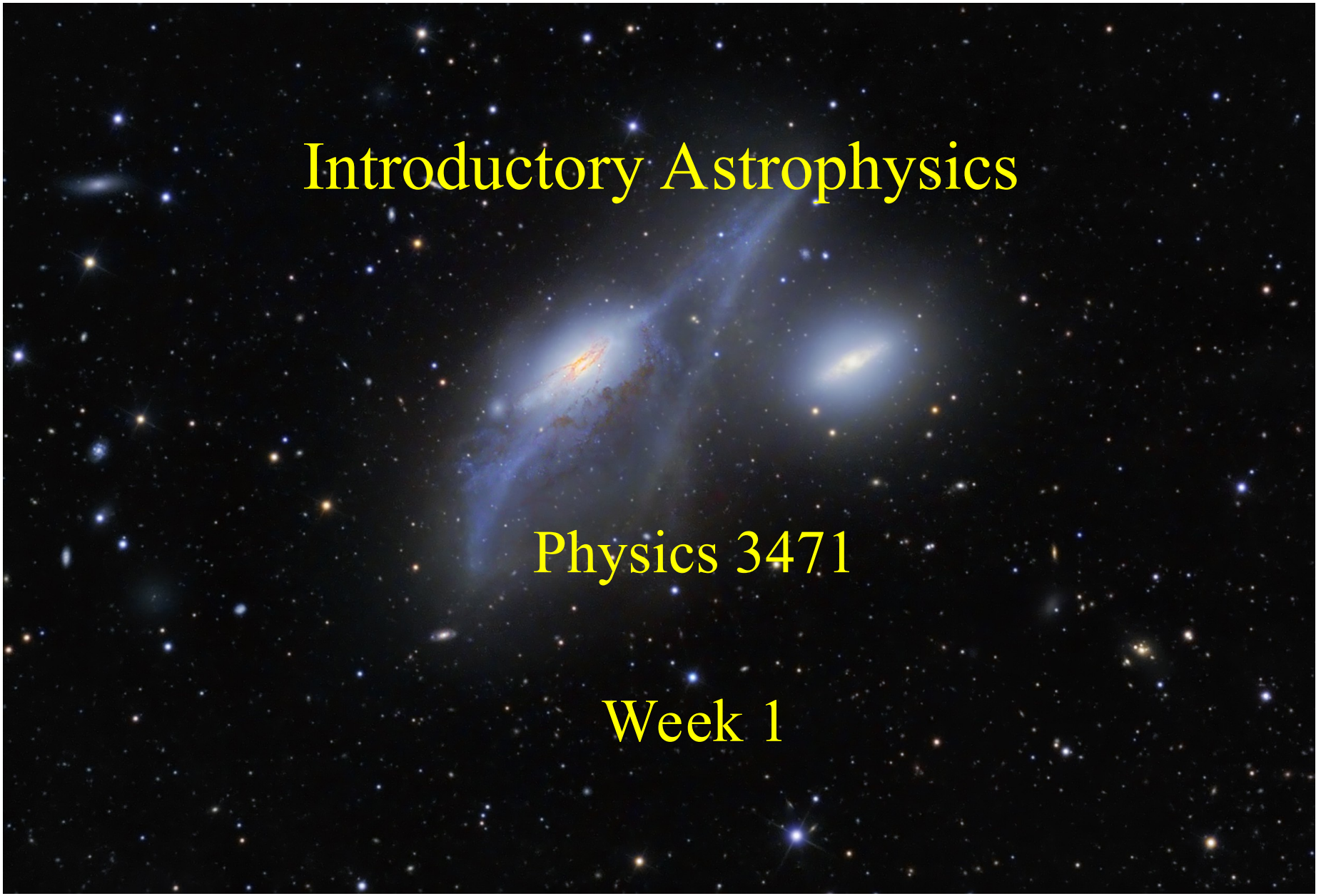

Introductory Astrophysics
Physics 3471
Week 1

Outline

- The sky – predictable, yet mysterious
  - Periodicities, Naked eye universe
  - Greek knowledge/models, Ptolemaic system
- Planetary Configurations.
- Copernican Revolution
- Coordinate systems
- Telescope basics

Chapter One "The Celestial Sphere"

1.1 The Greek Tradition

1.2 The Copernican Revolution

1.3 Positions on the Celestial Sphere

1.4 Physics and Astronomy

6.2 Optical Telescopes

Astronomy is mysterious

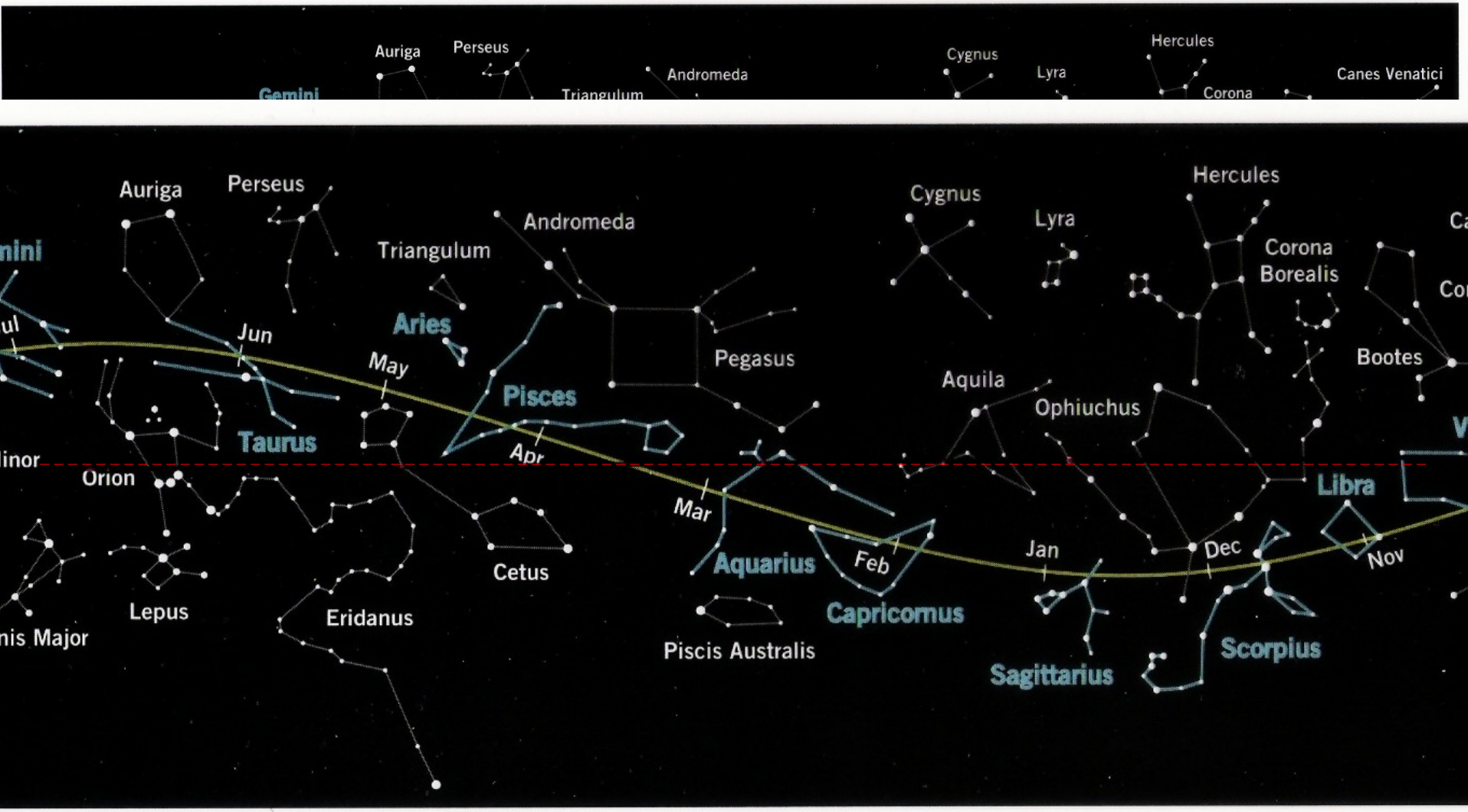
- The *nature* of the Sun, Moon, stars, and planets were completely unknown to ancients.
- Can't touch, smell, hear, or taste them, only see.
- Usually limited to one perspective.
- Our lifetime << astronomical timescales
- Occasional unexpected events:
  - Comets
  - Novae, supernovae
  - Eclipses
- Coincidences ---> astrology

Periodicities in Astronomy

- 24 hours between 2 transits of the Sun (solar day)
- 23 h 56 m between 2 transits of a star (sidereal day)
- 365.2564 d for Sun to circle celestial sphere (sid. yr)
- 365.2422 d for Sun to return to vernal equinox (trop. yr)
- " " " for Sun to oscillate about celestial equator
- 29.5 days for Moon to go through phases
- Planets have repeatable periods between configurations
- Many, many more !

