Astr 2310 Tues. Feb. 2, 2016

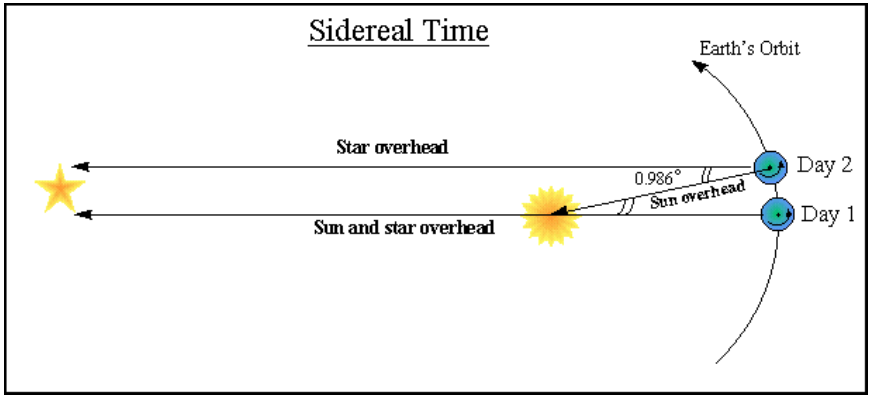
Today's Topics

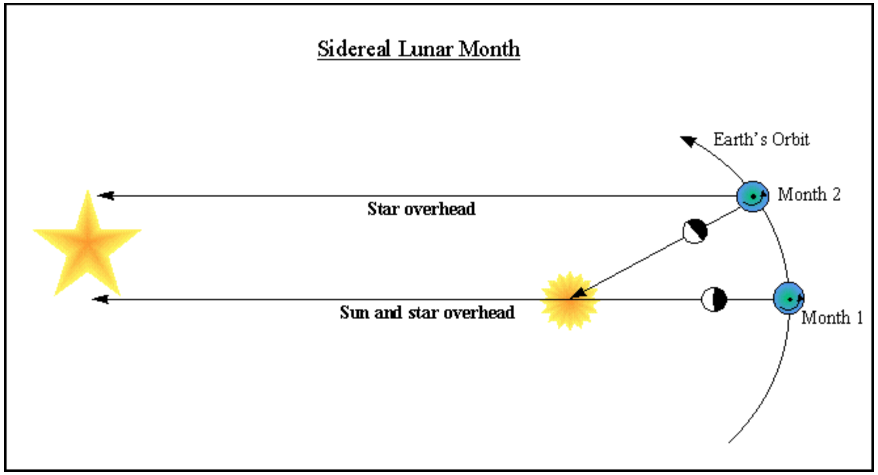
- Celestial Sphere Continued
  - Effects due to Earth's Orbital Motion
    - Apparent path of Sun across the sky
    - Seasons
  - Apparent Motions of Planets
  - Complications
- Ancient Astronomy
  - Babylonians and early culture
  - Greeks
    - Aristarchus
    - Hipparcos
    - Ptolemy

Celestial Sphere Continued

- **Effects of Earth's Orbital Motion**
  - **Sun's Apparent Path Across the Sky**
    - **(Ecliptic and Zodiac)**
  - **Origin of Seasons**
  - **Annual Drift of Stars**
  - **Analemma and the Equation of Time**
- **Complications**
  - **Precession of Earth's Rotational Axis**

Consequences of Earth's Orbital Motion

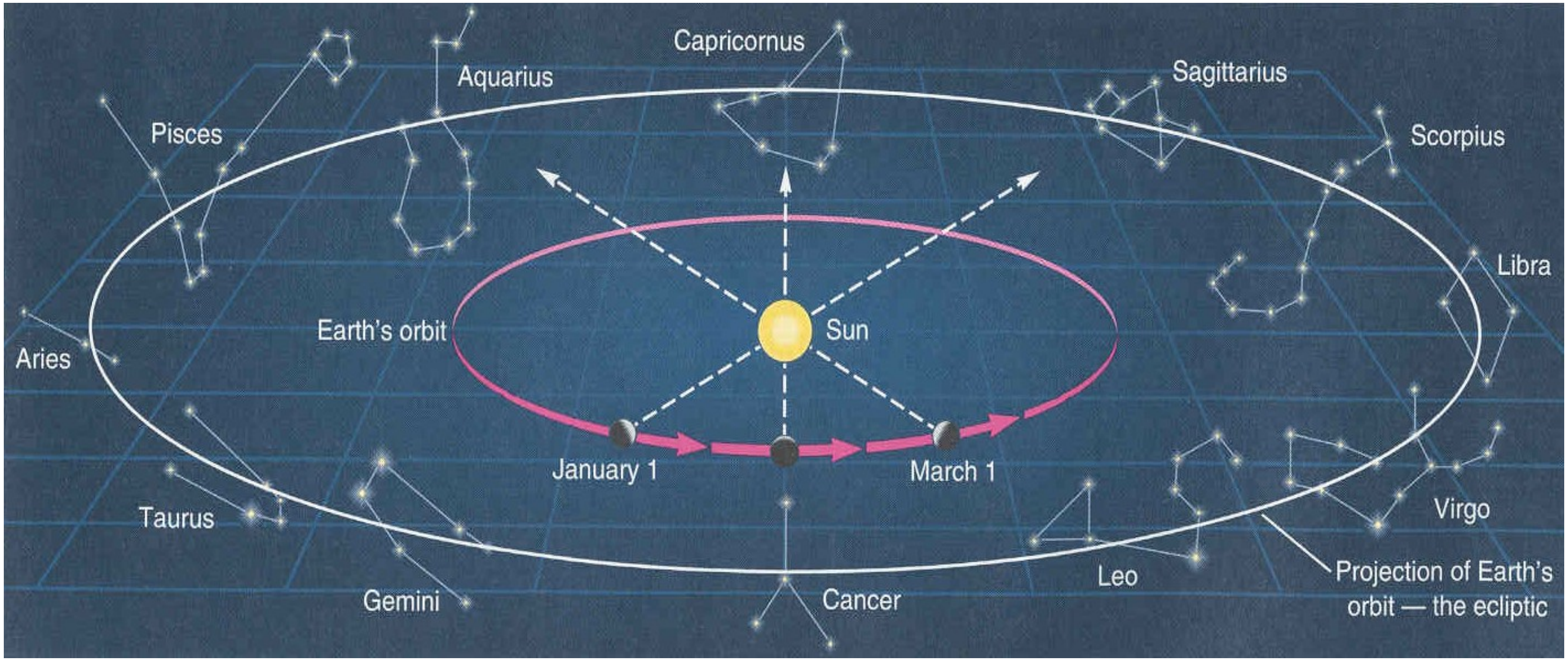




- Earth moves 360°/365.26 days = 0.95°/day
  - Each day the Earth has to turn a little further for the Sun to rise
  - Solar day = 24 hrs (time between successive sunrises)
  - Siderial Day = 23 hr 56 min. (time between successive rises of a given star
  - Stars rise slightly earlier each night creating a "drift" of the night sky over the course of 1 year

Motion of the Sun through the year

– **Follow position of Sun relative to stars, over one full year.**
  - **Each morning stars further east are revealed. Can determine day of the year (when to plant crops) by when a given star is seen.**
  - **Over the course of 1 year the entire sky is visible.**

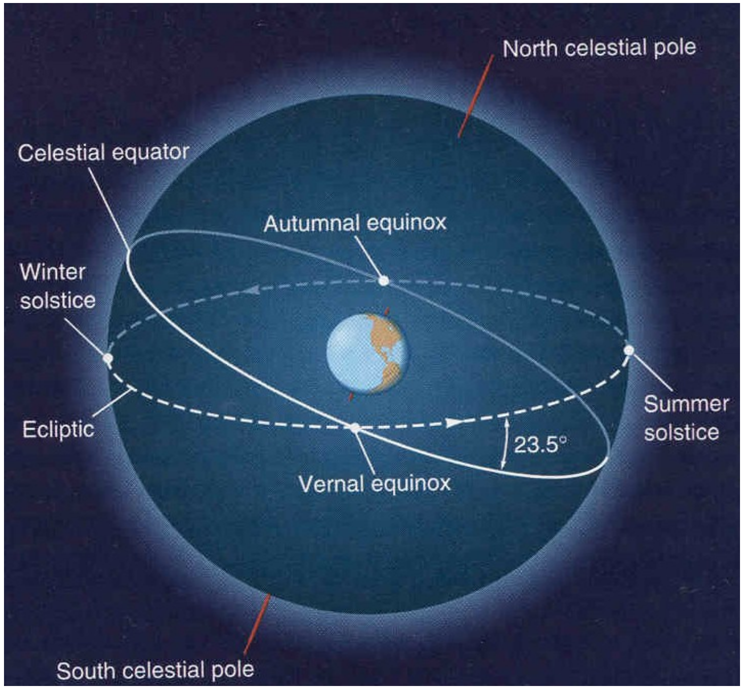


From Horizons, by Seeds)

Apparent path of sun around the sky is called the <u>ECLIPTIC</u>

Set of constellations through which it passes is called the <u>ZODIAC</u>

Plotting the Ecliptic on the Celestial Sphere

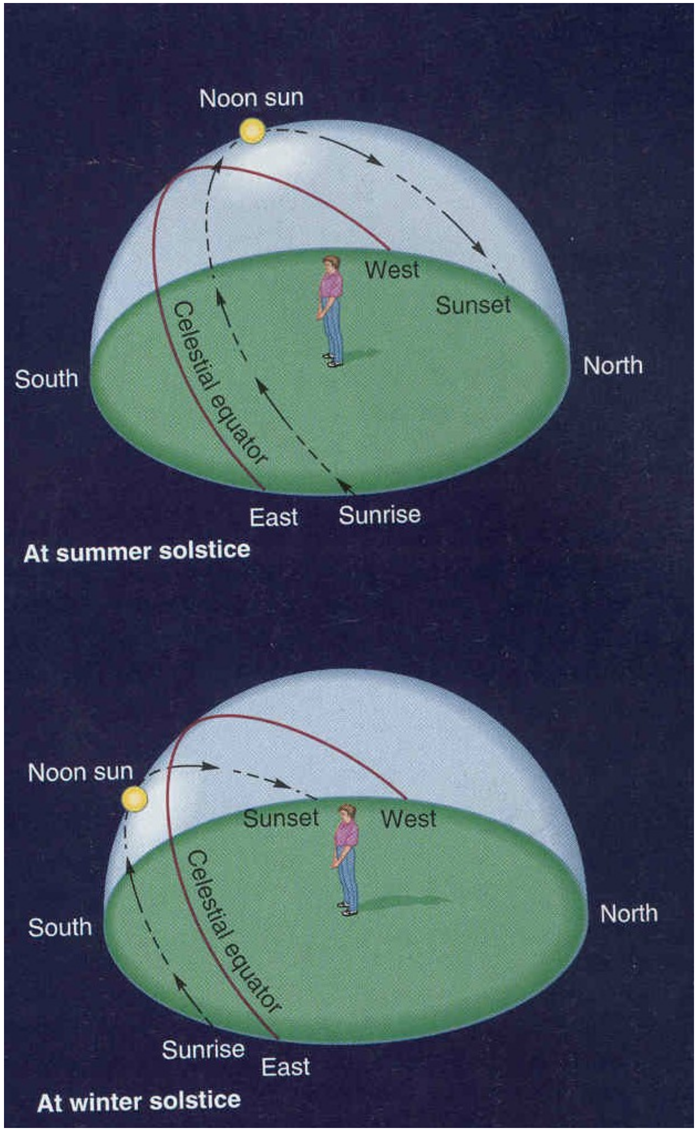


From Horizons, by Seeds

- The ecliptic is tilted relative to the celestial equator by 23.5°
- The sun is at the northernmost point on the ecliptic on June 22 – a time and location called the SUMMER SOLSTICE
- The Sun is at the southernmost point on the ecliptic on Dec. 22 – a time and location called the WINTER SOLSTICE
- The Sun just crossing the equator going N on March 21 – a time and location called the VERNAL EQUINOX

The Sun is just crossing the equator going S on Sept. 22 – a time and location called the AUTUMNAL EQUINOX

Consider the Sun's daily motion thru the year



From Horizons, by Seeds)

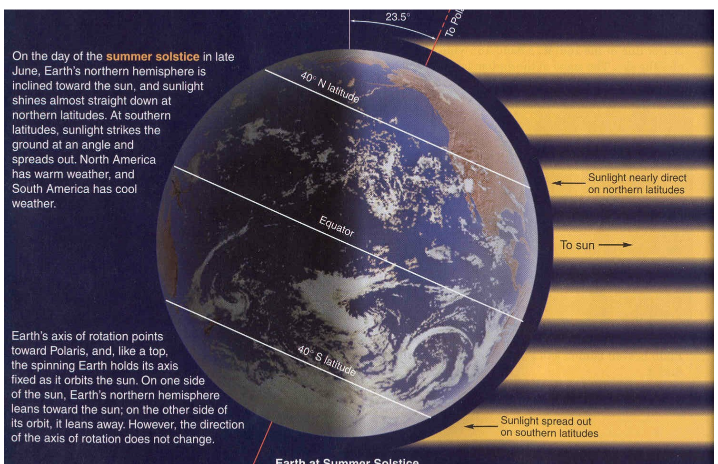
Key point: Consider sun fixed at a given spot on ecliptic over the period of one day.

