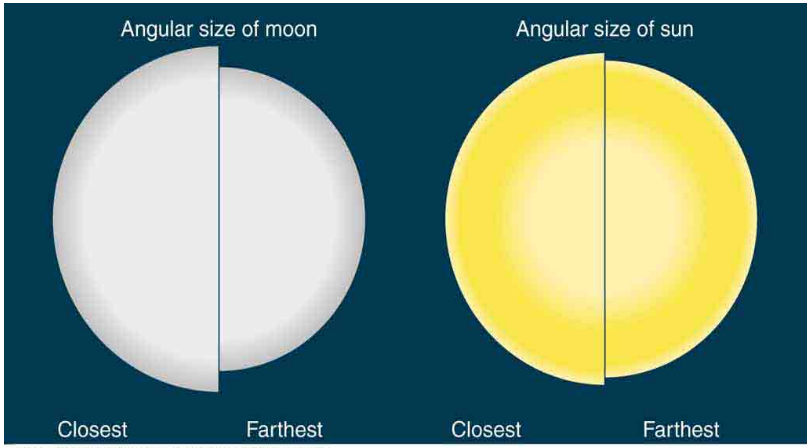
Eclipses and Nodes

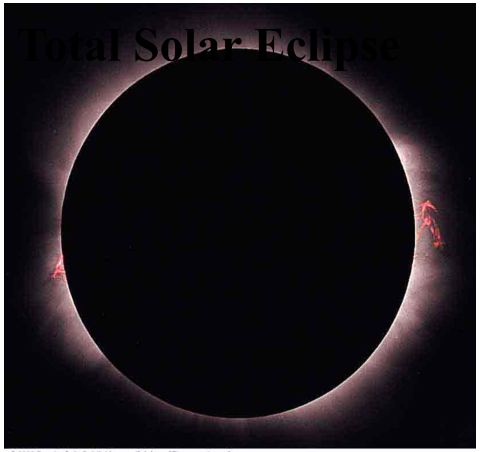


From our textbook, Horizons by Seeds.

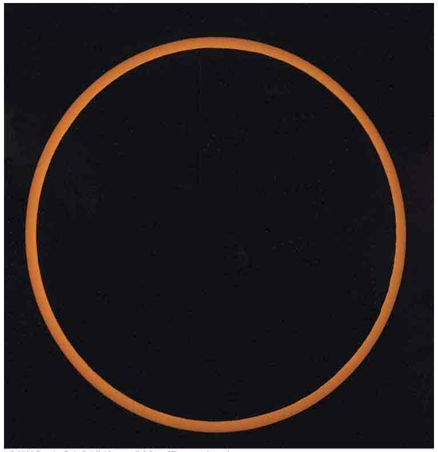
Variations in Solar Eclipses

Elliptical orbits mean *angular size variation*.