Annual “oscillation” of Sun

Ecliptic = The apparent path of the Sun on the sky as seen from Earth.



The naked-eye universe

- The Sun
- The Moon (and its phases)
  Eclipses
- 5 Planets (plus the Earth)
  - Mercury, Venus, Mars, Jupiter, Saturn
- 6500 Stars (contained within 88 constellations)
- 3 galaxies
- Occasional novae and supernovae
- comets
- Aurora, meteors, and other atmospheric phenomena

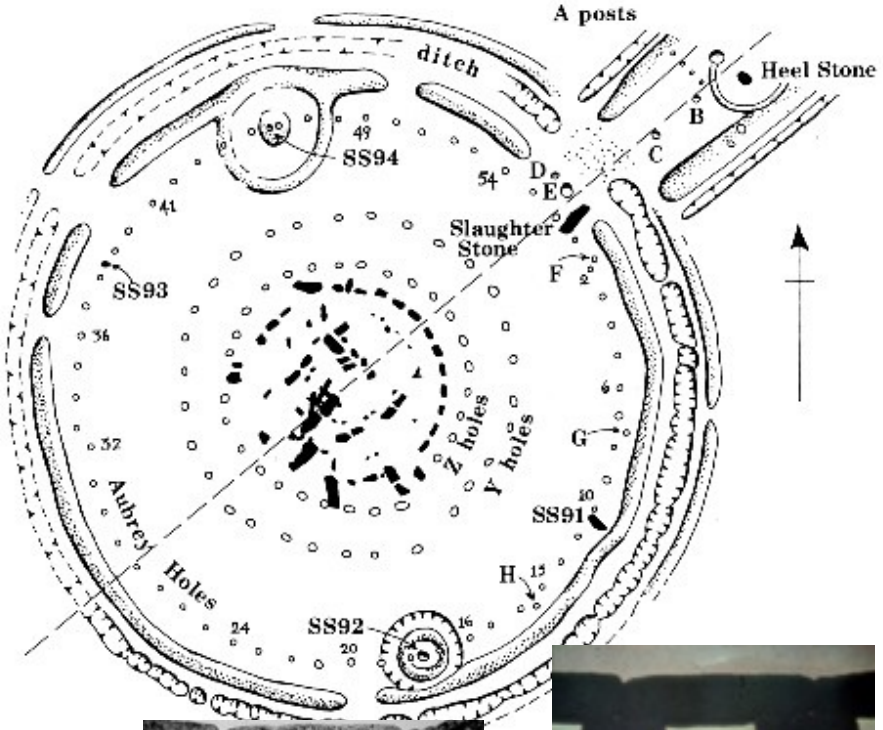
What did the Ancients know?

- Poorly documented/understood cultures
  - People of stonehenge
  - Plains Indians, Anasazi
  - Mayans
  - ►These left behind calendar-like constructions.
- Well documented cultures
  - Chinese
  - Mesopotamian (Babylonians, etc), Egyptian
  - Islam
  - Greek (more to come)
  - Records of Seasons, lunar cycles, eclipses, comets, novae, star maps, models
- Unknown nature ►superstition► astrology
- Sun provides life
  - Understand seasons for farming
  - Luminaries are deities? - religion

Stonehenge

Check out: http://arthistoryresources.net/stonehenge/stonehenge.html

- 2950 BC – 1600 BC (3 phases)
- 56 Aubrey holes = 2xlunar periods = 3 lunar node precession cycles (18.6 yrs)



- Heel stone marks sunrise on Summer Solstice
- 30 Y holes and Z holes ~ synodic month

(a)

(b)

(c)

Knowledge of the Ancient Greeks

- Ideas and philosophies were rich and varied, some bad for science:
  - Plato: truth through pure thought over observations
  - Aristotle (and almost everybody): Earth is unmoving, heavens are perfect
  - The Geocentric universe model (Ptolemy AD 140)
- Many ideas still accepted today:

1) Earth, Moon and planets are spherical (Pythagoras c 570-497 BC)
2) Phases of Moon due to shadows cast by Sun (Aristotle c 384-322 BC)
3) Eclipses caused by Earth-Moon-Sun alignments (Aristotle)
4) A moving Earth *should* cause parallax effects (Aristotle) *
5) Earth revolves around the Sun (Aristarchus 310-230 BC) *
6) Distance ratios between Earth, Moon, and Sun (Aristarchus)
7) Measured size of Earth (Eratosthenes c 276-195 BC)
8) Earth's spin axis precesses with 26,000 yr period (Hipparchus 160-127 BC)
9) Approximate sizes and distances of Earth, Moon and Sun (Hipparchus)
10) Retrograde motion of planets can be modelled with epicycles and deferents *

Knowledge of the Ancient Greeks

(1) How did they know the Earth is a sphere?

a) shadow of Earth during lunar eclipses

b) masts of ships disappear last as sail away

c) new constellations appear when travelling S

d) flat horizon is consistent with being close to a large sphere

Why do WE know its a spinning sphere?