- **At the Vernal Equinox Sun is on the celestial equator.**
- **At the Autumnal Equinox the Sun is also on the celestial equator.**
  - **It rises due E, sets due W**
  - **It is up exactly 12 hours**
- **At the Summer solstice Sun is a "northern" star.**
  - **It rises N of E, sets N of W**
  - **It is up more than 12 hours**
- **At the Winter Solstice it is a "southern" star**
  - **It rises S of E, sets S of W**
  - **It is up less than 12 hours**

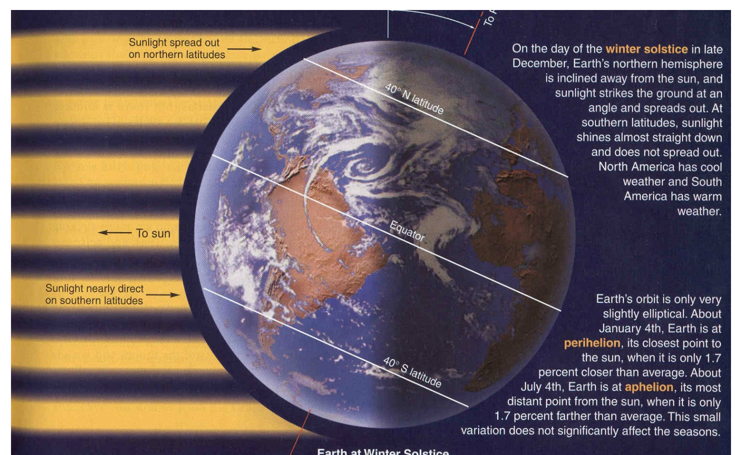
How the Sun’s location affects the seasons:

- The angle of the sun’s rays:
  - In the summer it passes closer to overhead and therefore shines more directly on the summer hemisphere
- The time the Sun is up
  - In the summer it spends more than 12 hours above the horizon.

- The seasons are NOT due to the slightly elliptical shape of the Earth’s orbit and the fact that it is slightly closer to the Sun during part of the year.
  - Test of that hypothesis: If the distance were the cause, then when it was summer in the northern hemisphere, what season would it be in the southern hemisphere?



SUN



(From our Text: Horizons, by Seeds)

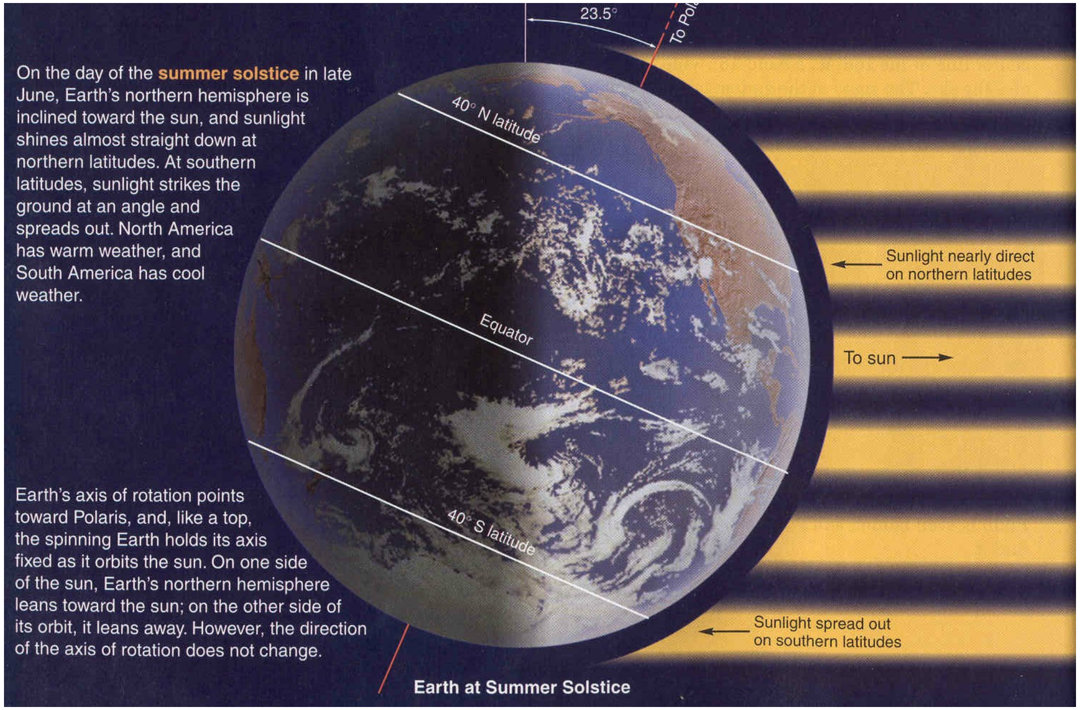
Special Locations on the Earth

•How close to the North Pole do we need to go before the Summer Solstice sun becomes a "circumpolar star" and is above the horizon all day?

- **•Within 23.5º of the pole: THE ARCTIC CIRCLE**

•How close to the equator do we need to get before the Summer Solstice sun passes directly overhead rather than somewhat to the south:

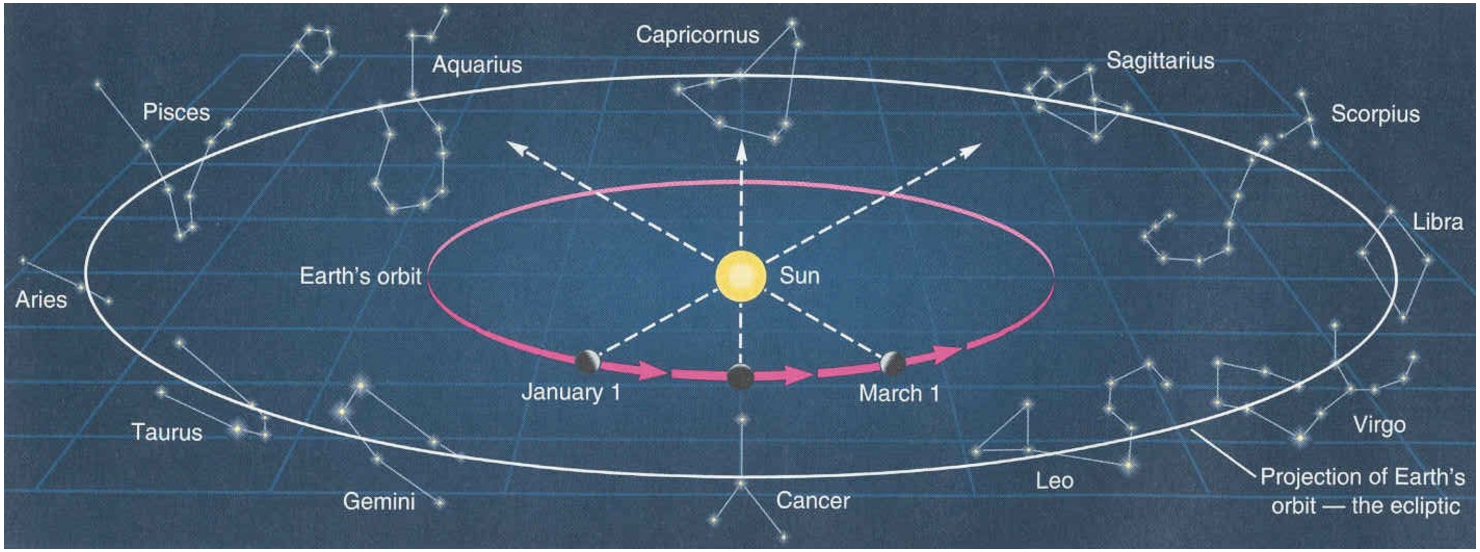
- **•Within 23.5º of the equator: The TROPICS**



(From our Text: Horizons, by Seeds)

Why are the planets found near the ecliptic?

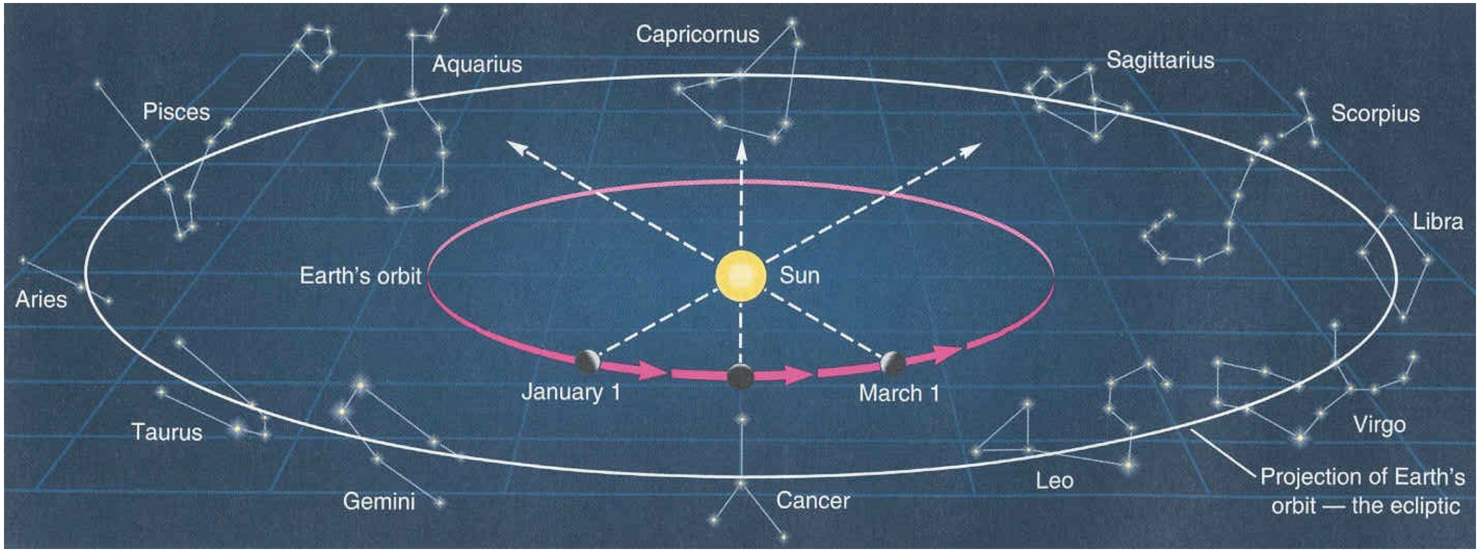
- The ecliptic is defined by the *plane* of the Earth's orbit around the Sun.
- If the other planets are always found near the ecliptic, they must always be located near the plane of the Earth's orbit – at most slightly above or below it.
  - The planes of their orbits around the sun must almost match the Earth's.
  - Their slight motions above and below the ecliptic means the match isn't exact. (Their orbits are slightly tilted relative to ours.)



From our text: Horizons, by Seeds

Superior vs. Inferior Planets

- **Superior planets (Mars, Jupiter, Saturn, Uranus, Neptune, Pluto) have orbits larger than the earth and *can* appear opposite the sun in the sky. They can be up at midnight. Never show phases.**
- **Inferior planets (Mercury, Venus) have orbits smaller than earth and can never appear far from the Sun. They form "morning stars" or "evening stars" visible a little before sunrise or after sunset. Show phases.**



From our text: Horizons, by Seeds

Apparent Motion of Inferior Planets

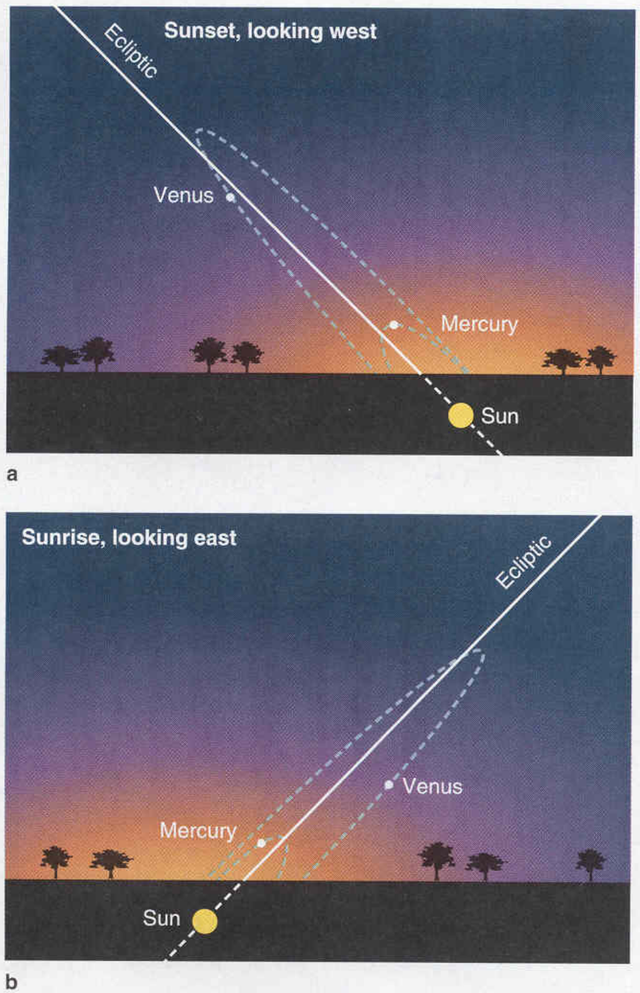


Figure 3-2
Mercury and Venus are sometimes visible in the western sky just after sunset (a) or in the eastern sky just before sunrise (b).