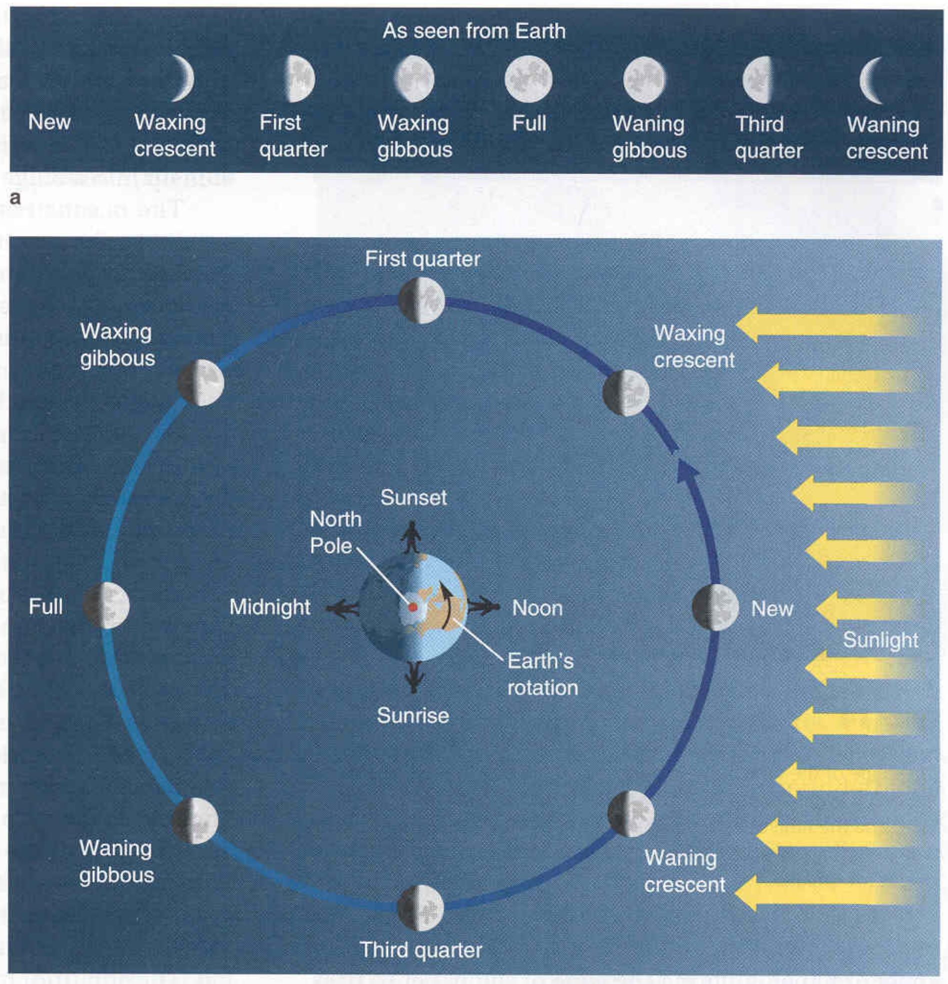


Diamond-Ring Effect



Annular Eclipse

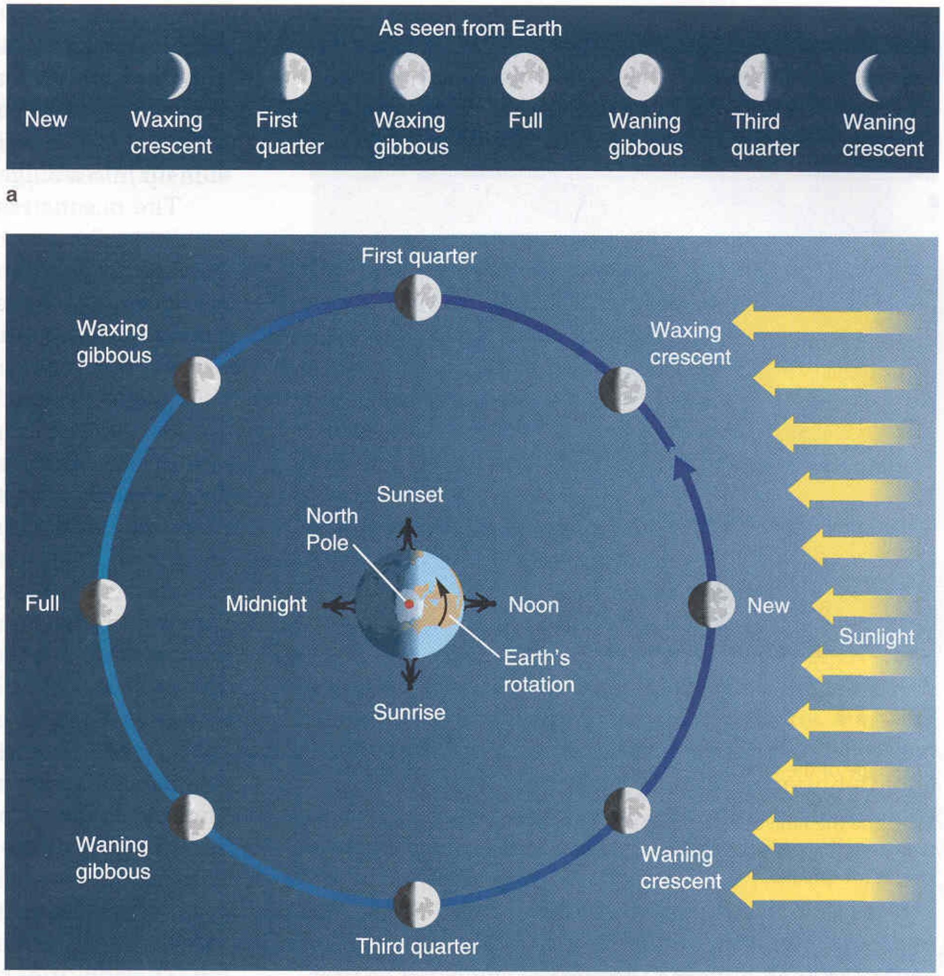
Phases of the Moon and its orbit around the Earth (1).



From our text: Horizons, by Seeds

1. Everything (almost) in the solar system rotates or orbits counterclockwise, as seen from the North.
2. The illumination of the Earth and the moon will be almost the same, since the sun is so far away that both receive light from (almost) the same direction.
3. It takes 4 weeks for the moon to complete an orbit of the earth.
4. The moon is *phase-locked.* In other words, we always see the same face, although the illumination pattern we see changes. How long is a lunar day?

Phases of the Moon and its orbit around the Earth (2).



From our text: Horizons, by Seeds

Suppose you are asked when the first quarter moon will rise, when it will be overhead, and when it will set. Which side will be illuminated?

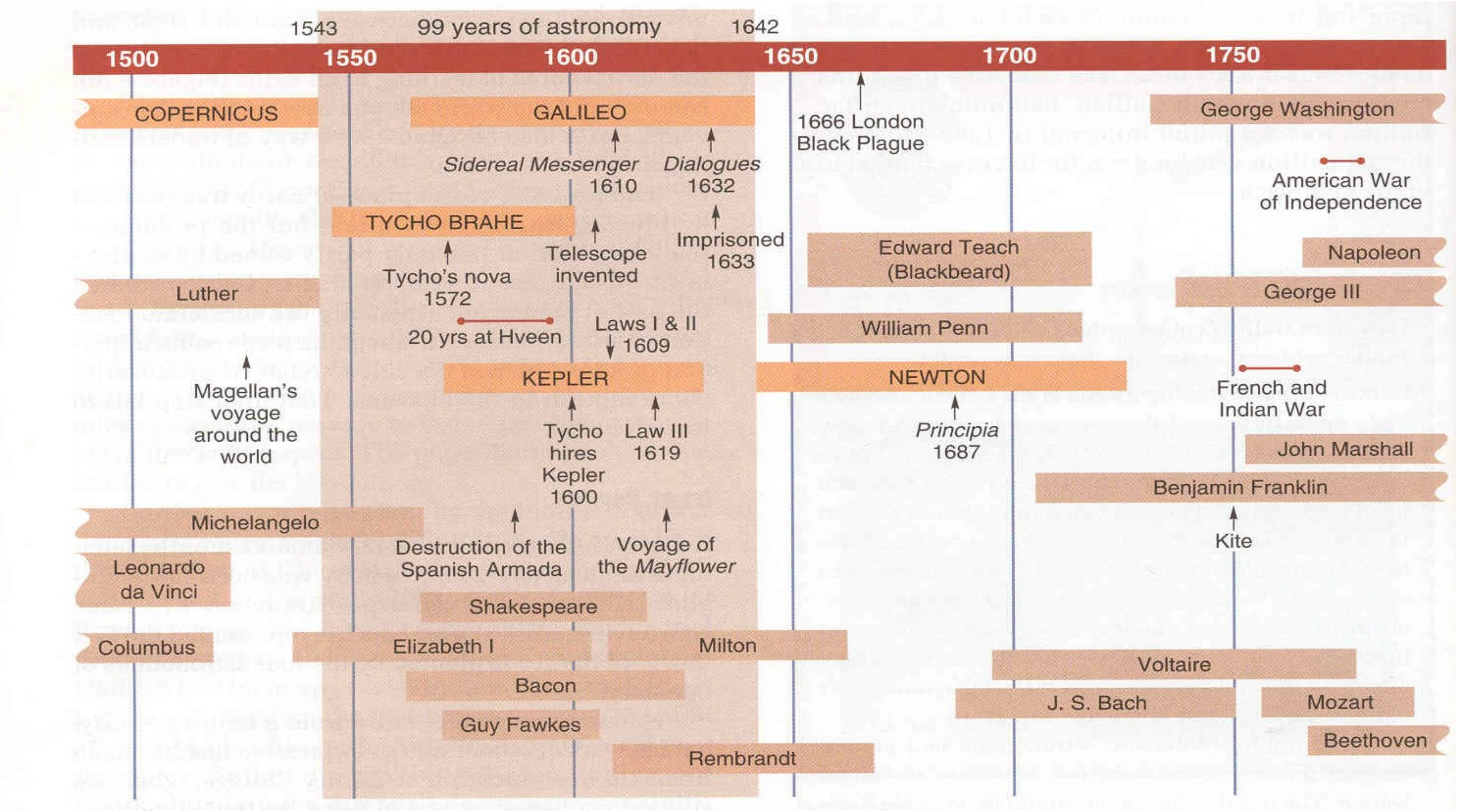
- **If it is first quarter, it has moved ¼ revolution around from the new moon position, so it is at the top of the diagram.**
- **For a person standing on the earth, the moon would rise at noon, be overhead at 6 pm, and would set at midnight.**
- **It has to be the side towards the sun which is illuminated. Imagine yourself lying on the ground at 6 pm, head north, right arm towards the west. That west (right) arm points towards the sun. That must be the side which is illuminated.**