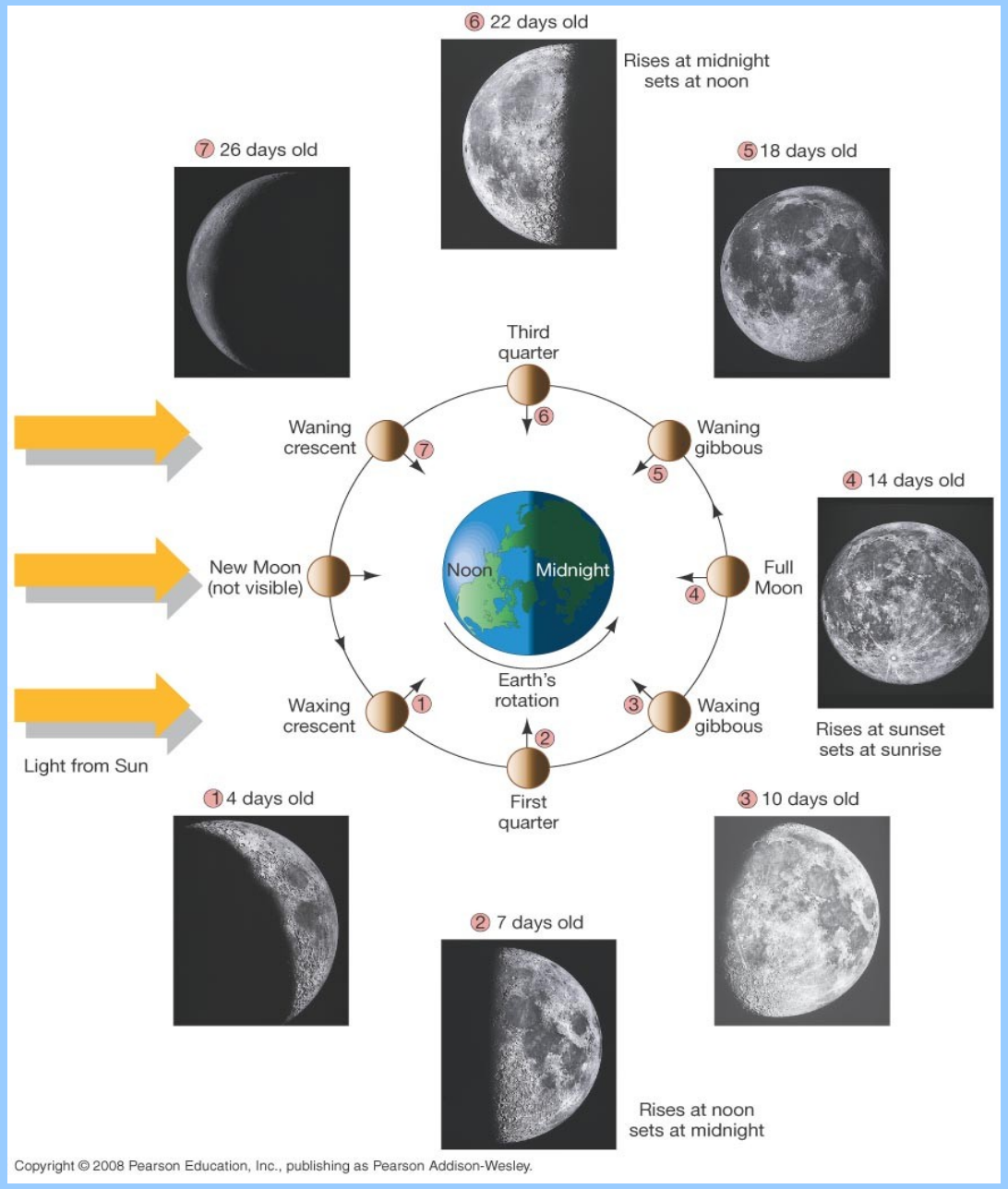
a) space/satellite photography

b) consistent with shapes of other massive worlds

c) foucault pendulum

Knowledge of the Ancient Greeks

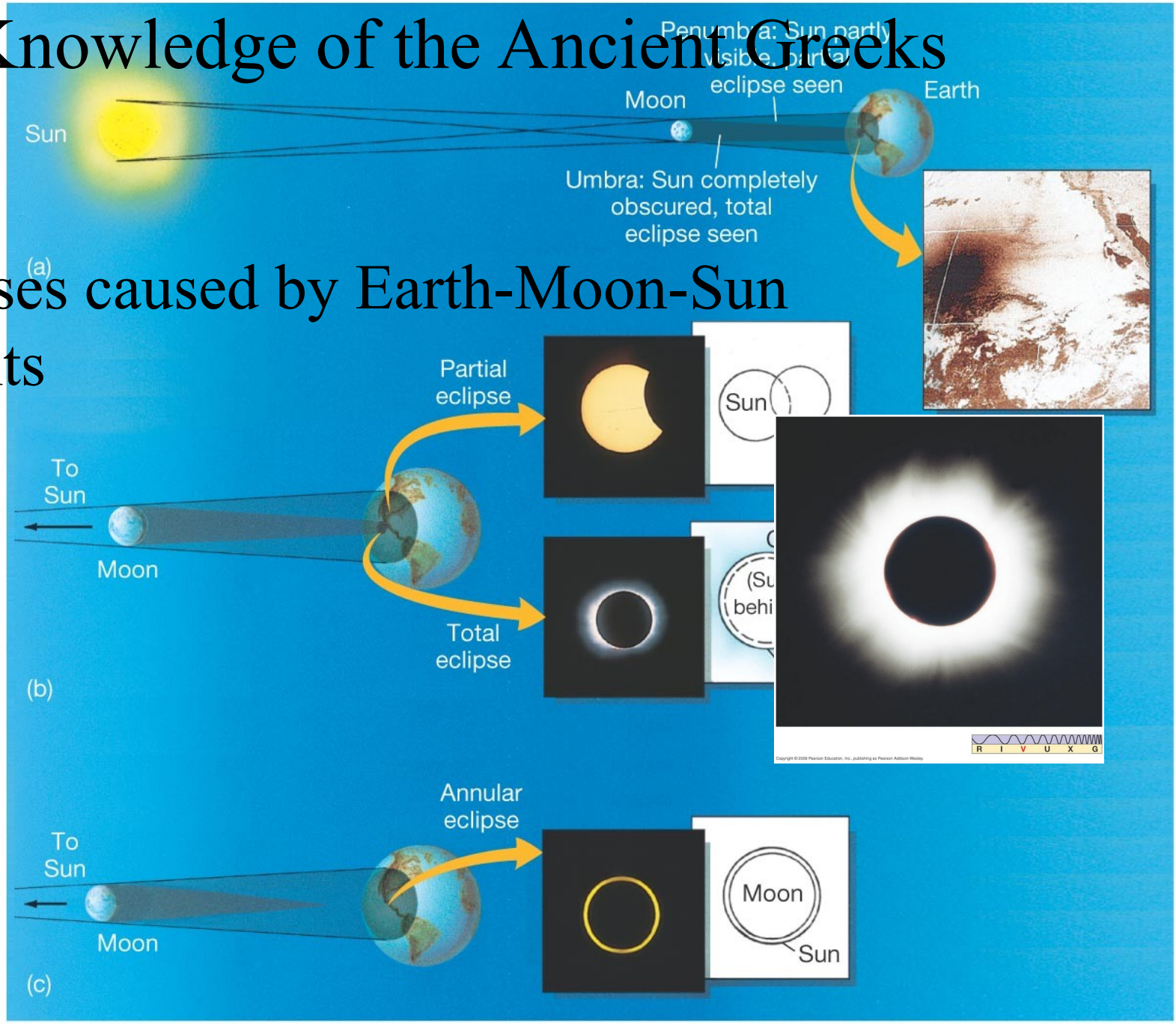
(2) What causes the phases of the Moon?