- **Inferior planets (Mercury, Venus) have orbits smaller than earth and can never appear far from the Sun. They form "morning stars" or "evening stars" visible a little before sunrise or after sunset.**
- **If the inferior planet sets before the Sun it won't be visible in the evening sky. Look for it instead in the morning sky and vice versa.**

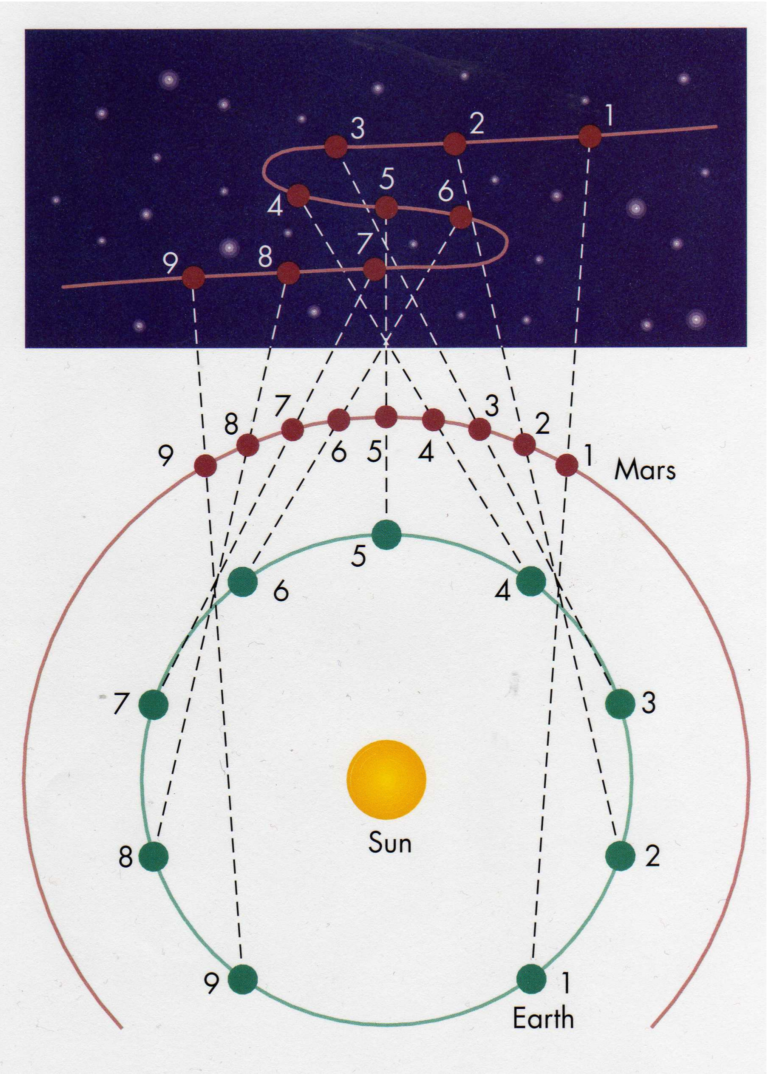
From our text: Horizons, by Seeds

Apparent Motion of Superior Planets

- **Earth's Orbital Motion is Faster than that of the Outer Planets**
  - **Change of perspective over time**
    - **Superior planet appears to slow and even backup as the Earth passes it (Retrograde Motion)**
  - **Very Difficult to Explain from Geocentric View**

Retrograde Motion

As Earth overtakes the slower supior planet the outer planet can appear to reverse its direction in the sky.

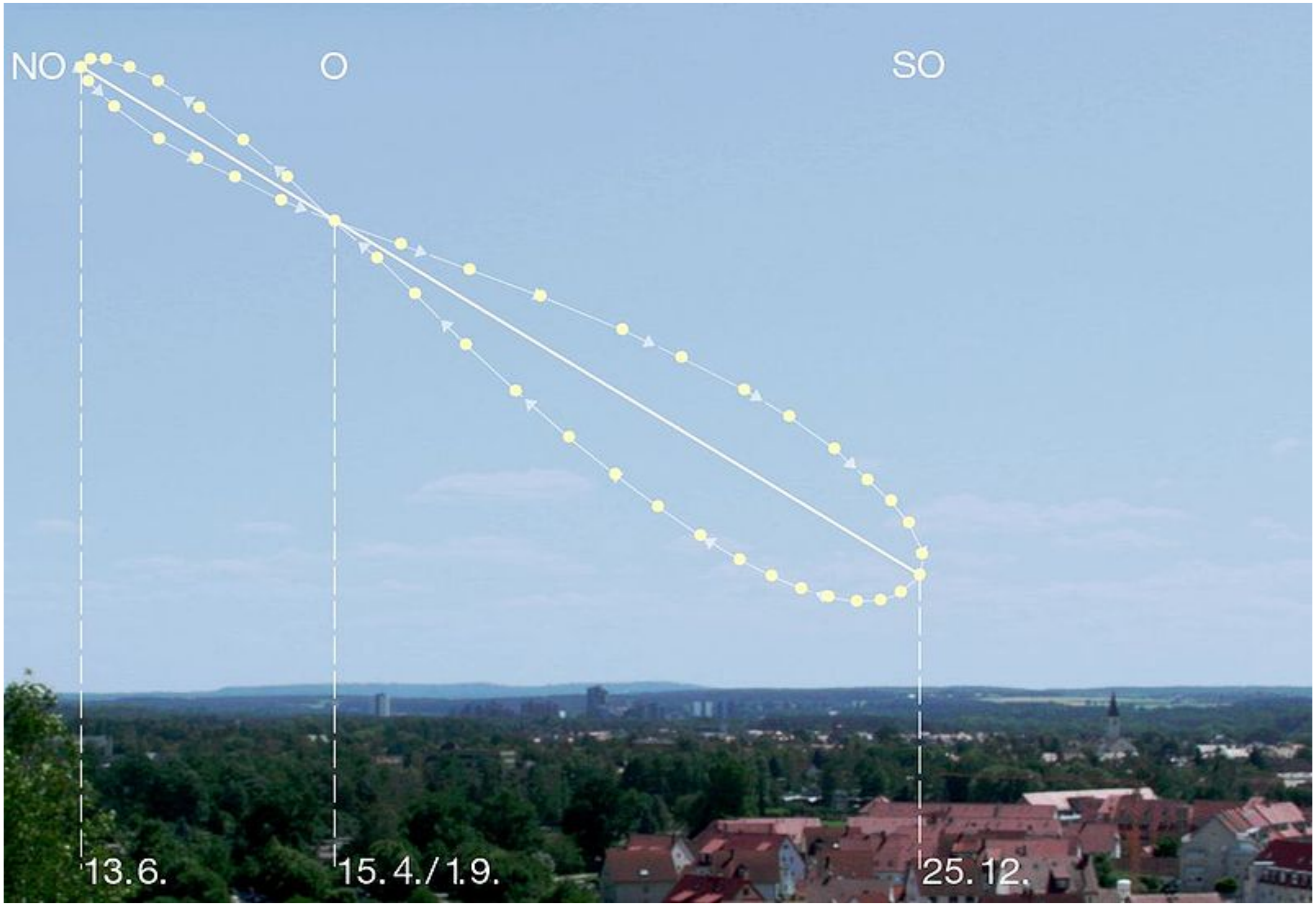


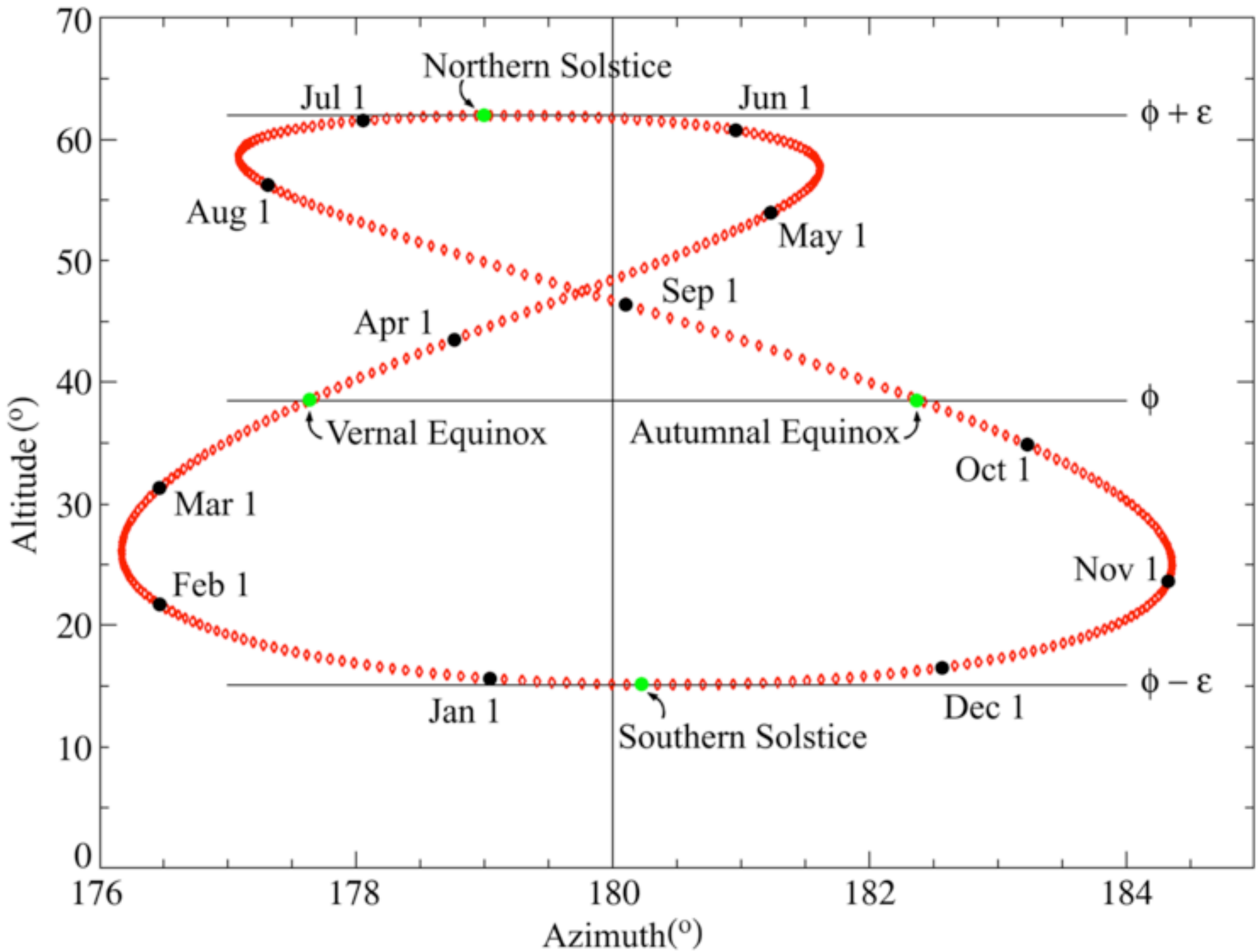
Earth Axis is Tilted and its Orbit is Elliptical

- Apparent path of the Sun across the sky depends upon the season.
- Elliptical orbit results in faster orbital speed of the Earth when closest to the Sun and slower speed when further.
  - The position of the Sun at midday drifts E/W with respect to the Meridian.
    - Sometimes behind and sometimes ahead of average.
    - i.e., length of Solar day depends on day of year.
- Result is the Analemma and the Equation of Time

Analemma

- Photograph Sun at same time each day.