Chapter 1: The Origin of Modern Astronomy

- **The development of modern science**
  - **The Aristotelian Universe**
  - **The Copernican Revolution**
  - **The rules of modern science**

- **References:**
  - ***The Beginnings of Western Science*** **by David Lindberg**
  - ***Galileo's Daughter*** **by Dava Sobel**
  - ***Coming of Age in the Milky Way by Timothy Ferris***

The Historical Setting



- **The Renaissance**
- **The European Discovery of the New World**
- **The Reformation**

From our text: Horizons, by Seeds

Reniassance Astronomers

• Nicolaus Copernicus	1473 - 1543	Heliocentric model Explanation of retrograde motion
• Tycho Brahe	1546 - 1601	Observations of changes in sky Accurate planet positions
• Johannes Kepler	1571 – 1630	Mathematical description of planetary orbits
• Galileo Galilei	1564 – 1642	Observations using telescope supporting Copernican model
• Isaac Newton	1642 – 1727	Physics to explain Kepler's orbits

Planetary Configurations

The standard planetary configurations. Note that the terms describe the position of the planet relative to the Earth and Sun (as if the Earth weren't moving.

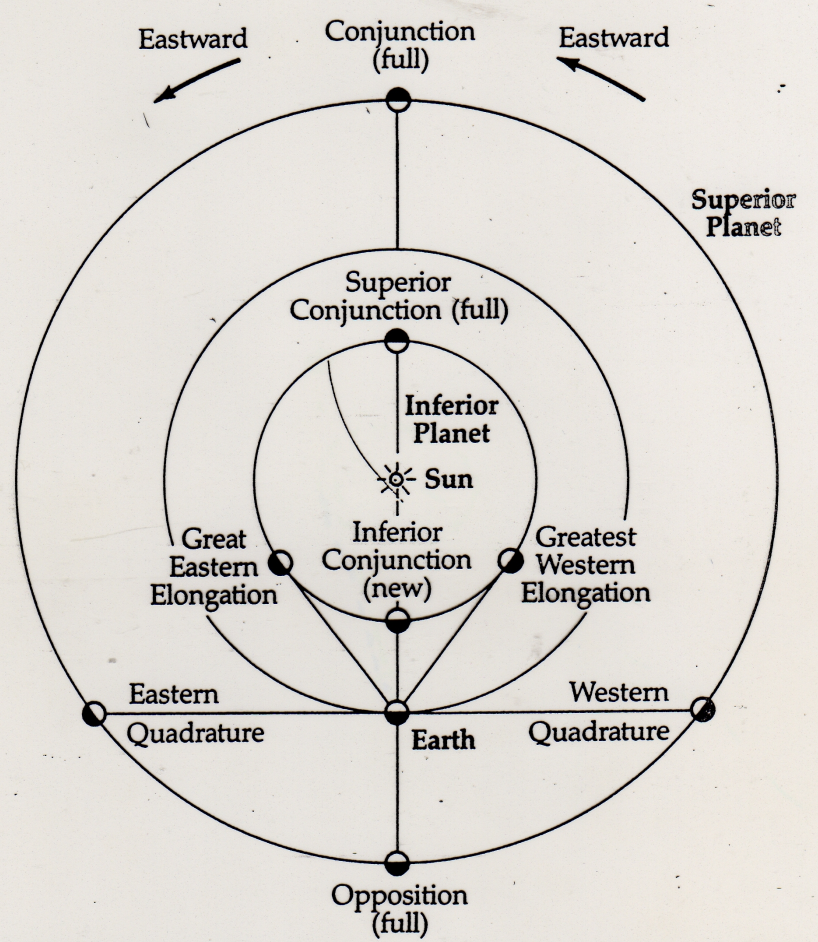


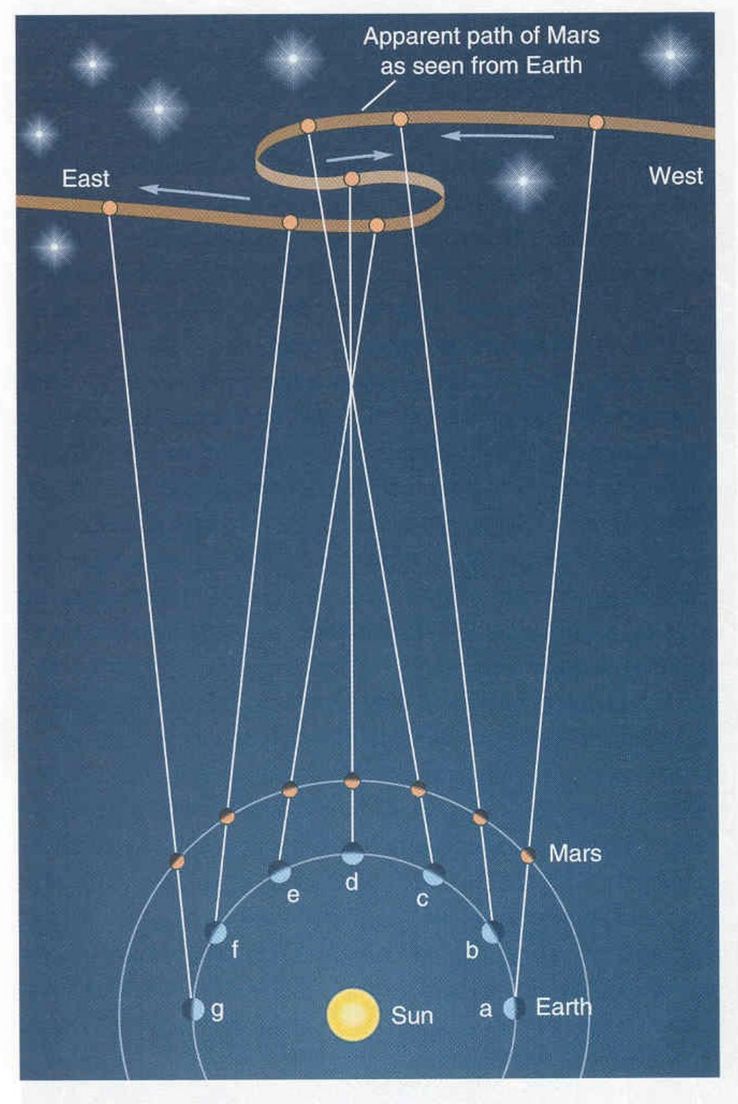
Figure 1–2 Heliocentric planetary configurations. Arrows indicate the direction of orbital motion as well as the rotational direction of the Earth. The phases of the planets' illumination, viewed from the Sun, are also shown.