Knowledge of the Ancient Greeks

(3) Eclipses caused by Earth-Moon-Sun alignments

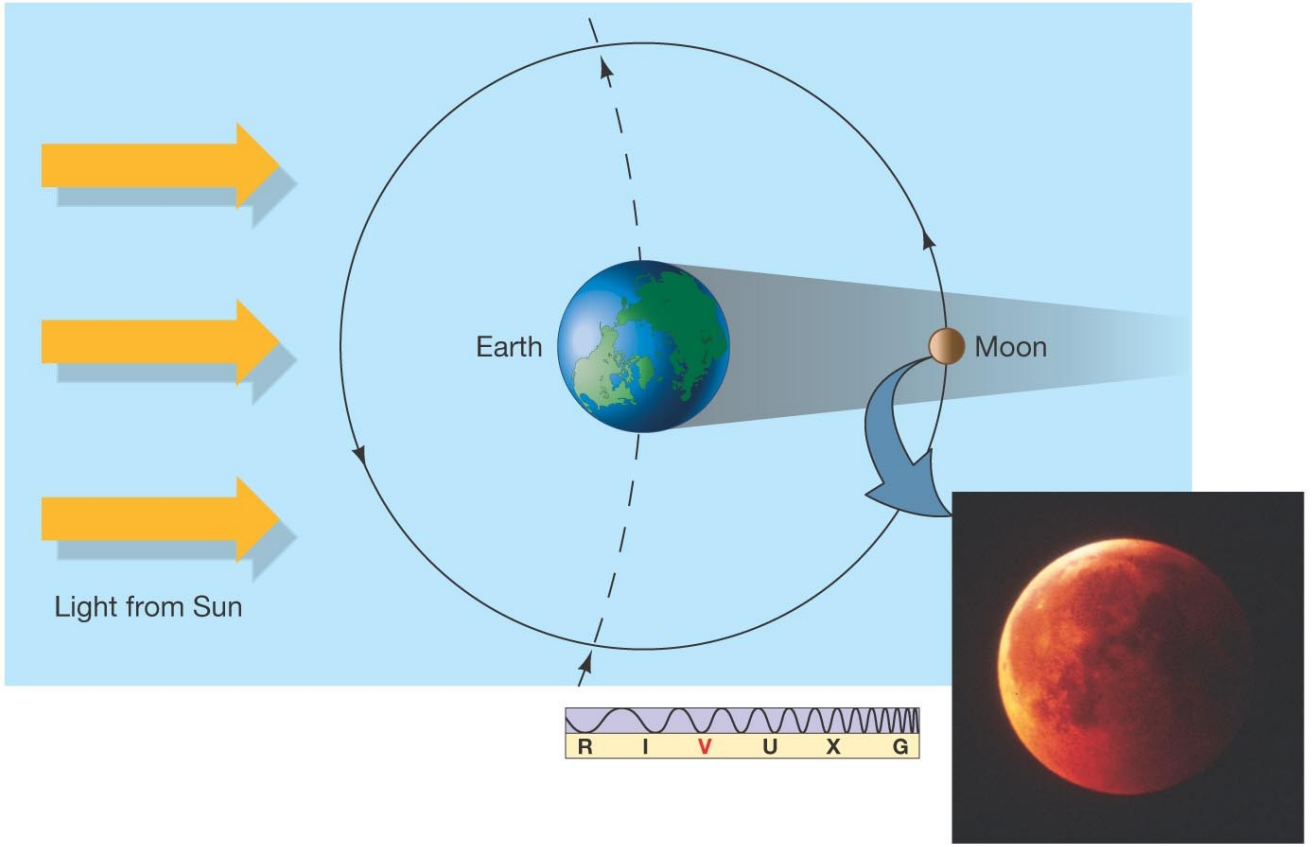
Solar Eclipses



Knowledge of the Ancient Greeks

(3) Eclipses caused by Earth-Moon-Sun alignments

Lunar Eclipses



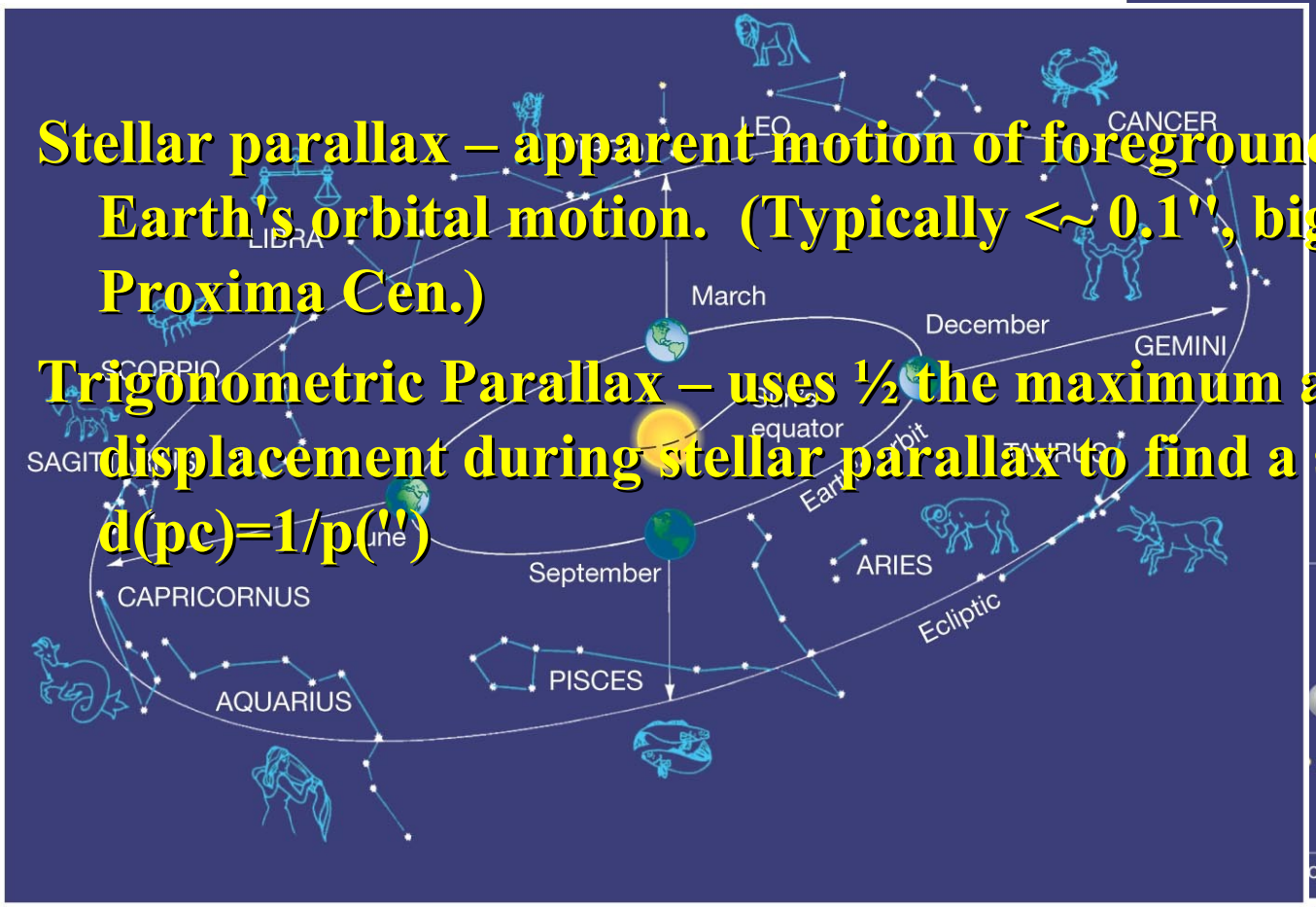
Knowledge of the Ancient Greeks (cont.)

(4) If Earth is moving, parallax effects should occur.

Parallax = the apparent motion or shifting of an object caused by the motion or shifting of the observer.

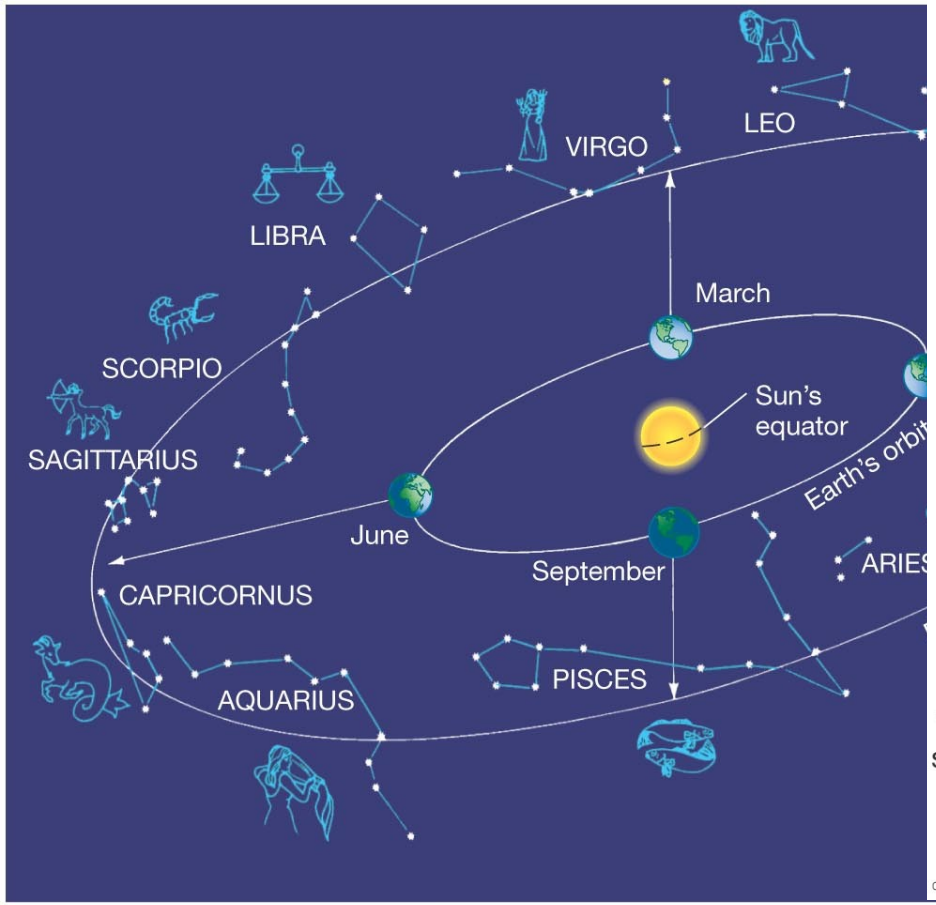
Stellar parallax – apparent motion of foreground stars due to Earth's orbital motion. (Typically <~ 0.1", biggest ~1.0" Proxima Cen.)