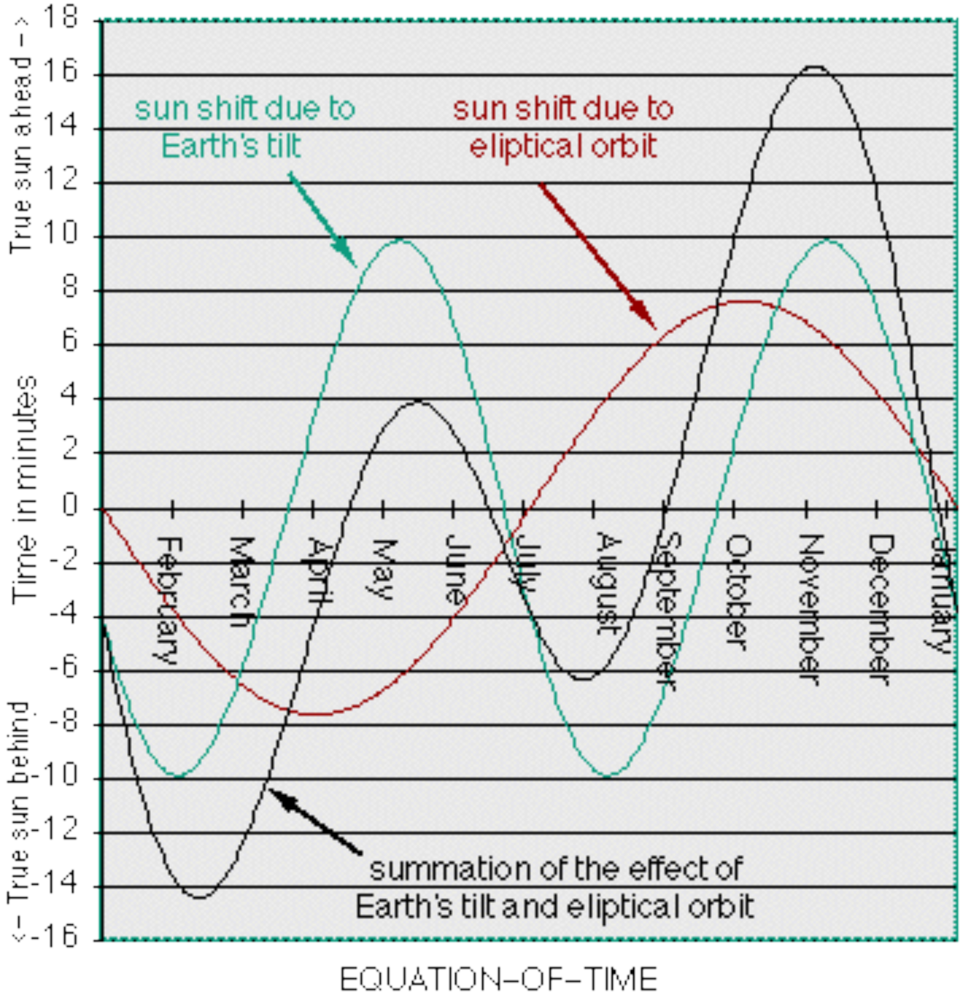




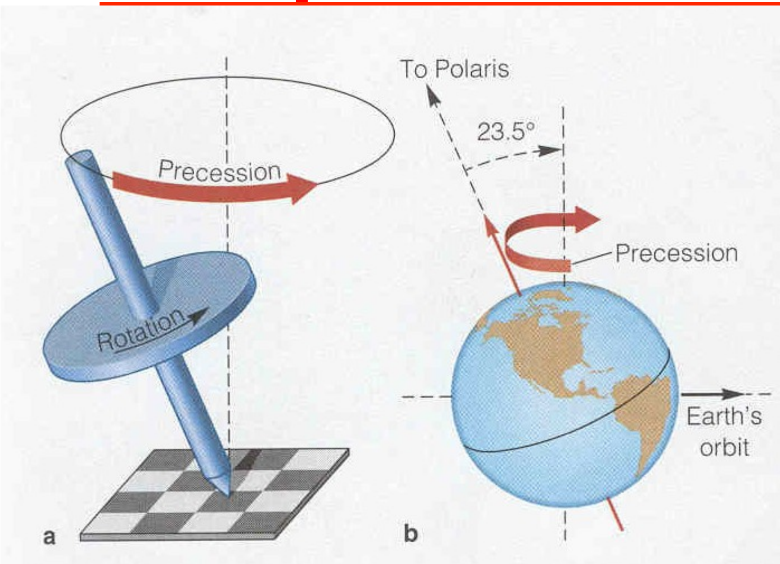
Highly enlarged view, sometimes shown on globes. Note the faster motion of the Earth in Dec/Jan when closest to the Sun and slower motion in Jun/July when we're furthest.

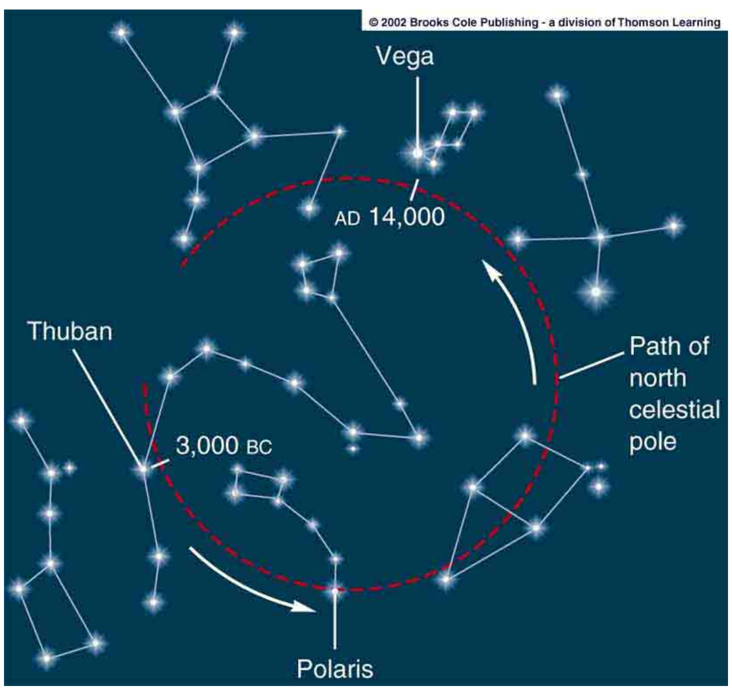
Equation of Time

- Drift can be expressed as a difference between the local apparent time and the mean solar time (averaged over the year).
- This correction is known as the Equation of Time



Complications: Precession of the Earth





- **The earth's axis of rotation is tilted 23.5^0 relative to the plane containing the sun and other planets (obliquity).**
- **The gravity from the Sun and moon is trying to tip the earth just like gravity is trying to tip a spinning top (torque).**
- **As with the top, the axis of the earth wobbles or PRECESSES in space, with a 26,000 year period.**
- **Because the directions to the celestial poles are defined by the spin axis – those poles appear to move with time.**
  - **It isn't that the stars move – it is that the grid we paint on the celestial sphere has to be redrawn from time-to-time.**
  - **Polaris has not always been the "pole" star. Evident from Egyptian tomb paintings**

FromHorizons, by Seeds)

Ancient Astronomy

- Babylonians, Assyrians, Egyptians, Bronze-age British, Mayans, Polynesians
  - Sophisticated knowledge of celestial motions and seasons.
  - Developed calendars and predicted eclipses
- Chinese
  - Long, detailed record of unusual events
    - Comets
    - Novae, supernovae
- All these cultures viewed universe as geocentric.
  - How would the sky look if Sun and planets really did orbit the Earth?

Early Greek Astronomy

- Pillar of Western Thought for 2000 yrs
- Developed Concepts Still Used Today
  - Constellations
  - Star brightness classification (magnitudes)
  - Planets
  - Understood Phases of the Moon
  - Discovered Precessional Motion
  - Established Rough Scale of the Solar System
  - First Application of Mathematics to Astronomy
- Developed a Quantitative Geocentric Perspective
  - The universe is just what we perceive.
- Some suggested the Earth might orbit the Sun
  - The universe not be all that it seems

Early Greeks and Their Contributions

- **Plato** 427 – 347 B.C. Simple motion using spheres Perfection of the heavens,
- **Eudoxus** 390 – 337 B.C. Retrograde motion
- **Aristotle** 384 – 322 B.C. Shape of Earth, Multiple Spheres
- **Aristarchus** 310 - 230 B.C. Heliocentric Model, Size of the Moon, Distance of the Sun
- **Eratosthenes** 276 - 194 B.C. Size of the Earth
- **Hipparchus** 190 - 120 B.C. Size of the Moon, Distance of the Sun. Star Catalogs, Magnitudes, Stellar Precession
- **Ptolemy** 83 - 168 A.D. Models for planetary motion

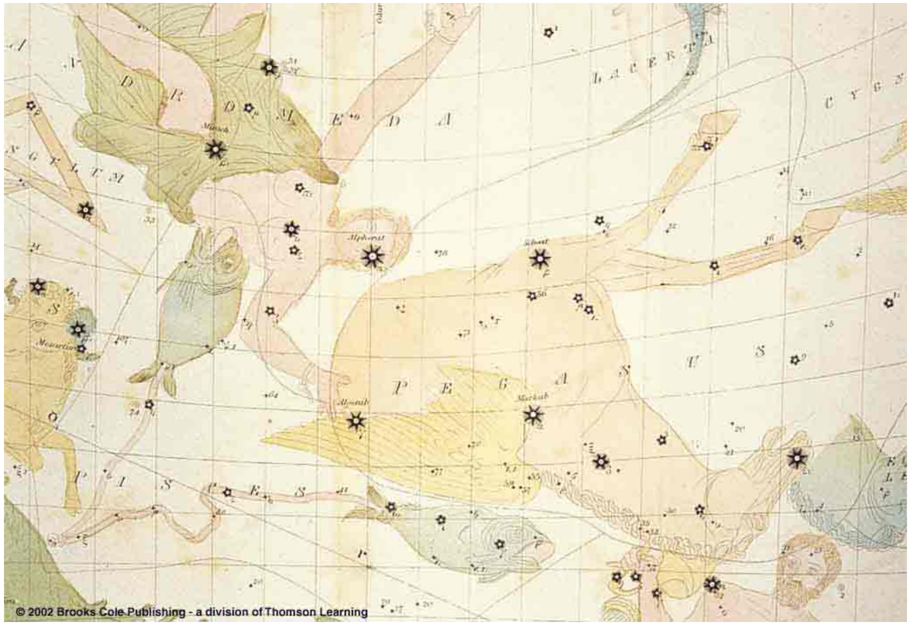
The Sky Today

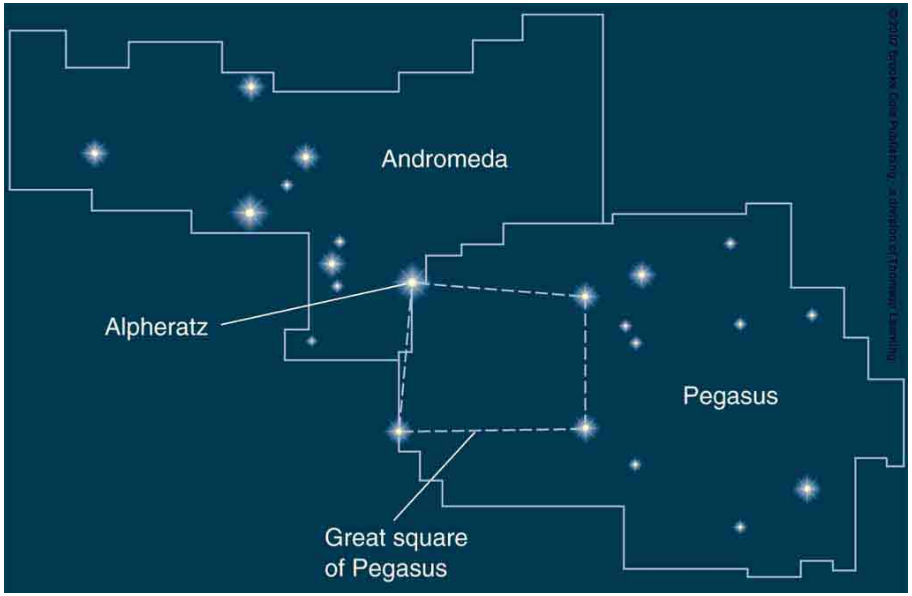
Constellations:

- **-Originally vague**
- **-Mostly Greek**
- **-Now well defined, including the southern hemisphere**
- **-Total of 88 to cover the sky**

Asterisms:

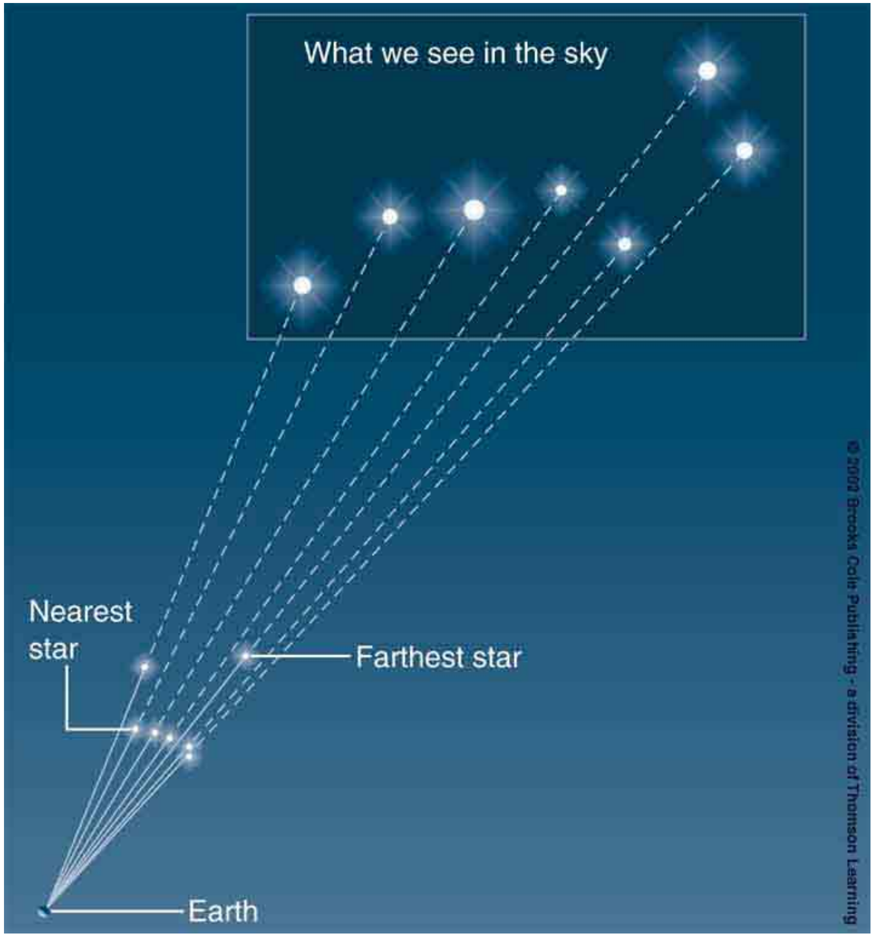
- **-Less Formal Groups (Big Dipper)**





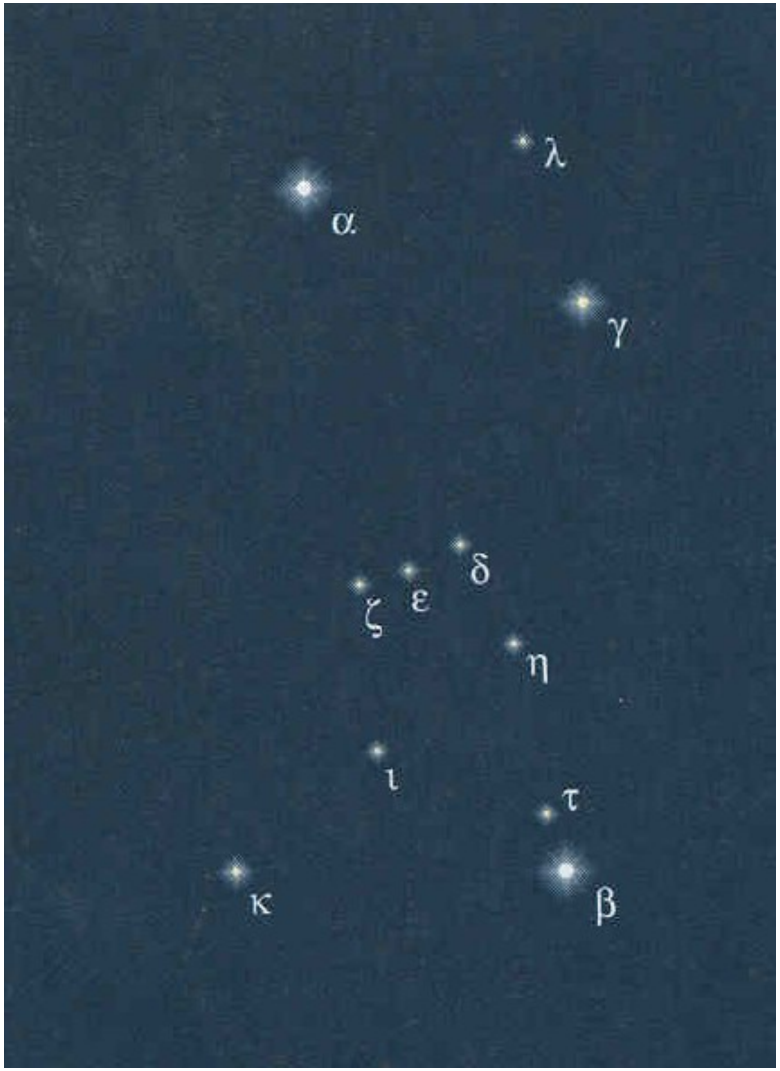
Big Dipper

- **The stars in a constellation or asterism like the Big Dipper are NOT necessarily at the same distances.**
- **These are just chance arrangements as seen from Earth.**



From Horizons, by Seeds

Names of stars



Orion

Horizons, by Seeds)

- Proper names mostly from Arabic astronomy
- **Astronomers use (α, β, δ, ε, ...) + Constellation Name in approximate order of brightness**
  - Alpha Orionis = Betelgeuse
  - Beta Orionis = Rigel
  - Alpha Tauri = Aldebaran
- **Numbers and other schemes for fainter stars. (About 6000 stars are visible to naked eye.)**

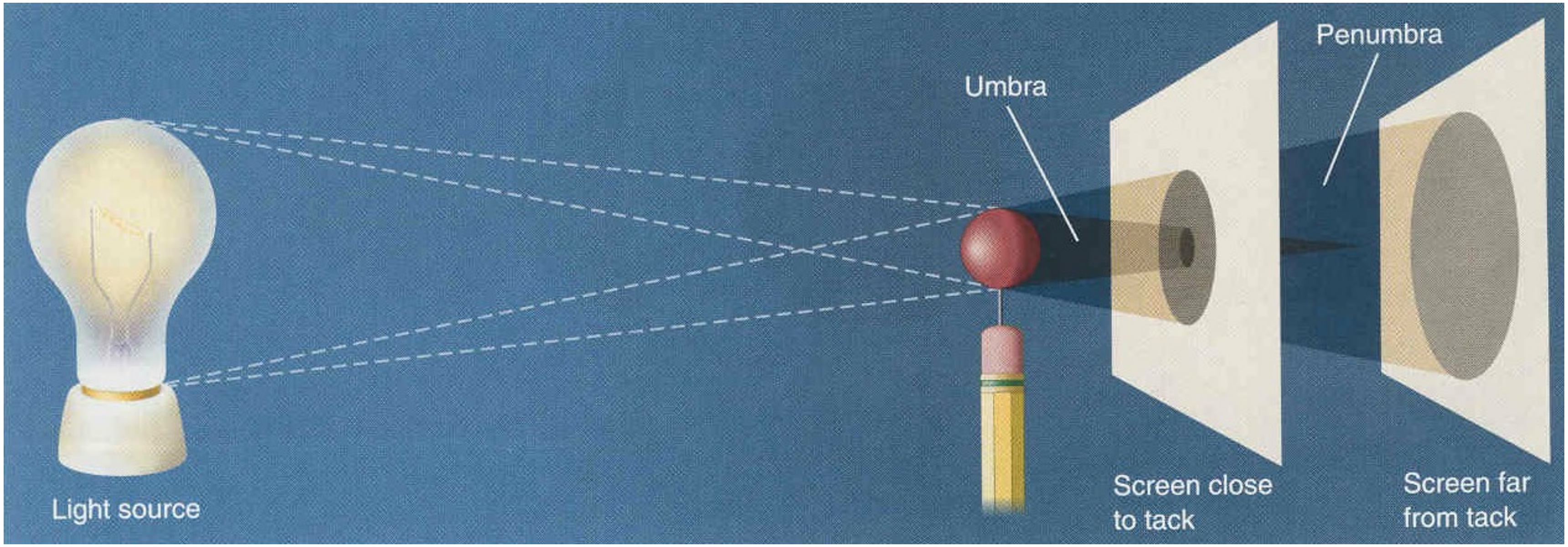
Eclipses (1)

- Very Dramatic
  - Significant to primitive cultures
    - Religious significance
    - Astrological meaning
- Long detailed records reveal patterns
  - Eclipses can be predicted

Eclipses (2)

- Early Greeks were well aware of the phases of the moon and their origin
- Aristotle noted that the shape of the Earth's shadow during a lunar ecipse proved the Earth was round
- Eratosthenes measured size of Earth by measuring the position of the Sun from two locations at the same time.

Shadows and Eclipses



From 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.

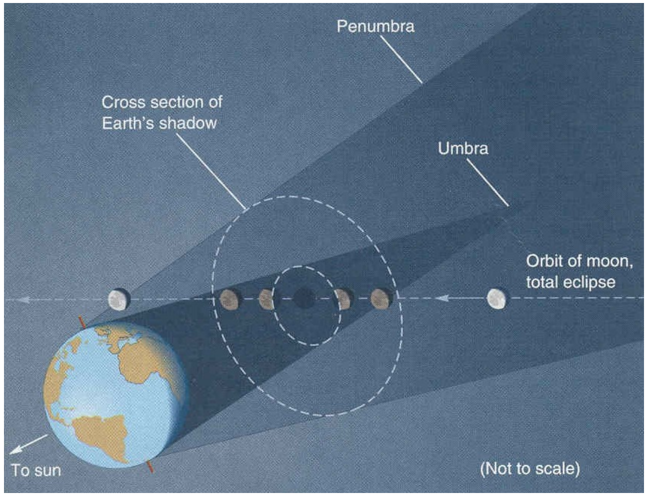
Umbra — **Portion of shadow where it is completely dark.**
(for a person in the shadow, the light bulb would be completely blocked out)

Penumbra — **Portion of shadow where it is only partially dark.**
(for a person in the shadow, the light bulb would be partially blocked out)

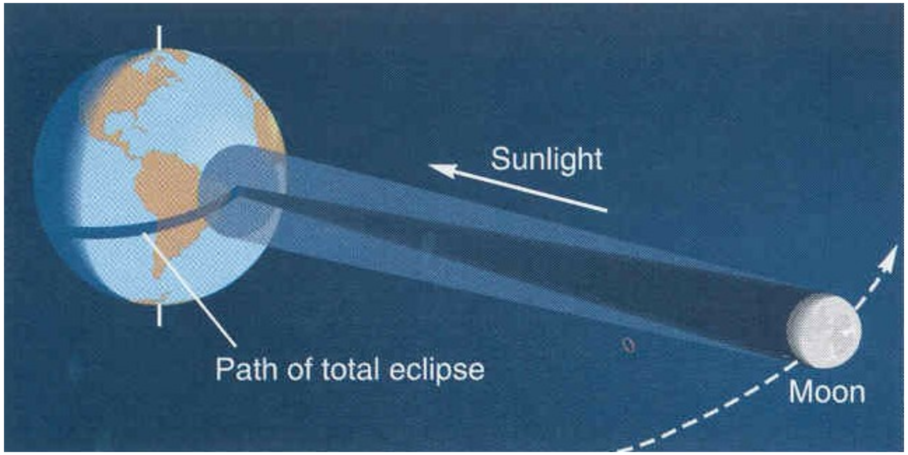
(To remember the names, think of "ultimate" and "penultimate")

Types of eclipses

Lunar Eclipse



Solar Eclipse



From Horizons, by Seeds

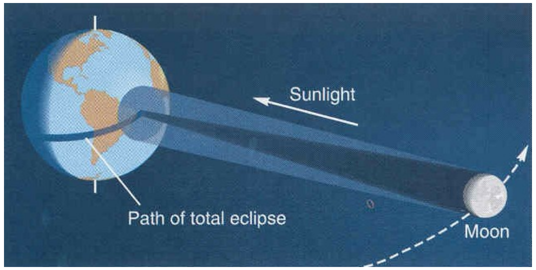
We view the illuminat<u>ed</u> object and watch it go dark.

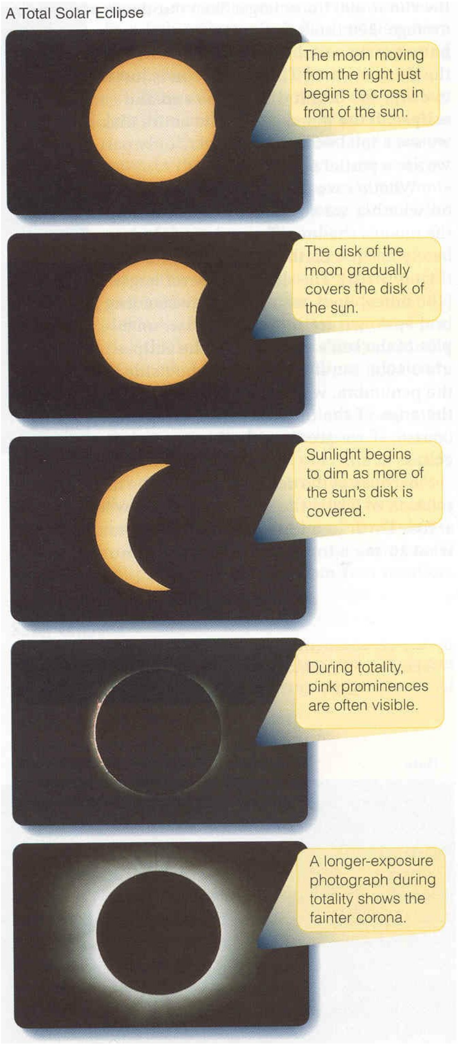
Everyone on one side of the Earth can see the Moon – so a given lunar eclipse is visible to many people.

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 (Moon and Sun are nearly the same size).

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





From Horizons, by Seeds

Solar eclipses

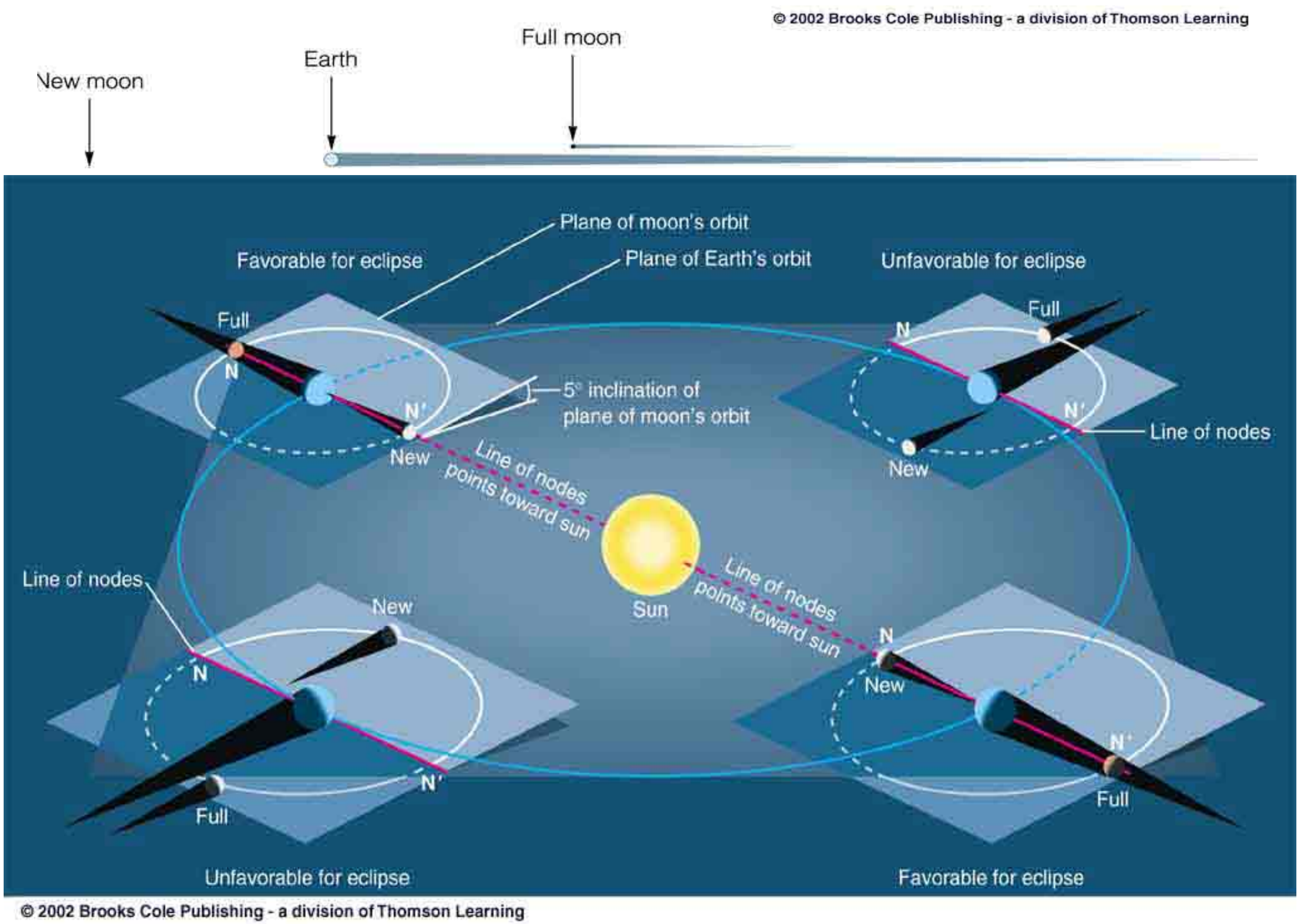
- If you are outside the penumbra you see the whole sun.
- If you are in the penumbra you see only part of the sun, a partial eclipse.
- If you are in the umbra you cannot see any of the sun, a total eclipse.