Copernicus: 1473 –1543

- Proposed heliocentric model
- Circular orbits and uniform motion
- Less accurate for predicting positions but more "physically realistic"
- Simple explanation for retrograde motion

- De Revolutionibus Orbium Coelestium published in 1543

- Computed the scale of the Solar System relative to Earth's orbit (i.e., in AU)



From: Horizons, by Seeds

Copernicus continued

- Copernicus also claimed:
  - Planets were all round worlds, like the Earth
  - Earth was just another planet
  - Copernicus' model was just an alternative model. It was simpler and elegant but there was no physical evidence.
  - Proof came 100 years after his death.

Copernicus and Scale of the Solar System

- Inferior Planets: Angle of Greatest Elongation gives Orbital Radius

Copernicus and Scale of the Solar System

- **Determining the Siderial Period of a Planet:**
- **S – synodic period (viewed from Earth)**
- **P – siderial period f planet**
- **E – siderial period of Earth**
- **θ = (S-E)(360/E)**

  = S(360/P)

  With deg = days*(deg/ day)

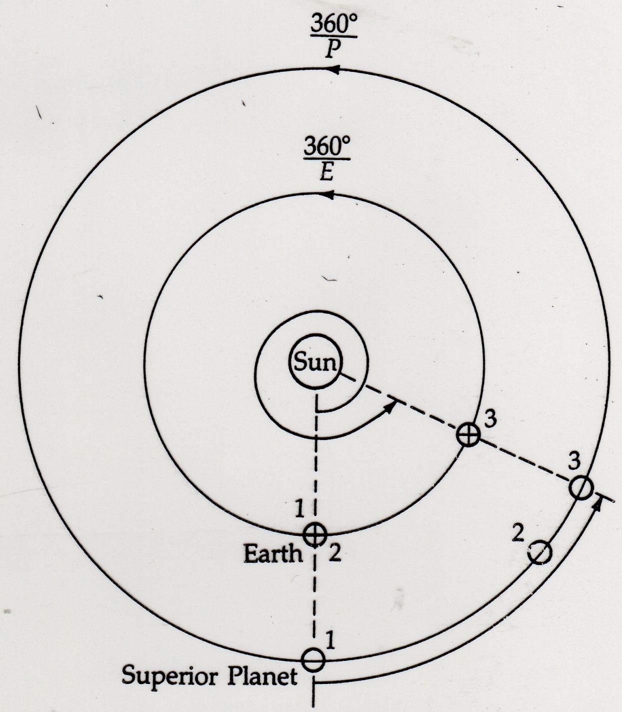


Figure 1–4 Synodic and sidereal periods in a heliocentric model. As the Earth orbits the Sun at an angular speed of 360°/E degrees per day, a superior planet moves at 360°/P degrees per day (as seen from the Sun). The Earth moves from position 1 to position 2 after one orbit and has $S - E$ days to reach the next opposition (at position 3). During this time, the superior planet has moved from position 1 to position 3.

- (S-E)(360/E) = S(360/P)
- Simplfying further:
- (S/E)(360) – (E/E)(360) = (S/P)(360)
- (S/E) – 1 = (S/P)
- Dividing by S yields:
- 1/E – 1/S = 1/P (valid for superior planet)
- For an Inferior planet just switch E & P:
- 1/P – 1/S = 1/E
- Or:
- 1/P = 1/E + 1/S (valid for inferior planet)

Copernicus and Scale of the Solar System

Copernicus used relative geometry of the Eatrh, Sun and planet to determine the radius of all the planet’s orbits.

Inferior Planets: Use angle of greatest elongation.

Superior Planets: Measure position of Planet at two successive siderial periods (planet in the same place).

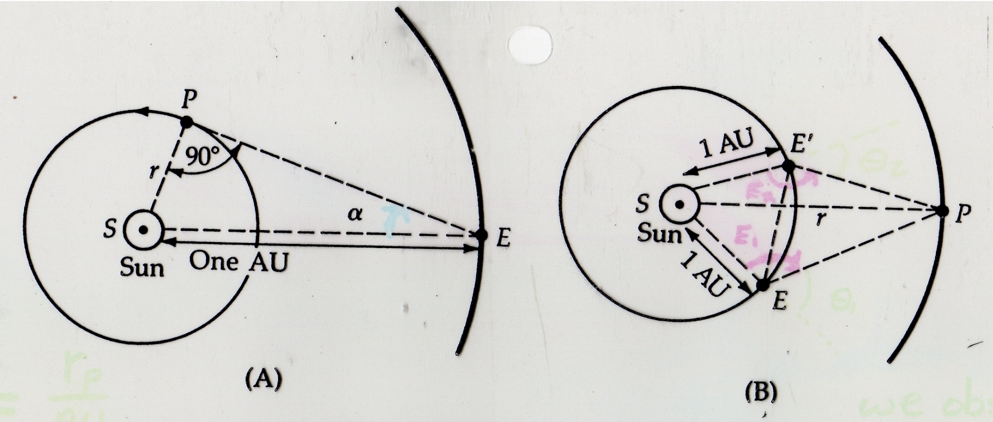


Figure 1–5 Distance determinations in a heliocentric model. (A) When an inferior planet reaches greatest elongation *P*, we know angle *SEP* and can find *r* because angle *SPE* is a right angle. (B) A superior planet is at *P* at the start and end of one sidereal period; at these times, the Earth is at *E* and *E′*. Angles *PES* and *PE′S* are observed; they are the elongations of the planet from the Sun.

Tycho Brahe: 1546 - 1601

- 1563 "Conjunction" Jupiter and Saturn show problems with Ptolemaic predictions of positions.
- 1572 Tycho's "supernova" challenges ideas of unchanging nature of the heavens
  - Lack of parallax shows it was at least as far away as the moon.
- 1576 – 1596 Most precise observations of positions of the planets
- 1596 Moves to Prague, hires Johannes Kepler as assistant
- Brahe advocated a combination of heliocentric and geocentric model for the Solar System
- 1601 Collapses, requests Kepler be appointed his replacement, then dies.

Johannes Kepler: 1571 – 1630
The nature of planetary orbits

- **Problem:** Copericus' heliocentric model just wouldn't fit the precise data from Brahe.
- Realized Mars' orbit must be elliptical, not circular
- Everything now fit:
  - 1) The orbits of all

Kepler's Laws, #1 and #2

- **1609 Published two laws showing:**
  - **#1** Planets orbit the sun in ellipses, with the Sun at one focus
  - **#2** Motion is faster when they are near the Sun, in such a way that a line from the planet to the sun sweeps out equal areas in equal times