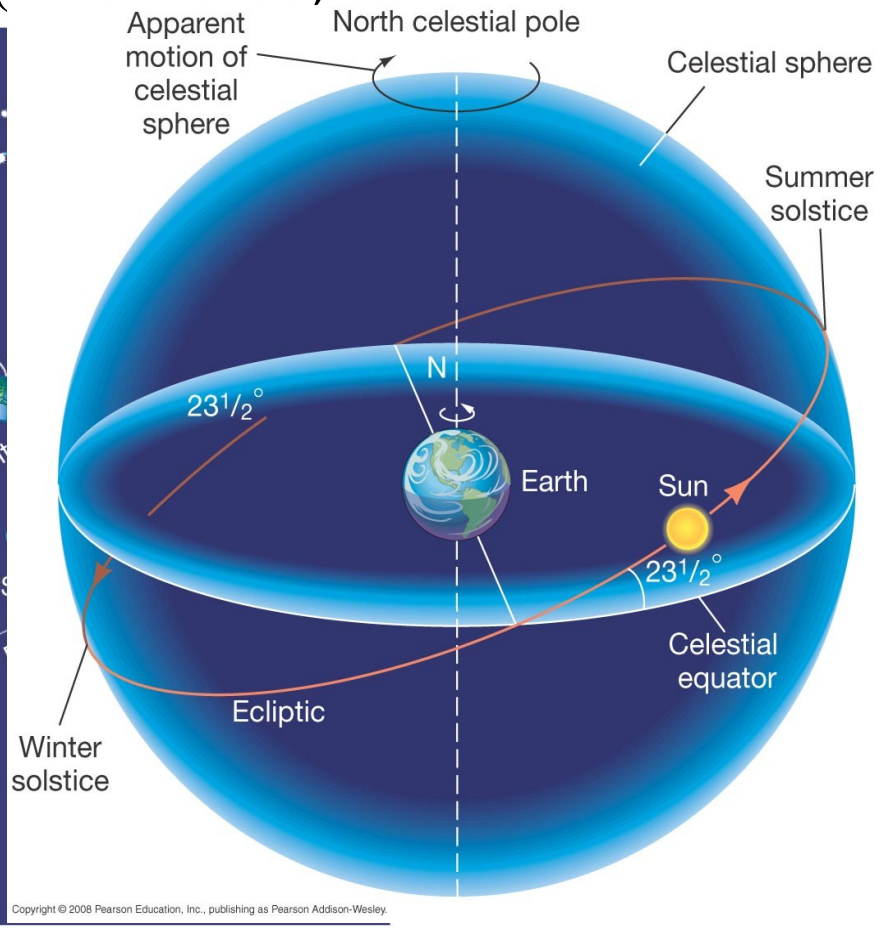
Trigonometric Parallax – uses ½ the maximum angular displacement during stellar parallax to find a stars distance. d(pc)=1/p(")



Knowledge of the Ancient Greeks (cont.)

(5) Earth revolves around the Sun (Aristarchus).





A geocentric model can also produce changing midnight constellations and seasons. More info about planets was needed to distinguish the two models...

Knowledge of the Ancient Greeks

(7) Measured size of the Earth

Eratosthenes' measures radius = 6460 km in 200 B.C.

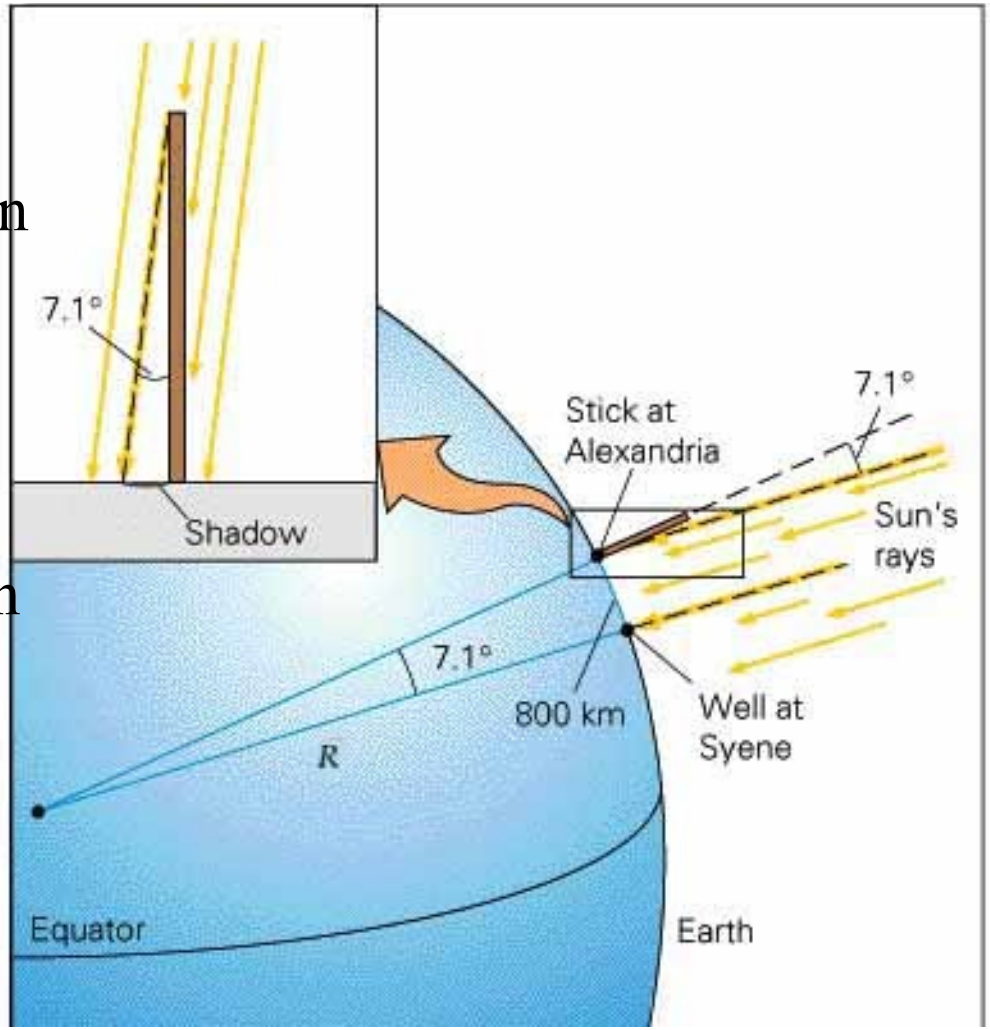
- Modern value is 6378 km

Derivation requires assumption of a spherical shape:

S = distance between Syene and Alexandria,
C = circumference of the Earth

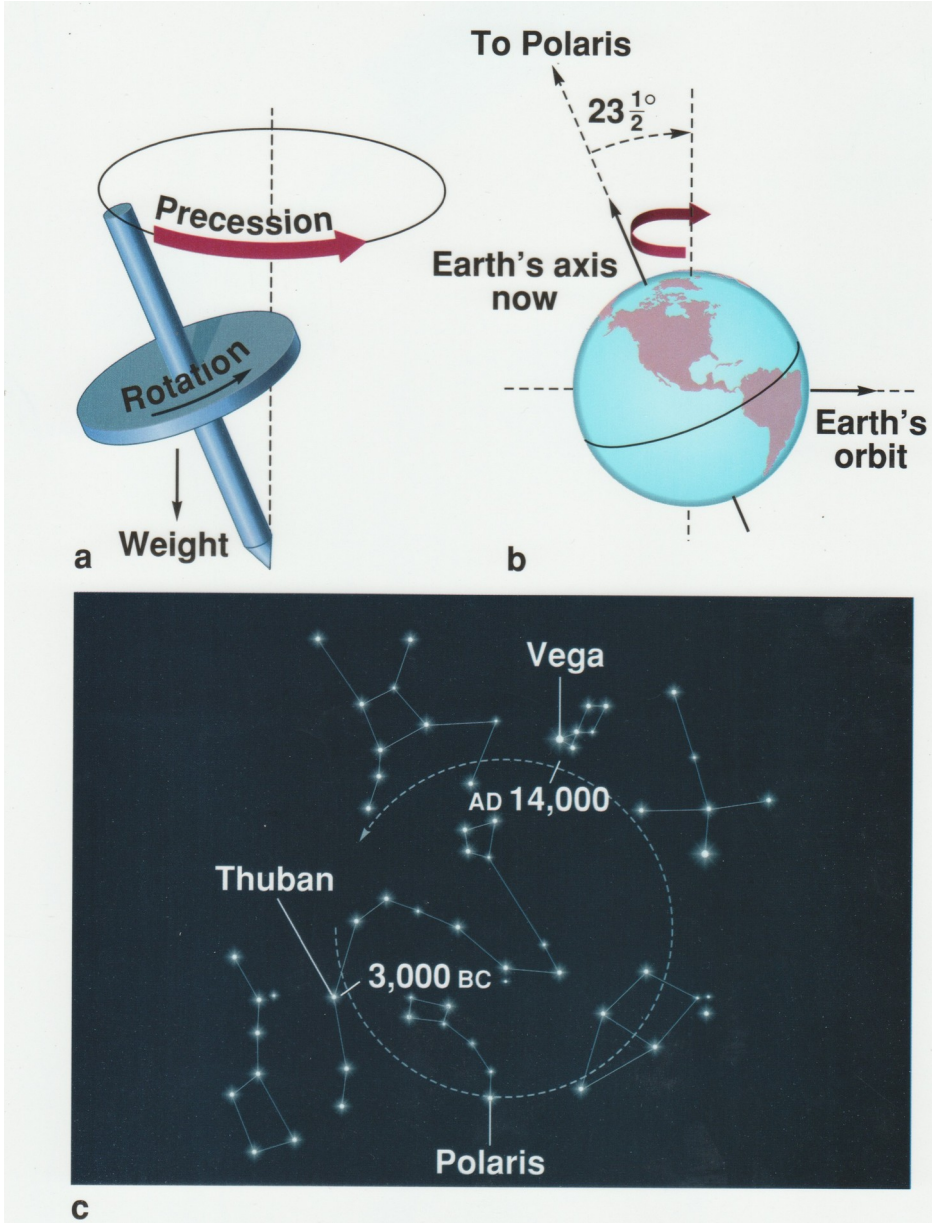
Then

S/C = 7.1/360
C = S (360/7.1)



Knowledge of the Ancient Greeks (cont.)

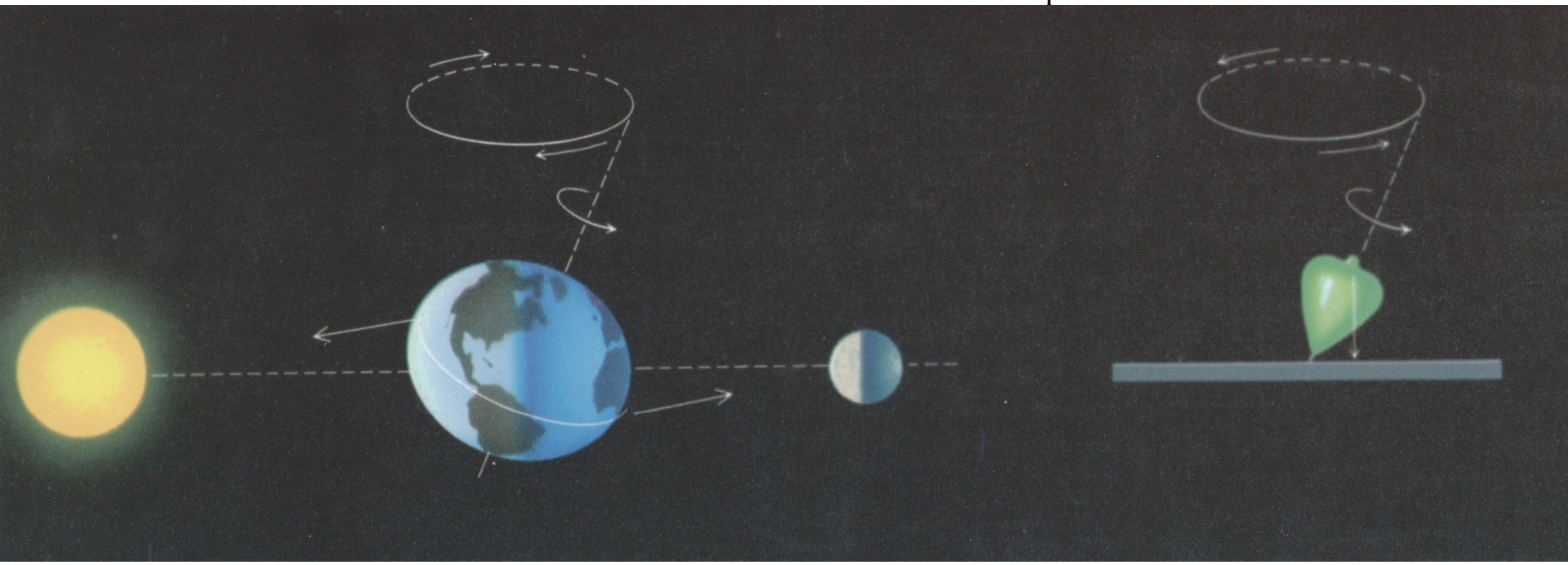
8) Earth's spin axis precesses with 26,000 yr period (Hipparchus 160-127 BC)



Knowledge of the Ancient Greeks (cont.)

8) Precession (continued)

Cause: the pull of the Moon and Sun on Earth's equatorial bulge exerts a Torque, τ. (Precession freq: $\omega_p = \tau/L$)



Left: gravity from S and M are trying to tip the spin axis UPRIGHT. Pole precesses CW seen from above.

Right: gravity is trying to tip the spin axis OVER. Pole precesses CCW seen from above.

Knowledge of the Ancient Greeks (cont.)

Precession of the Equinoxes (cont.)