- 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, a ring.

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). Stonehenge is thought to be a device for predicting eclipses.**

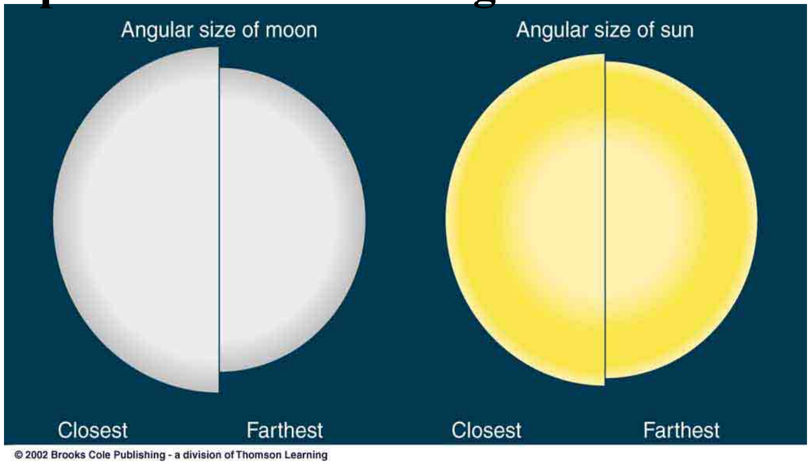
Eclipses and Nodes



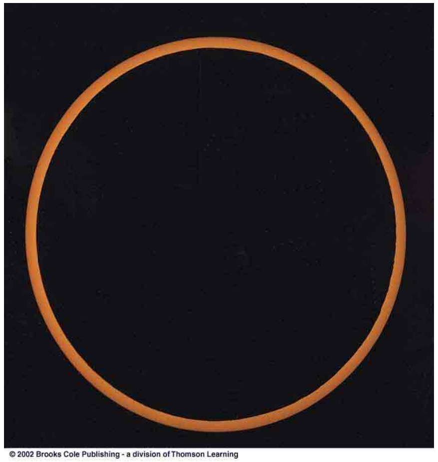
From Horizons by Seeds.

Variations in Solar Eclipses

Elliptical orbits mean angular size variation.



Diamond-Ring Effect

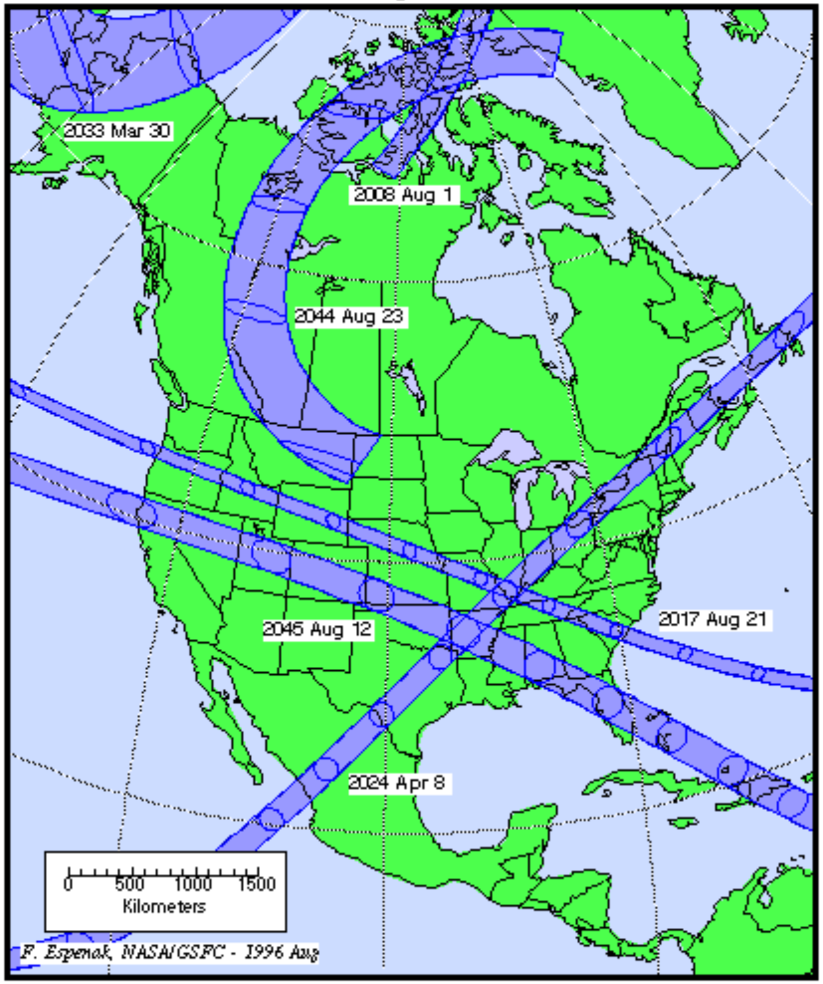


Annular Eclipse

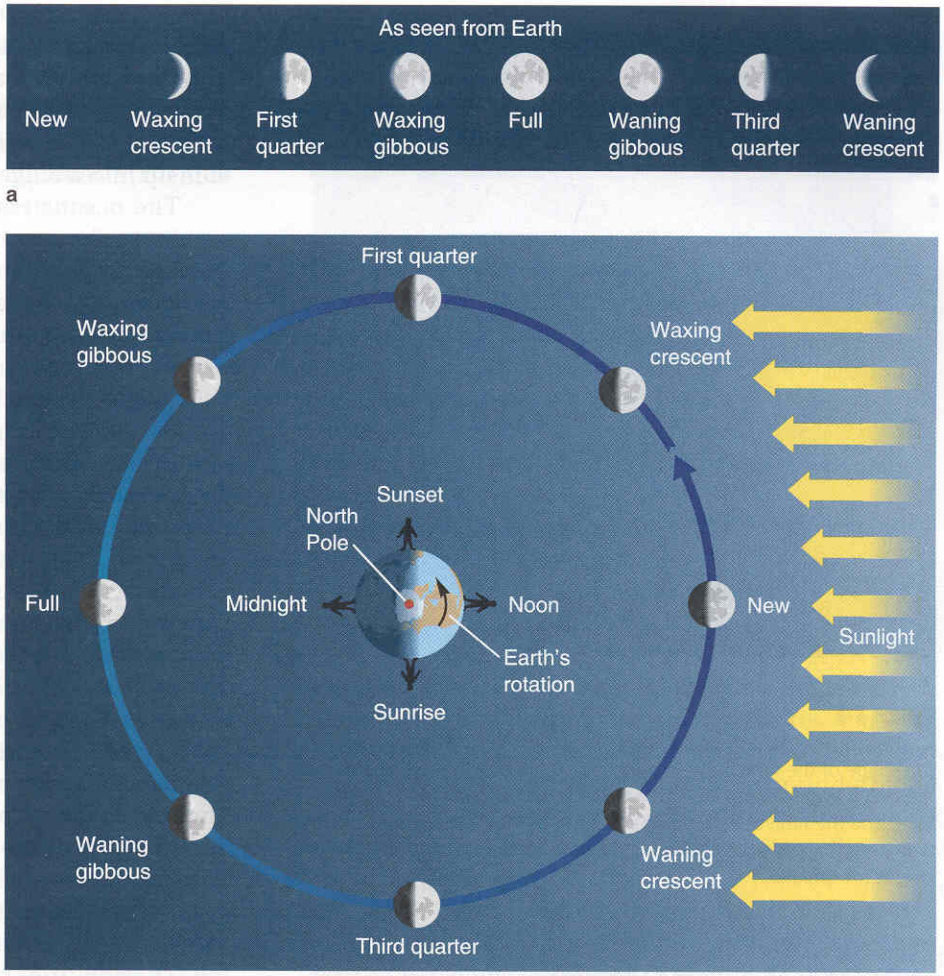
Future Solar Eclipses

- A good web page for solar eclipses:
- http://eclipse.gsfc.nasa.gov/eclipse.html
- http://eclipse.gsfc.nasa.gov/SEmap/SEmapNA/TSENorAm2001.gif
- The most favorable next Solar eclipse is August 21, 2017

Total Solar Eclipses: 2001 - 2050



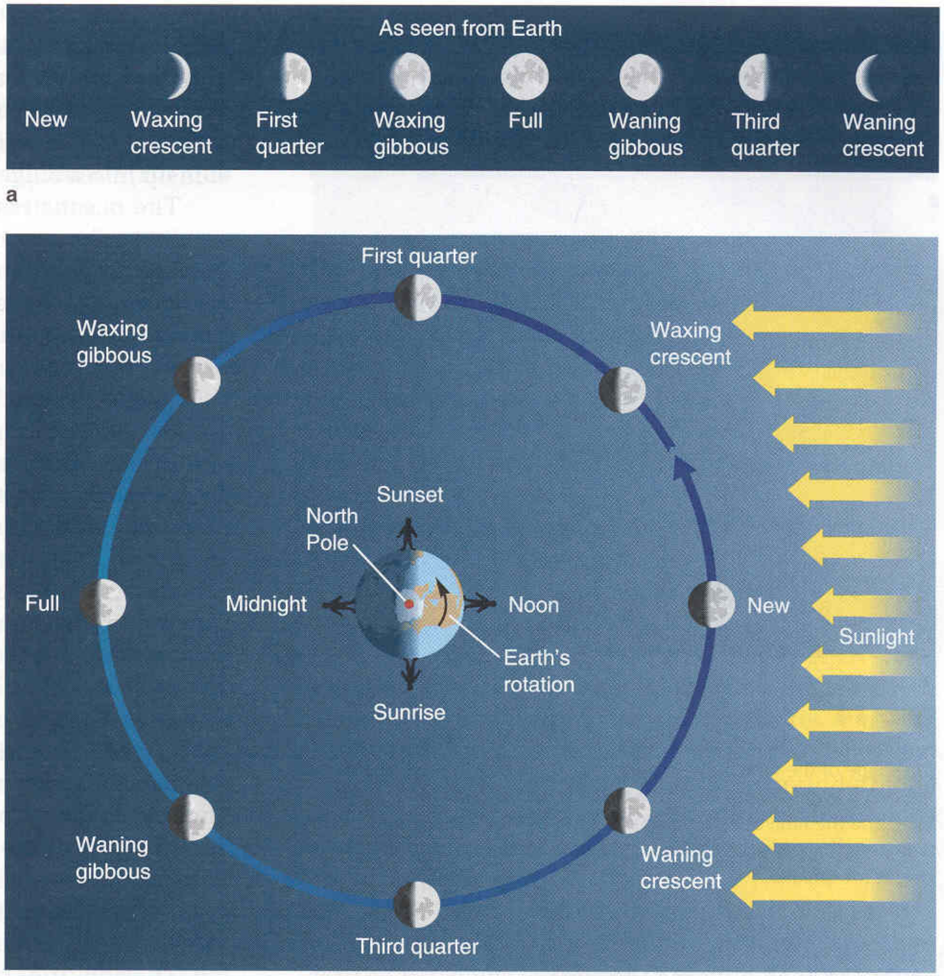
Phases of the Moon and its orbit around the Earth (1).



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.

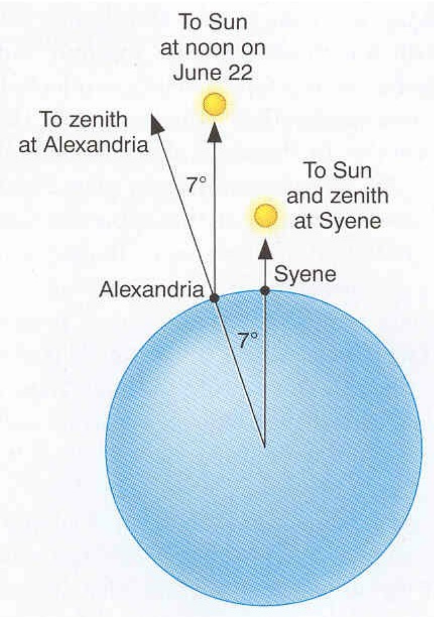
•It has to be the side towards the sun which is illuminated. Imagine yourself lying on the ground at 6 pm, head north, right arm towards the west. That west (right) arm points towards the sun. That must be the side which is illuminated.