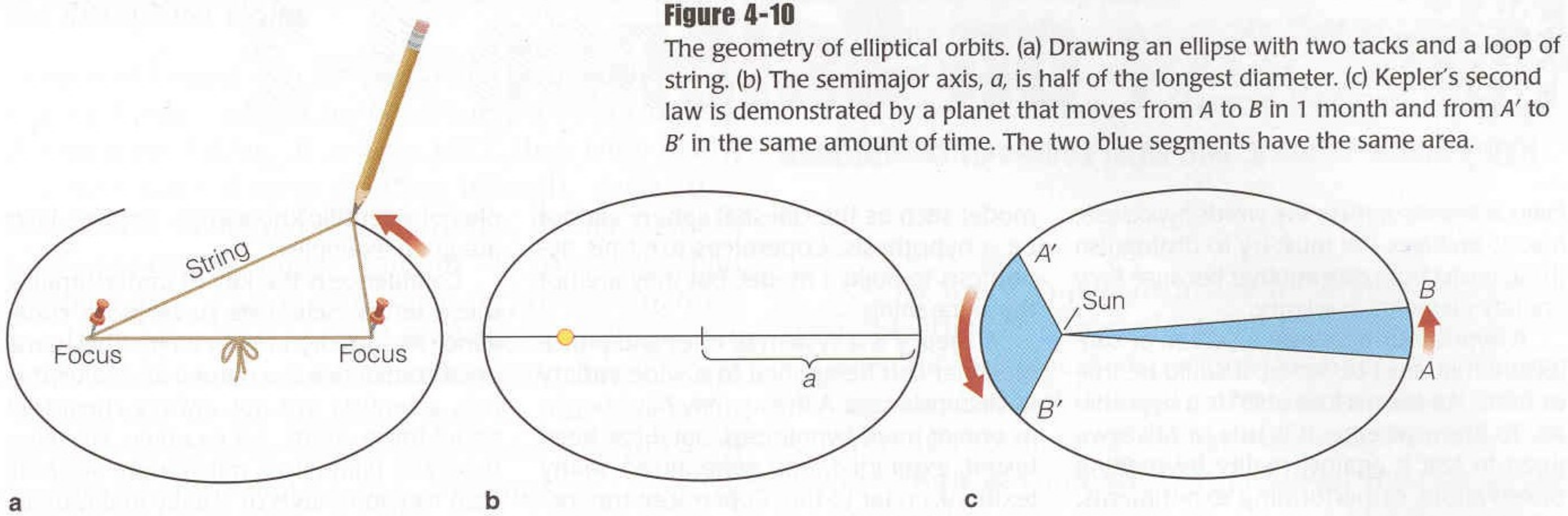


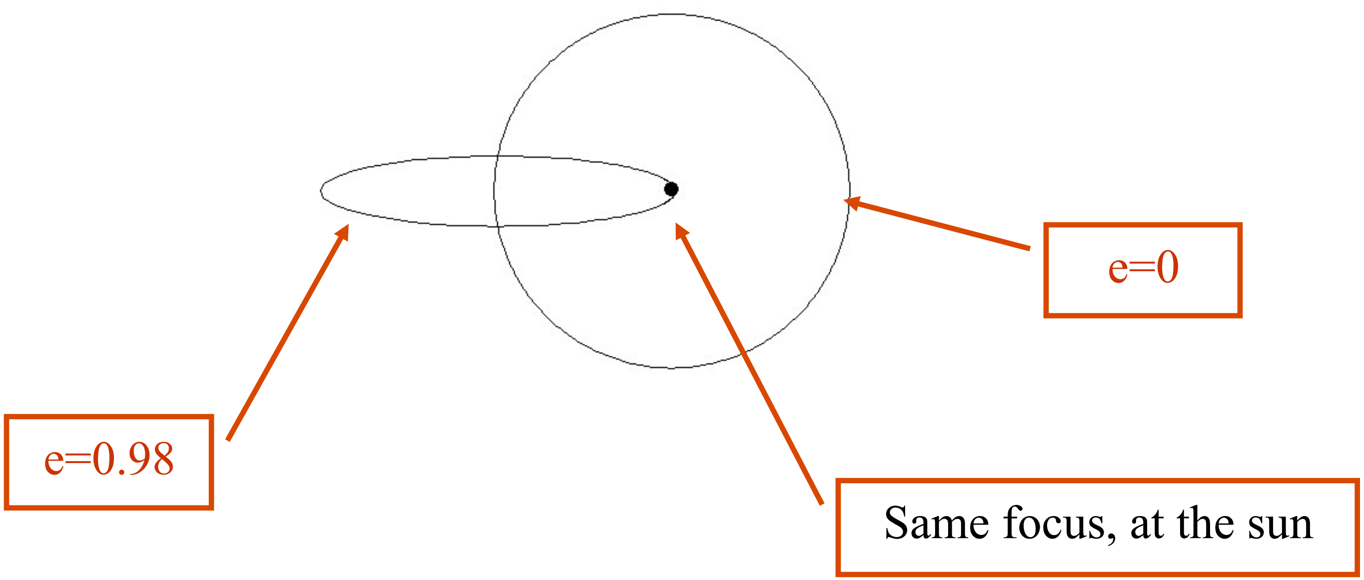
Figure 4-10
The geometry of elliptical orbits. (a) Drawing an ellipse with two tacks and a loop of string. (b) The semimajor axis, *a*, is half of the longest diameter. (c) Kepler's second law is demonstrated by a planet that moves from *A* to *B* in 1 month and from *A′* to *B′* in the same amount of time. The two blue segments have the same area.

From our text: Horizons, by Seeds

Properties of Ellipses

- Ellipse defined by two constants
  - semi-major axis a 1/2 length of major axis
  - eccentricity e 0=circle, 1 = line

Two ellipses with the same a but different e



Kepler's Laws, #3

- **1619 Publishes third law, showing that there is a relationship orbital period and semi-major axis:**

- **Exact relationship is $P^2 \propto a^3$.**
  - **Outer planets orbit more slowly than inner ones**

- **Example: Earth P = 365 days, a = 1.00 AU.**
  Mars p = 687 days, a = 1.524 AU

$$\left(\frac{687\text{ days}}{365\text{ days}}\right)^2 = \left(\frac{1.524\text{ AU}}{1.000\text{ AU}}\right)^3 \qquad (1.88)^2 = (1.524)^3 \qquad 3.54 = 3.54$$

- Orbital Period of some asteroid with a = 9 AU ?

$$\left(\frac{P_{\text{asteroid}}}{P_{\text{Earth}}}\right)^2 = \left(\frac{a_{\text{asteroid}}}{a_{\text{Earth}}}\right)^3$$

$$P_{\text{Asteroid}} = P_{\text{Earth}}\left(\frac{a_{\text{Asteroid}}}{a_{\text{Earth}}}\right)^{3/2} = 1\text{ year} \times (9)^{3/2} = (3)^3 = 27\text{ years}$$