Consequences

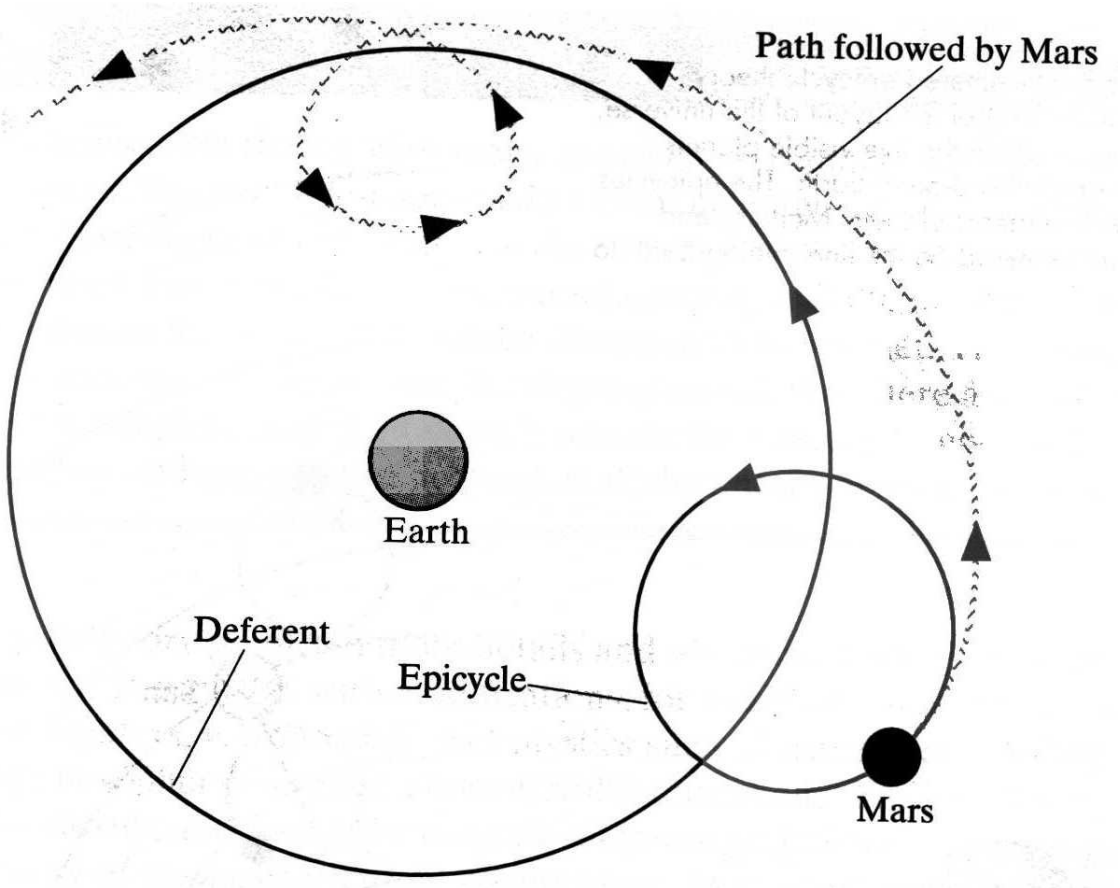
1) The NCP is changing position rel to stars

2) The equatorial coordinates (RA and DEC) of stars slowly change with time. → We need to specify "Epoch" of coordinates.

Knowledge of the Ancient Greeks (cont.)

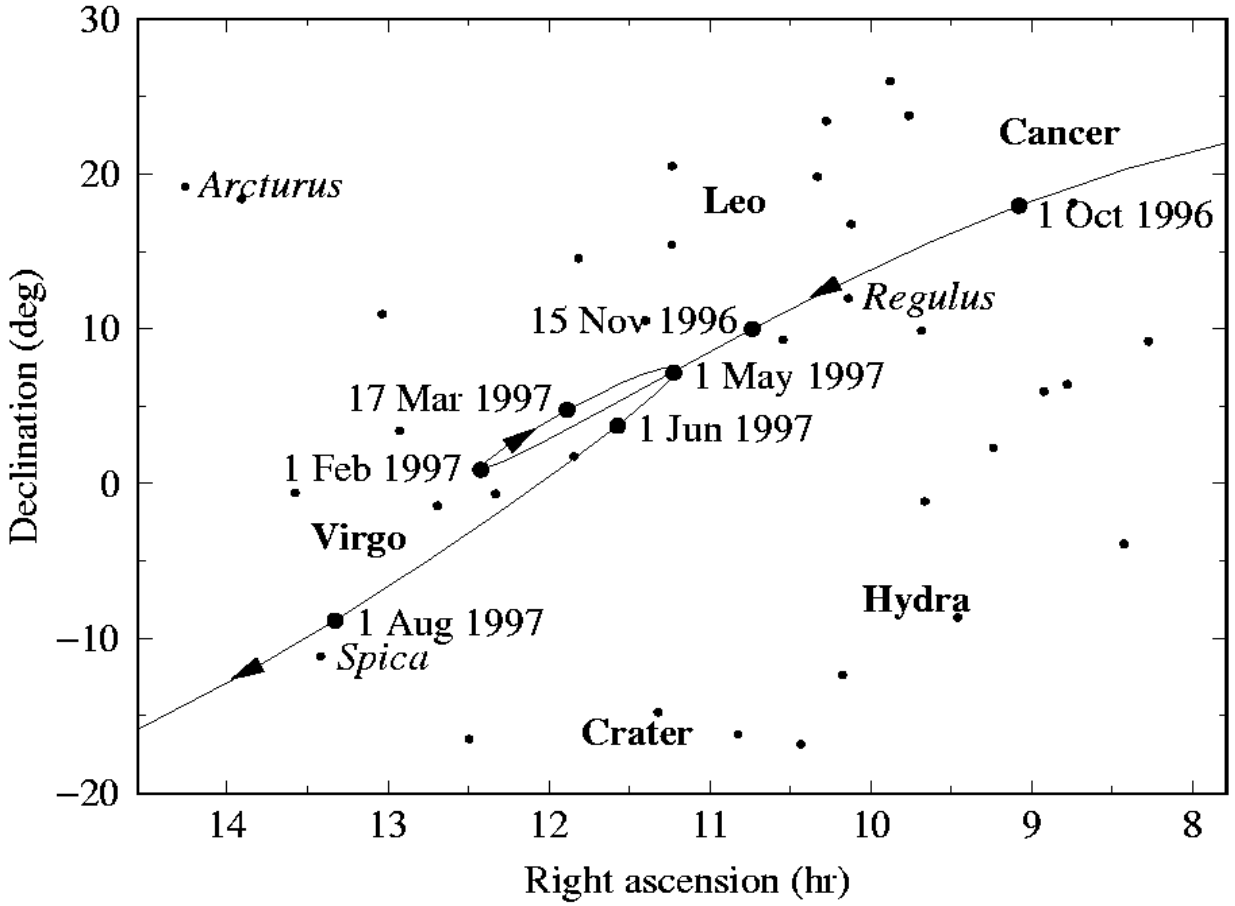
10) Retrograde motion of planets can be modelled with epicycles and deferents (Hipparchus)

- Desired uniform motion on circles, philosophically.



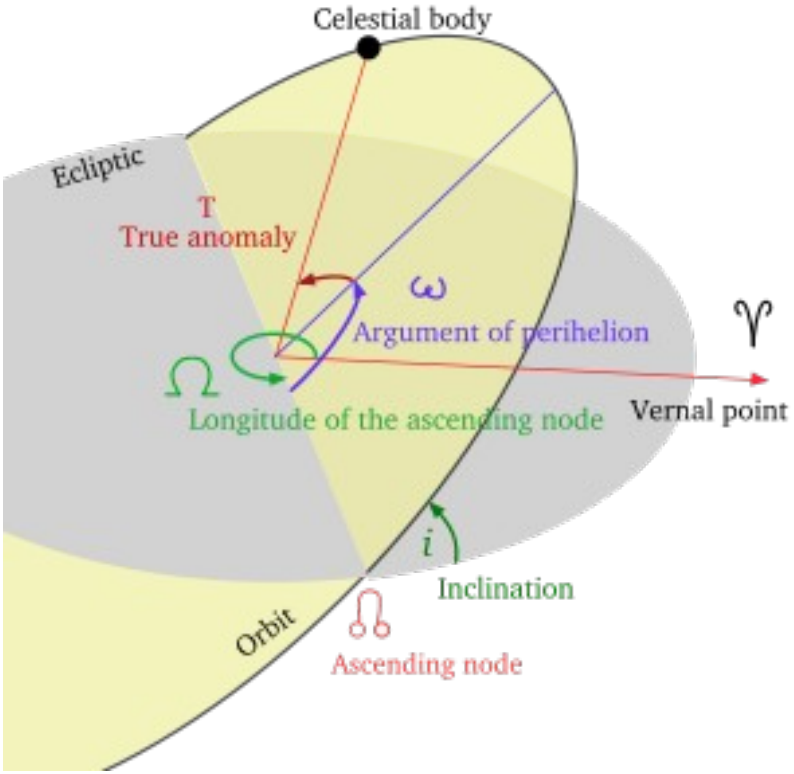
Retrograde Motion

- Planets change speed and brightness
- Example: Mars. Opposition of May, 1997 is shown.
- Closest opposition: Aug. 27, 2003. Recent: July 27, 2018.