Aristotle's Universe: Earth's Shape

From our text: Horizons, by Seeds

- **Aristotle knew the Earth was round:**
  - Shadow of Earth during lunar eclipse
  - Changing height of Polaris and celestial pole as you moved south

- **Eratosthenes measured size of Earth** to better than 20%
  - ~200 BC, Greek living in Alexandria Egypt
  - Observed that
    - Sun was overhead at Syene on summer solstice
    - Sun was 7° to the south of zenith at Alexandria
  - Circumference of Earth must be 360/7 times distance from Syene to Alexandria

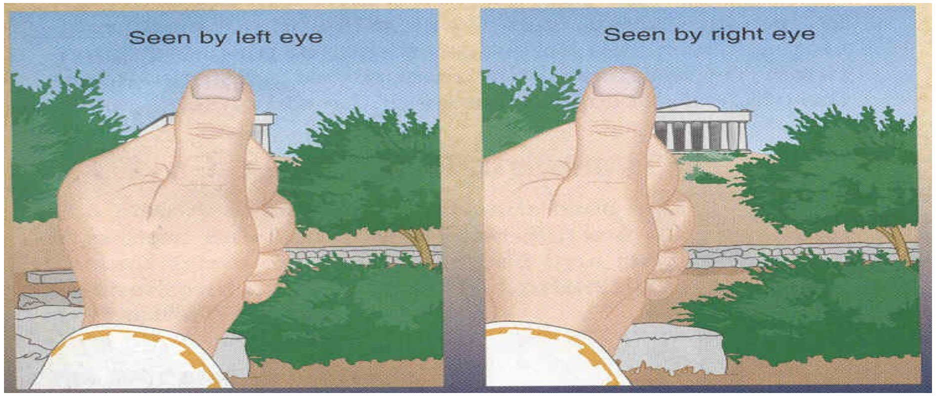


From Voyages by Fraknoi et al.

Aristotle's Universe: Earth's Motion

- **Aristotle had good reasons to think the Earth stood still:**
  - **Absence of any detectable parallax**

    If the Earth orbits the sun (rather than the reverse) then we should be able to see shifts in the positions of the stars due to parallax.



From our text: Horizons, by Seeds

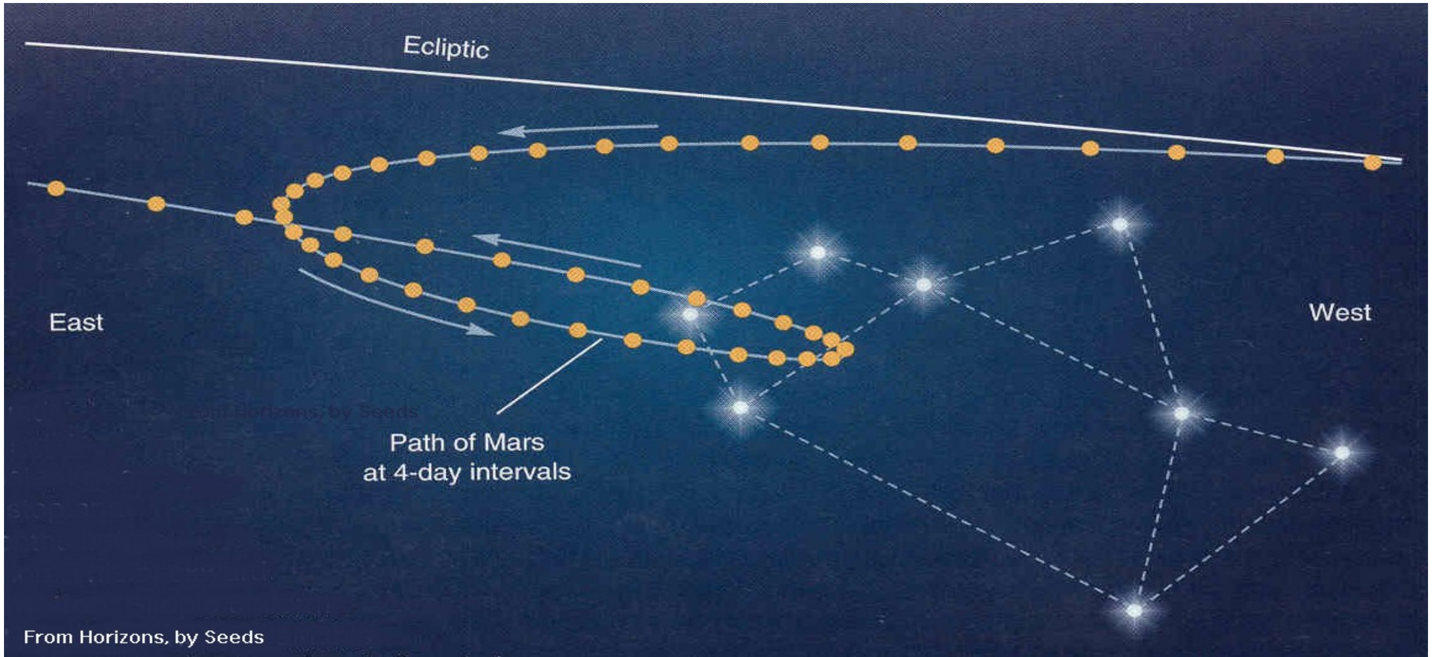
- **The amount of parallax is proportional to** $\dfrac{\text{Radius of Earth's orbit}}{\text{Distance to star}}$
  - **We now know the distance to the <u>nearest</u> star is so large that even it only has a parallax of 1 second of arc = 1/3600 deg. 1 parsec = 3.26 ly. This is much too small to be measured with the naked eye.**

Aristotle's Universe: Planets' Motion

- Heavens composed of "perfect" fifth element
  - Elements: Earth, Air, Fire, Water, Quintessence
  - Heavens are unchanging except for rotation:
- Motion produced by multiple nested spheres
  - Rotate at constant rate
  - Are offset and inclined in ways to produce motion of planets
  - Our "Celestial Sphere" of stars is just the outermost of many he had. VERY complicated for a "perfect" system!

Recall Retrograde Motion

- Planets stay almost on the ecliptic
- Most of the time they move East (relative to stars)
- Rates drop from Mercury to Venus to Mars to Jupiter to Saturn.
- Superior planets exhibit "retrograde" motion near opposition.

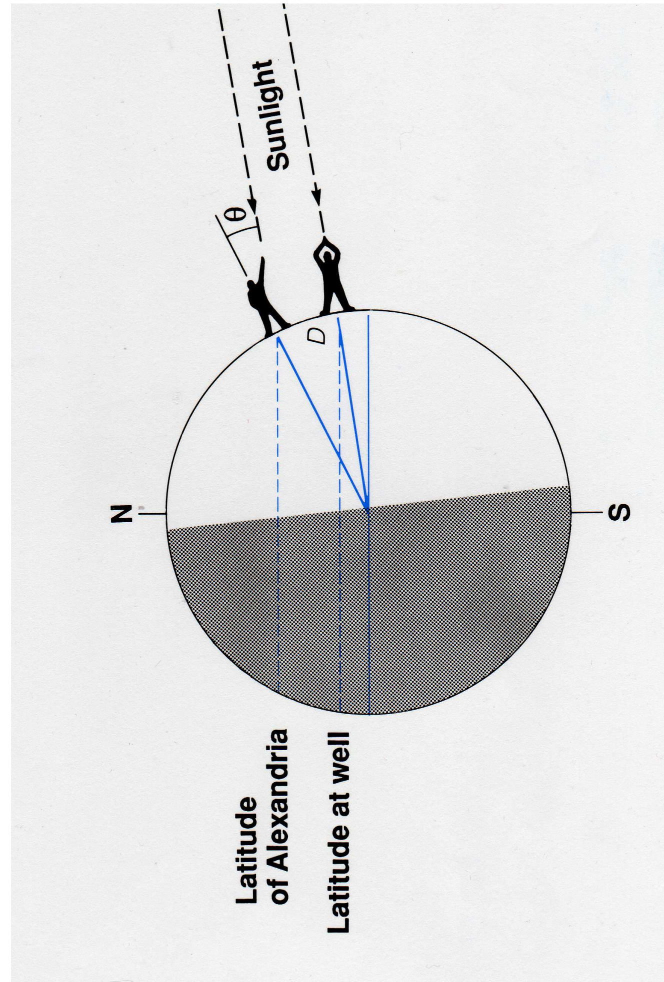


Eratosthenes and the Radius of the Earth (1)

- **Eratosthenes hears Sun shines directly down a well in Syene on a particular day of the year, i.e., at zenith. On that day he notes that it is significantly south of the zenith at Alexandria.**
  - **He knows the Earth is round from the shape of the Earth's shadow during an eclipse.**
    - **He realizes he can now measure the Earth's radius.**

Eratosthenes and the Radius of the Earth (2)

- Recall the arc-length formula ($s = r\theta$)
- So, $D = R_E\,\theta$ if θ is in radians
- D = 5000 stadia (~ 800 km)
  - $\theta = 7.^{\circ}2 = 0.1257$ radian (Eratosthenes)
- $R_E = 800/0.1257 = 6364$ km
- (actually 6378 km, so very close!)



Aristarchus and the Scale of the Solar System

- **Aristarchus realized that the relative geometry of the Earth, Moon and Sun could be determined.**
  - **Time between phases of the Moon give the distance of the Sun relative to that of the Moon**
  - **Angular size of the Moon compared to that of the Earth's shadow gives the size and distance of the Moon relative to the Earth's radius.**
  - **Given the Earth's radius (Eratosthenes) the scale of the Solar System can be computed.**

Aristarchus continued (2)

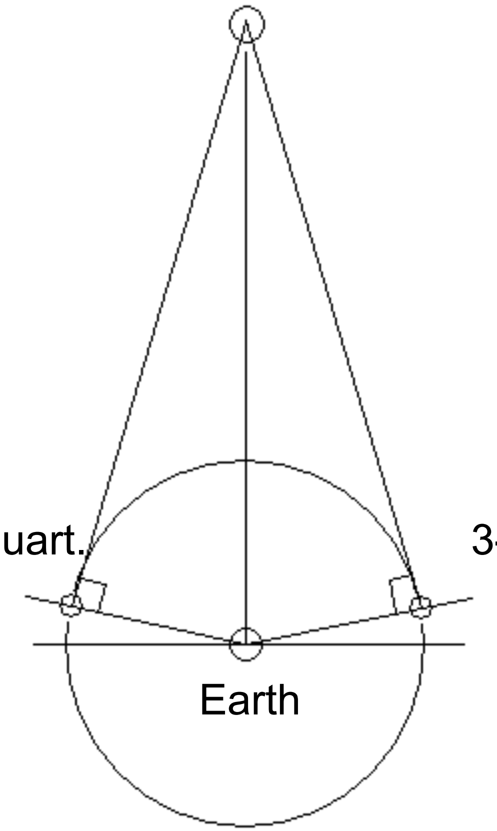
- **Aristarchus stated that the Moon appeared half-full when the angle between the Moon & Sun (θ) is 87^o.**
- **Sin ϕ = d_M/d_S**
- **How did he get θ = 87$^{o?}$**
- **One way might have been by measuring the time between moon phases:**

(Time1 –Time2)/period = 2(90^o- θ)/ 360^o = 2ϕ/360^o

- **θ = 87^o gives:**

  d_S = 19 d_M

  The real value is 400x!



Aristarchus continued (3)

Aristarchus assumed:

θ of Sun & Moon is 1/2°.

Earth's shadow is 8/3 θ_M

$d_S >> d_M$ ($d_S \sim 400\ d_M$)

From similar triangles:

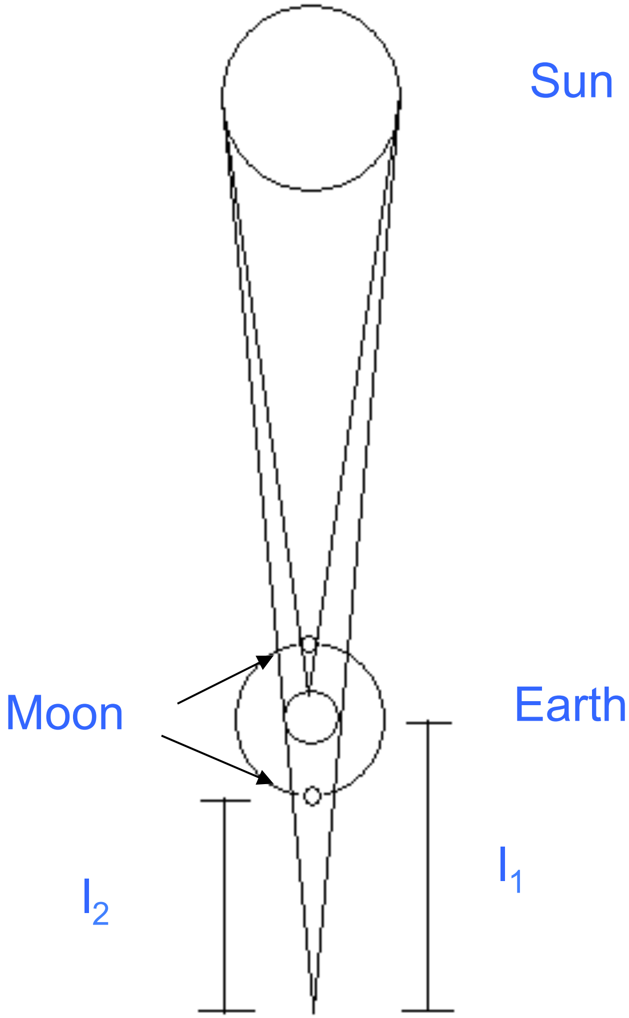
$2R_E/l_1 \sim 2R_S/d_S = 2R_M/d_M$ (1)