$P^2 = k a^3$

Earth orbital units $\Rightarrow k = 1$

$\log(P^2) = \log(ka^3)$

$2 \log(P) = \log(k) + 3 \log(a)$

$\log(P) = 3/2 \log(a) + \log(k)$

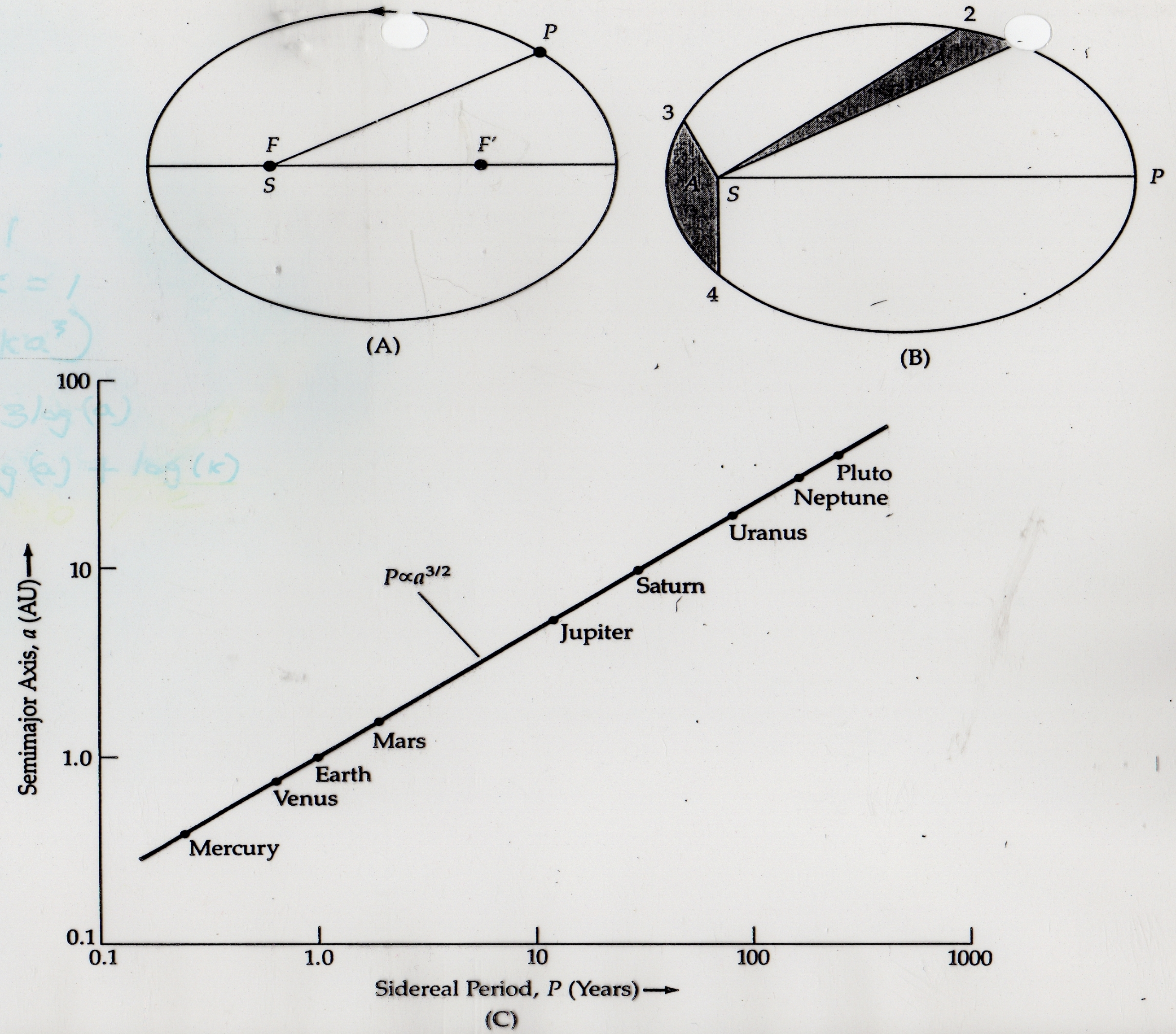


Figure 1–6 Kepler's laws of planetary motion. (A) Each planet P traces an elliptical orbit E around the Sun S, which is at one focus F of the ellipse. (B) Consider two equal time intervals, that from 1 to 2 and that from 3 to 4. The radius vector to the planet SP sweeps out the same area A during these times. (C) For all major planets, this log–log plot of semimajor axes a versus sidereal periods P falls very close to a straight line of slope 3/2, confirming Kepler's third law.

Kepler's Laws Continued

- Form ($P^2 = Ka^3$) of the law results from gravity so it is valid for any orbit:
  - Units used determine K
    - K = 1 if a is in AU and P is in years (Solar System units)
    - For other units K must be computed.
  - Moon and artificial satellites around the Earth
  - Satellites around other planets
  - Stars orbiting each other
  - Stars orbiting the Galaxy

Galileo Galilei 1564 - 1642

- Galileo's earlier work
  - Invented Physics
    - Developed concept of inertia and force
  - 1590 Masses fall at same rate – heavier do not fall faster (unless affected by air resistance)
  - 1604 Observes a supernova (Kepler's), no parallax $\Rightarrow$ must be beyond the Moon

- Telescopes:
  - 1609 Hears of invention of telescope, which at that point just use eyeglass lenses

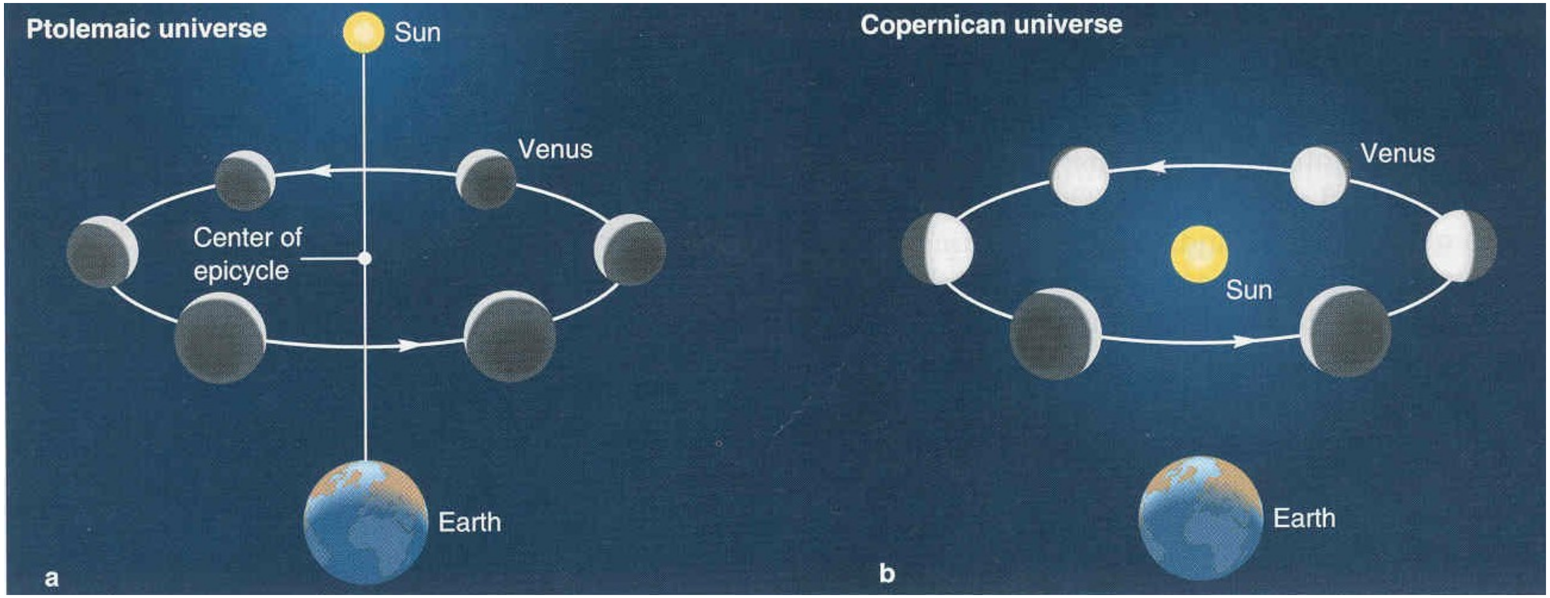
  - Works out details of better lenses and lens placement, builds improved ones himself

Galileo: First telescopic observations

- "Sidereus Nuncius" (The Starry Messenger) published in 1610 reporting:
  - Moon isn't "perfect" (violating Aristotelian principles for heavens)
    - Shows mountains and valleys
      - » Uses shadows to estimate heights
  - Milky Way made up of myriad faint stars
    - Doesn't directly violate Aristotelian principles, but suggests that a few simple phenomena can explain many features of the heavens
  - Discovers 4 moons (Galilean Satellites) orbiting Jupiter
    - Violates idea that all motion is centered on the Earth
    - Shows that orbiting objects can "follow" a moving body
    - 4 moons will also be seen to follow Kepler's 3rd law $P^2 \propto a^3$ (but with a different proportionality constant)

Galileo's additional observations

- Detects sunspots and the rotation of the Sun.
  - Further evidence of the "imperfect" heavens
- Detects the phases of Venus
  - Phases show that Venus must orbit the Sun.
    - "Full" Venus when it is on far side of Sun.
    - "Crescent" Venus when it is on near side of Sun.



From our text: Horizons, by Seeds

Galileo's critical observations

- Jupiter's moons show orbits which are not earth-centered
- Venus' phases show it must circle the Sun
- Several objects (Moon, Sun) show "imperfections" which are not supposed to be present in the heavens
- Galileo's observations clearly support Copernican model, but so far his printed work has mostly been reporting what he sees, rather than directly arguing for Copernican model.

Galileo and the "Dialog"

- Written as a debate between 3 people
  - Salviati — Copernican advocate – (really Galileo)
  - Sagredo — Intelligent but uninformed
  - Simplicio — Aristotelian philosopher – not very bright

- Hoped to avoid earlier ruling by not directly advocating Copernican model
- Actually made things worse by convincing accusers they were "Simplicio"

- 1633 Inquisition condemns him for violating 1616 order
  - Something like modern "contempt of court" ruling
  - Proceeding not a re-argument of Copernican vs. Aristotelian debate
  - But forced to recant, admitting "errors"
- Sentenced to life imprisonment –actually "house arrest"
- Dies in 1642
- Pope John Paul II finally makes some amends 350 years later.

Chapter 3: Orbital Mechanics

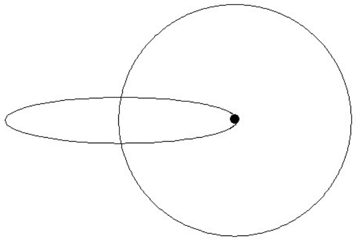
- *Newton (1642-1727) Principia* published in 1687

- 3 Law of motion
  - 1. A body continues at rest or in uniform motion in a straight line unless acted upon by some force.
  - 2. A body's change of motion is proportional to the force acting on it and is in the direction of the force. $\left(\vec{F} = m\vec{a}\right)$
  - 3. When one body exerts a force on a second body, the second body exerts an equal and opposite force back on the first body.
- Universal gravitation
  - There is an attractive force between all bodies, proportional to their mass, and inversely proportional to the square of their distance.

$$F = -G\frac{Mm}{r^2} \qquad G = 6.67 \times 10^{-11}\ \mathrm{m}^3/(\mathrm{s}^2\ \mathrm{kg})$$

Explanation for Kepler's Laws

- **Momentum keeps the planets moving – you do not need some force to do this.**
- **Gravity provides the force which makes orbits curve**
  - **Gravity of Sun curves orbits of Planets**
  - **Gravity of Earth curves orbit of moon (and also makes objects on earth fall downward)**
- **"Conservation of Angular Momentum" explains why motion is faster when closer to the sun.**



- **The inverse square law of gravity explains $P^2 \propto a^3$ and the details of why the orbits are ellipses.**

Circular Orbits: Limiting case of an ellipse.

- **Centripetal acceleration (v^2/r) caused by Gravity**

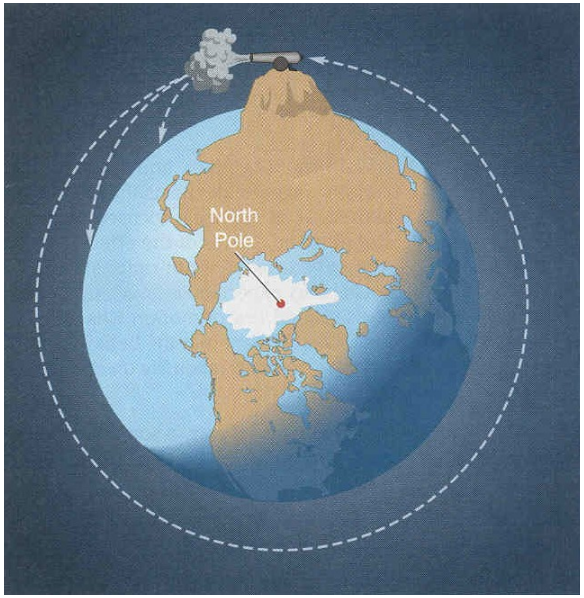
$$\frac{mv^2}{r} = G\frac{Mm}{r^2} \qquad v = \sqrt{\frac{GM}{r}}$$

- **Period found by**

$$\text{Period} = \frac{\text{distance}}{\text{velocity}} = \frac{2\pi r}{v} = \frac{2\pi r}{\sqrt{\frac{GM}{r}}} = \frac{2\pi}{\sqrt{GM}} r^{3/2}$$