$\sim (8/3)(2R_M)/l_2$

Since: $2R_M/d_M = 16R_M/3l_2$

and $d_M = 3l_2/8$ and $\tan(0.25) \sim R_E/l_1 \sim R_M/d_M$ so:

$l_1 = R_E/\tan(0.25) = 229\ R_E$



Aristarchus continued (4)

Continuing:

$l_1 = d_M + l_2$

$= 3l_2/8 + l_2 = 11l_2/8$

So:

$l_1 = 1.375\ l_2 = 229R_E$ (2)

$l_2 = 166.7\ R_E$ (3)

$d_M = l_1 - l_2 = (229 - 166.7)R_E$

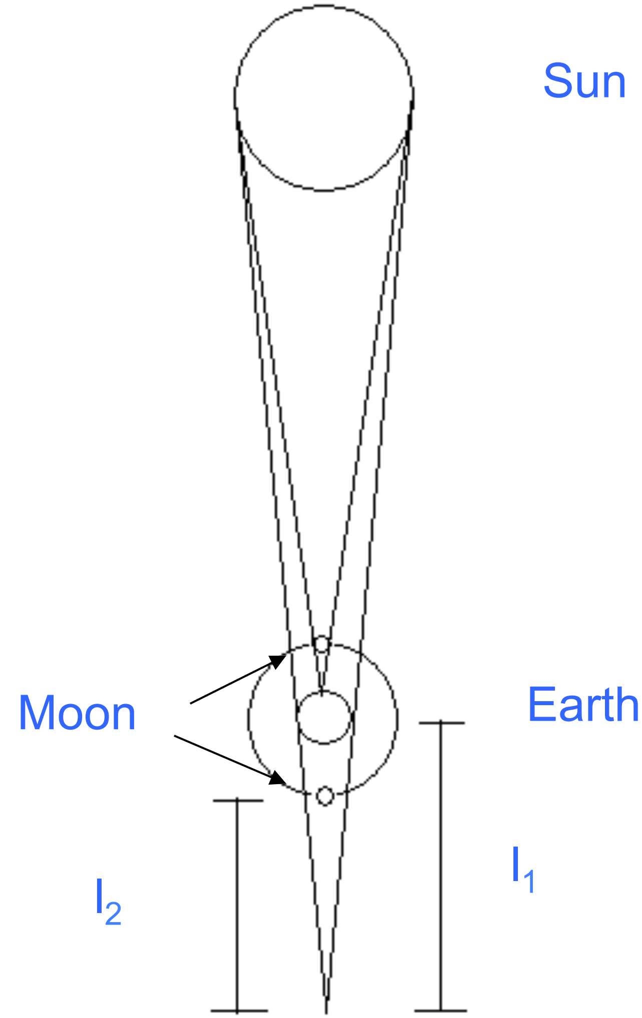
$d_M = 62.3\ R_E$ (actually 60.2)

From (1) and (2) we have:

$8R_E/11_{l2} \sim 8R_M/3l_2$ so:

$R_M \sim 3/11\ R_E$ (size of moon compared to the size of the Earth)

Since we know R_E and θ_M we can determine d_M along with R_M.



Aristarchus (summary)

- Aristarchus concluded:
  - Sun is about 19 further away than the Moon
    (actually about 400 times further away!)
  - Sun is about 7 times bigger than the Earth
    - (actually about 109 times bigger!)
- Although his values are pretty far off the importance is the use of geometry and algebra to astronomy.
- Aristarchus also advocated a heliocentric theory for the Solar System.
  - Aristotle had rejected this since stars don't show parallax.
  - Aristarchus argued that this is simply because the stars are very far away and similar to the Sun.
  - None of his writings survived so his work was mostly forgotten.

Hipparcos

- Improved the accuracy of Aristarchus' methods
- Cataloged the position and apparent brightness of several hundred stars
- Stellar magnitude scale
- Realized that the Earth's axis precesses by comparing his catalog with previous, smaller, catalogs.
  - At the time this was not appreciated or thought to be important.

<u>Magnitudes</u> (m) to denote brightness

- Ancient system created by Hipparchos
  - 1st magnitude = brightest stars in sky
  - 6th magnitude = faintest visible to naked eye
  - Confusing because smaller number implies brighter
    - (Think of first magnitude as "first in class")

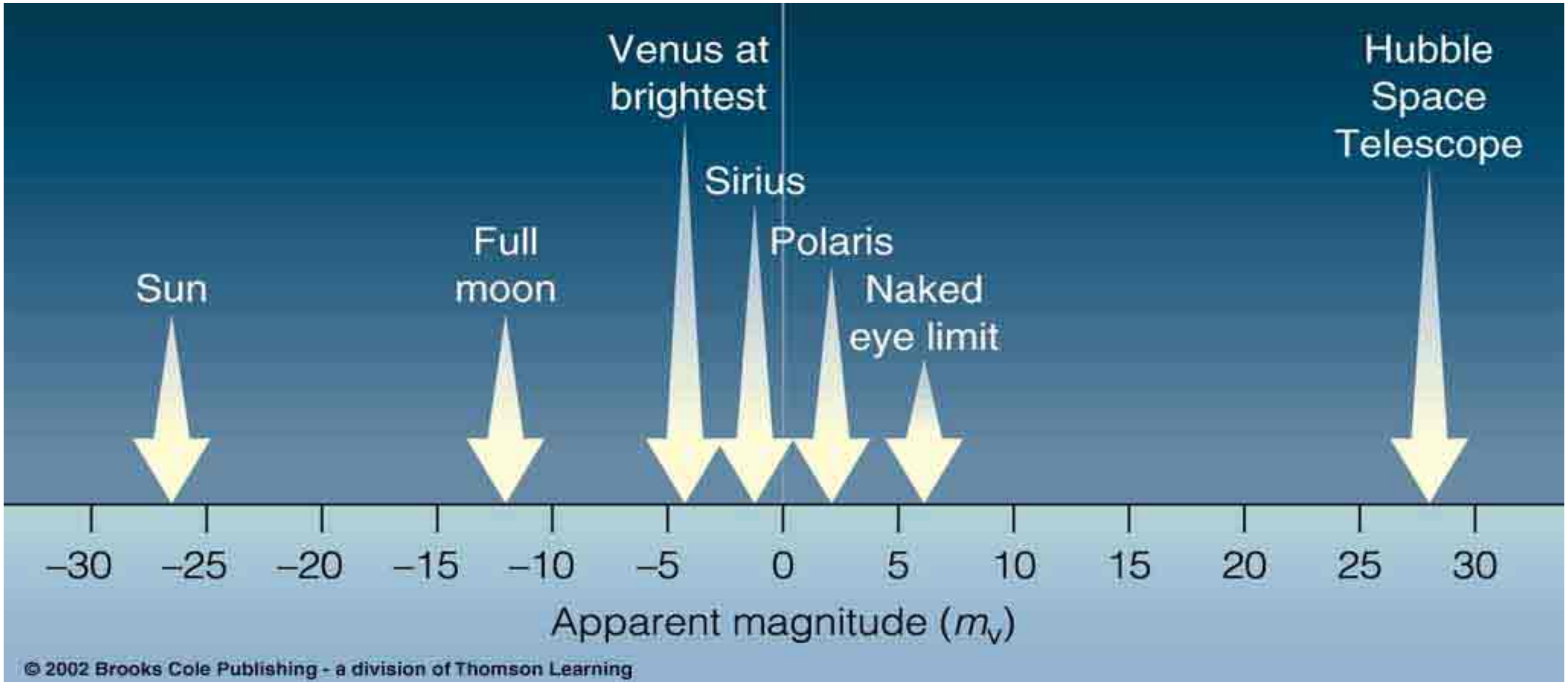
- Astronomers want a numerical measure of *Intensity (I)* which is proportional to energy per unit time received from the star.

- Relationship between *I* and m turns out to be "logarithmic" (result of properties of human eye)

Numerical Relationship between m and *I*

- **Every *increase* in *m* by 1 is a *drop* in brightness by a factor of 2.512**
  - **We receive 2.512 times less power from a 2nd magnitude star than from a 1st magnitude one.**
  - **We receive 2.512 $\times$2.512 = 6.310 times less from a 3rd magnitude than a 1st magnitude**
  - **We receive $(2.512)^5$ times less from a 6th magnitude star than a 1st magnitude. The 5 comes from 6-1.**
  - **Because $(2.512)^5$ = 100 (not by accident) the faintest stars we can see are 100 times fainter than the brightest.**

Apparent Visual Magnitude Scale



- From our Text, Horizons by Seeds

Formula for *Intensity* vs. m:

$$\frac{I_A}{I_B} = (2.512)^{(m_B - m_A)}$$

With mathematics which we won't derive here, you can show this is equivalent to the equation:

$$m_A - m_B = 2.5\log(I_B / I_A)$$

This second equation is easy to use on a calculator.

If you remember that log(10^n) = n, for example log(10^4) = 4, log (10^5) = 5, log(10^6) = 6, you can use it even without a calculator.

Magnitude Difference	Intensity Ratio
0	1
1	2.5
2	6.3
3	16
4	40
5	100
6	250
7	630
8	1,600
9	4,000
10	10,000
...	...
15	1,000,000
...	...
25	10,000,000,000

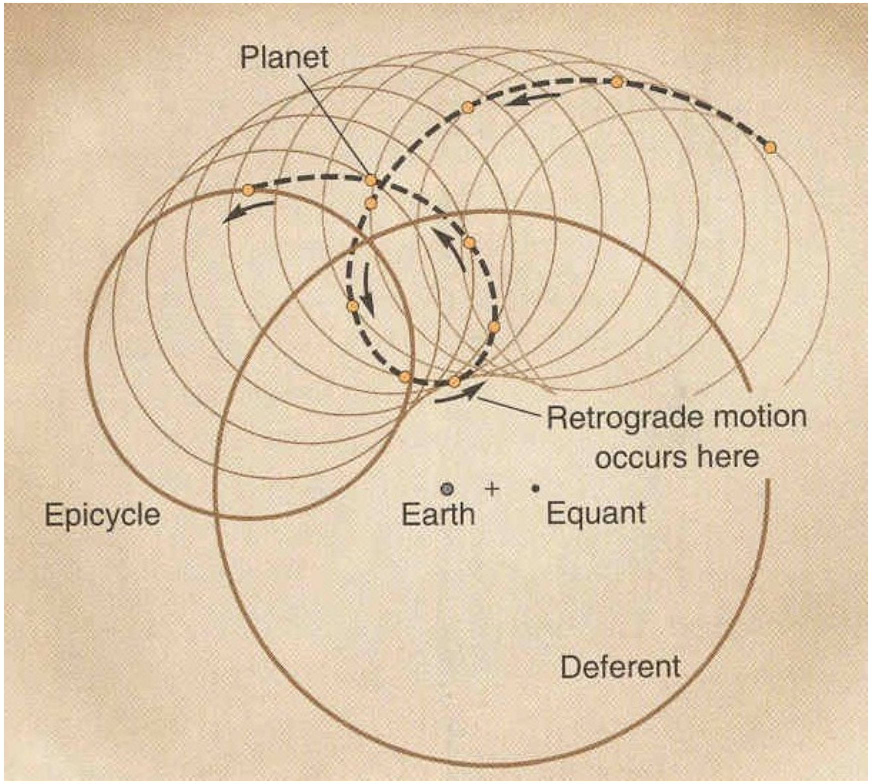
Ptolemy

- Provided the only record of Hipparchos' contributions (until recently)
- Expanded Hipparchos' stellar catalog
- Explained retrograde motion by a complex set of nested circles (epicycles: "wheels within wheels")
  - This system was complex but highly accurate. It was the accepted explanation for over 1000 years!
  - In order to achieve a significant precision hundreds of epicycles were eventually needed. This complexity finally became too much.
- Demonstrated that precession was real and significant

Ptolemy's Evidence for Precession

- Compared the position of Spica with the equinox.
  - Hipparchos noted that the star Spica was once visible at sunset on the autumal equinox.
  - Ptolemy noted that Spica was "now" visible in the sky at sunrise at that date.
  - Equinox was moving slowly along the ecliptic eastward.
  - He calculated the rate that the drift of positions was occurring.
  - Measured a drift of 2° 40' since Hipparchos (265 yrs)
  - The origin was a major mystery in astronomy

Ptolemy's explanation of retrograde motion: Epicycles



From our text: Horizons, by Seeds

- **Uses multiple levels of "circular" motion.**
- **Planet moves on a small circle called en <u>epicycle</u>.**
- **Center of epicycle moves on a larger circle called a <u>deferent</u>.**
- **Earth is fixed near (not exactly at) the center of the deferent.**
- **Motion around deferent is only constant as seen from point called <u>equant</u>.**
- **Add epicycles on epicycles to refine motion.**

Advantage: **Could predict precise positions of planets**

Disadvantage: **No physical explanation of why motion is like this**

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

Reading this Week

By Next Thursday:

Review Math, Appendix 9 (pg. A-20 - A-31)

- Review Celestial Sphere, Appendix 10 (pg. A-32 – A-36)
- http://en.wikipedia.org/wiki/Celestial_sphere
- History of Astronomy:
- http://en.wikipedia.org/wiki/History_of_astronomy

By Next Tuesday:

- Chapter 1 Celestial Mechanics

At the end of each chapter study the *Key Equations & Concepts.*