- **Kepler's 3rd Law just comes from this**

$$P^2 = \frac{4\pi^2}{GM} r^3$$



From our text: Horizons, by Seeds

- **Given *P* and *a* (and *G*) we can find the mass of a planet or star**

Geometric Properties of Ellipses

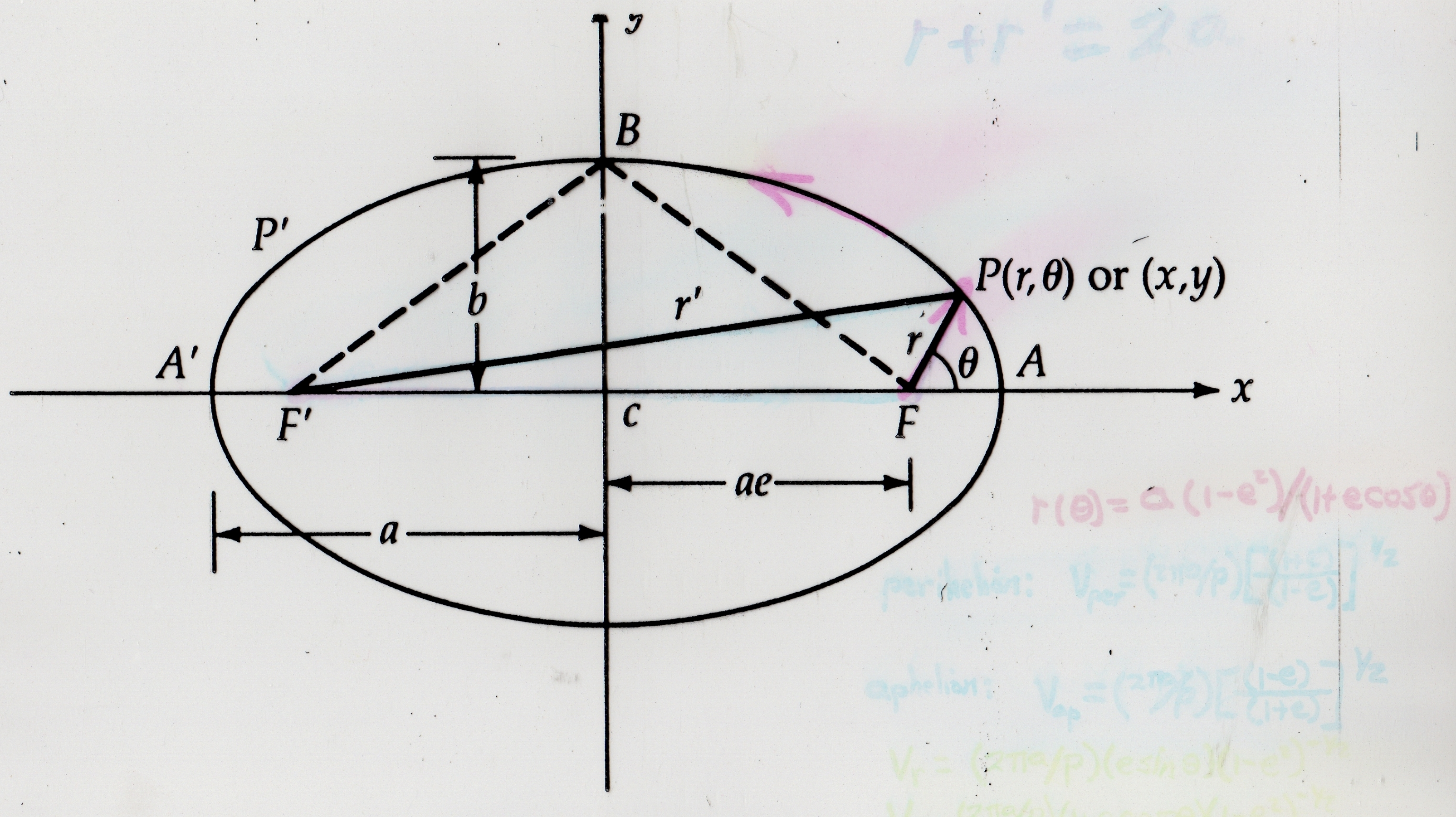


Figure 1–7 An ellipse. Important properties labeled here are *AF*, perihelion distance; *A′F*, aphelion distance; *a*, semimajor axis; *b*, semiminor axis; and *c*, center.

- FF' = 2ae (definition of e)
- Consider triangle BcF:
- $b^2 + a^2e^2 = r^2 = a^2$ (r+r' = 2a) so:
- $b^2 = a^2 - a^2e^2 = a^2(1-e^2)$
- $b = a(1-e^2)^{1/2}$ (relationship between b & a)
- Furthermore:
- $R_{min} = a - ae = a(1-e)$
- $R_{max} = a + ae = a(1+e)$

- (distances at perihelion, aphelion)

- Applying law of cosines to F' PF gives:
- $r'^2 = r^2 + (2ae)^2 + 2r(2ae)\cos\theta$
- But since $r' = 2a - r$ we have:
- $4a^2 - 4ar + r^2 = r^2 + 4a^2e^2 + 4rae\cos\theta$
- $a - r = ae^2 + re\cos\theta$
- $a - ae^2 = r + re\cos\theta$
- $a(1-e^2) = r(1+e\cos\theta)$ so:
- $r = a(1-e^2)/(1+e\cos\theta)$ (equ. for ellipse in polar coordinates)

What about the velocity?

- Kepler's 2^{nd} law:
- $\frac{1}{2} r^2 \, d\theta/dt$ = constant (must hold for entire period)
- $1/2 r^2 \, d\theta/dt = \pi ab/P$ (area/period)
- Since $b = a(1-e^2)^{1/2}$:
- $r^2 d\theta/dt = (2\pi a/P)[a(1-e^2)^{1/2}]$
- Or:
- $d\theta/dt = (2\pi/P)(a/r)^2(1-e^2)^{1/2}$
- Recall $s = r\theta$ so $ds/dt = r \, d\theta/dt = V_\theta$

Velocity continued

- $V_\theta = r\, d\theta/dt = r(2\pi/P)(a^2/r^2)(1-e^2)^{1/2}$

  $= (2\pi/P)[a^2(1-e^2)^{1/2}]/[a(1-e^2)/(1+e\cos\theta)]$

  So finally:

  $V_\theta = (2\pi a/P)(1+e\cos\theta)/(1-e^2)^{1/2}$

  Since $1-e^2 = (1+e)(1-e)$ so we consider 2 cases:

  Perihelion velocity ($\theta = 0^o$):

  $V_{peri} = (2\pi a/P)(1+e)/(1-e^2)^{1/2}$

  Aphelion velocity ($\theta = 180^o$):

  $V_{aph} = (2\pi a/P)(1-e)/(1-e^2)^{1/2}$

Summary: People and Contributions

• Nicolaus Copernicus	1473 - 1543	Heliocentric model Explanation of retrograde motion
• Tycho Brahe	1546 - 1601	Observations of changes in sky Accurate planet positions
• Johannes Kepler	1571 – 1630	Mathematical description of planetary orbits
• Galileo Galilei	1564 – 1642	Observations using telescope supporting Copernican model
• Isaac Newton	1642 – 1727	Physics to explain Kepler's orbits