The Appearance of the Planets

- Rise and set roughly with stars
- Change brightness, position and angular speed across sky.
- All orbit CCW as seen from "North".
- Usually eastward motion, occasional westward, *retrograde* motion
- Modern view
  - Kepler's 3 laws of elliptical orbits
  - It takes 6 numbers to specify an orbit
    - Inclination *i*
    - Longitude of ascending node, Ω
    - Argument of periapsis, ω
    - Eccentricity (or minor axis), ε (or b)
    - Major axis, *a*
    - Mean anomaly at epoch, Mo

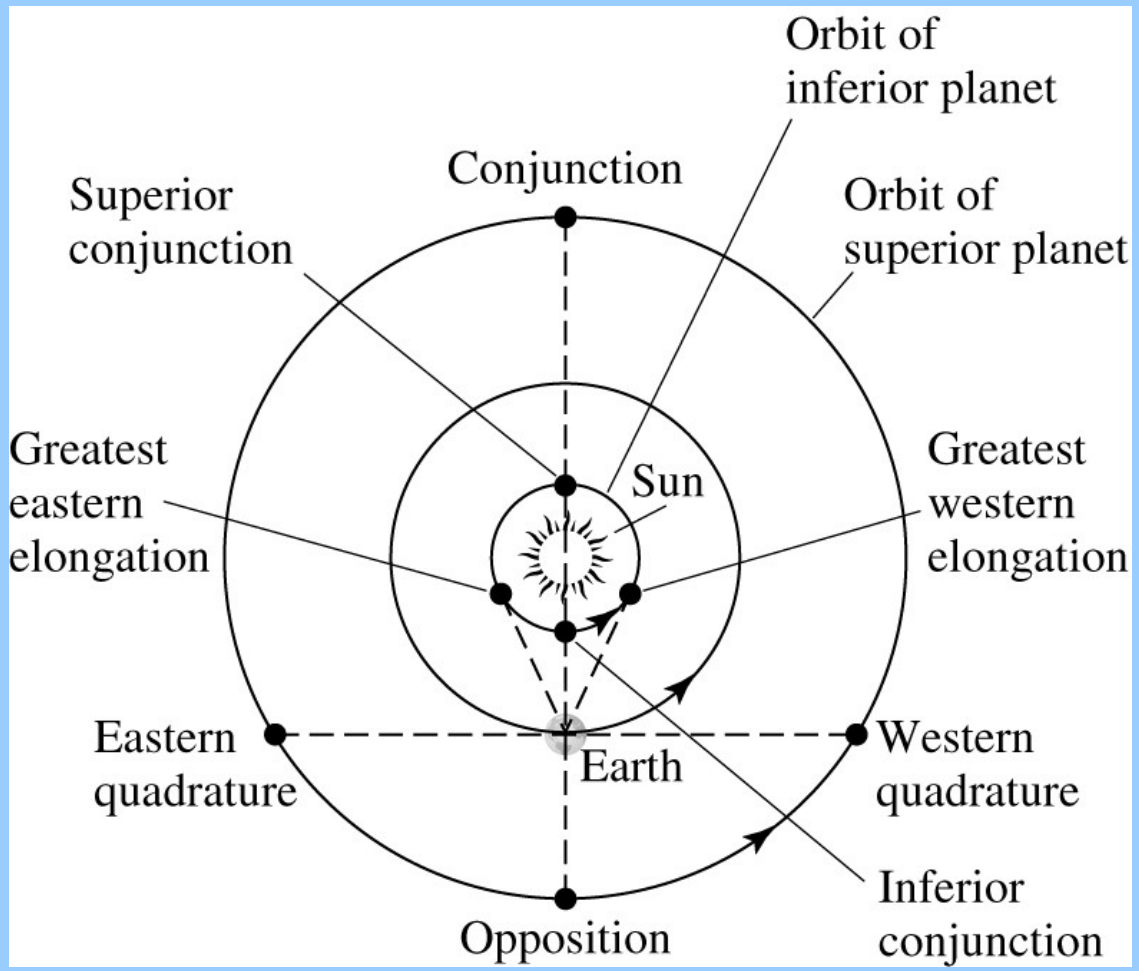


Planetary Configurations

- Inferior planets
  - Inferior conjunction
    - In front of the sun
  - Greatest elongations (morning and evening stars)
- Superior planets
  - Opposition

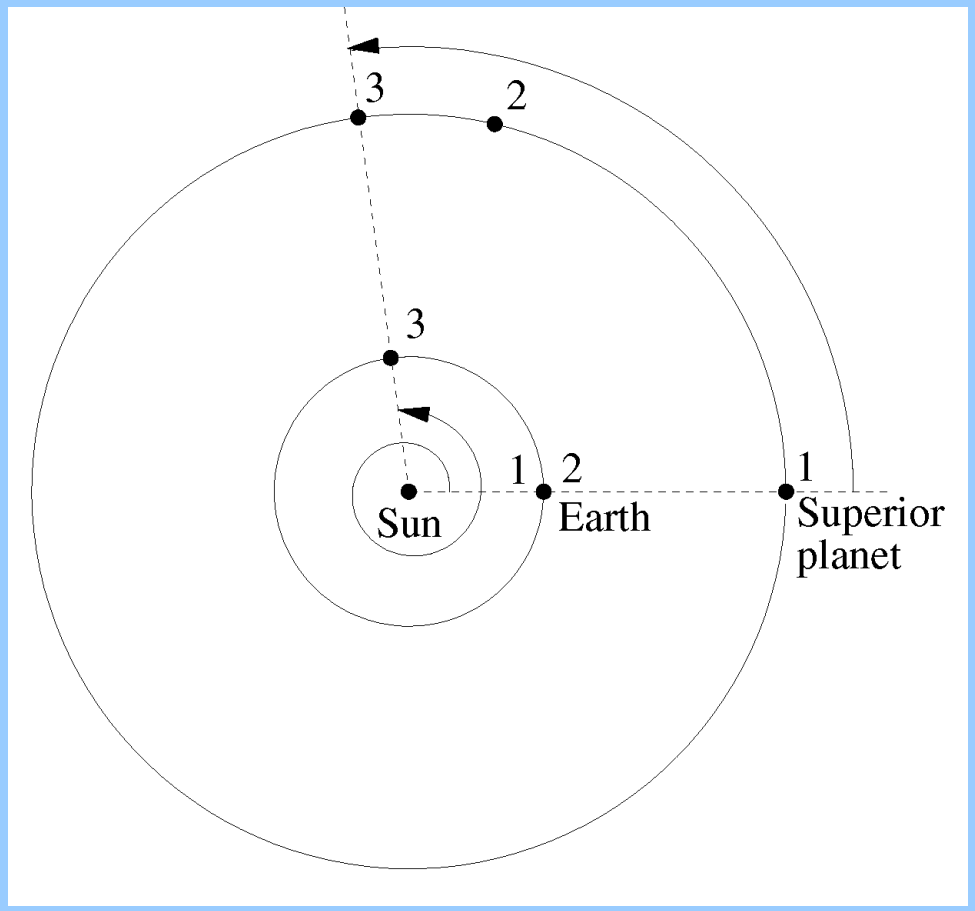
  180 deg away from Sun
  - Quadrature

  90 deg away from Sun
  - (Use for Prob. 1.2)



Synodic and Sidereal Periods

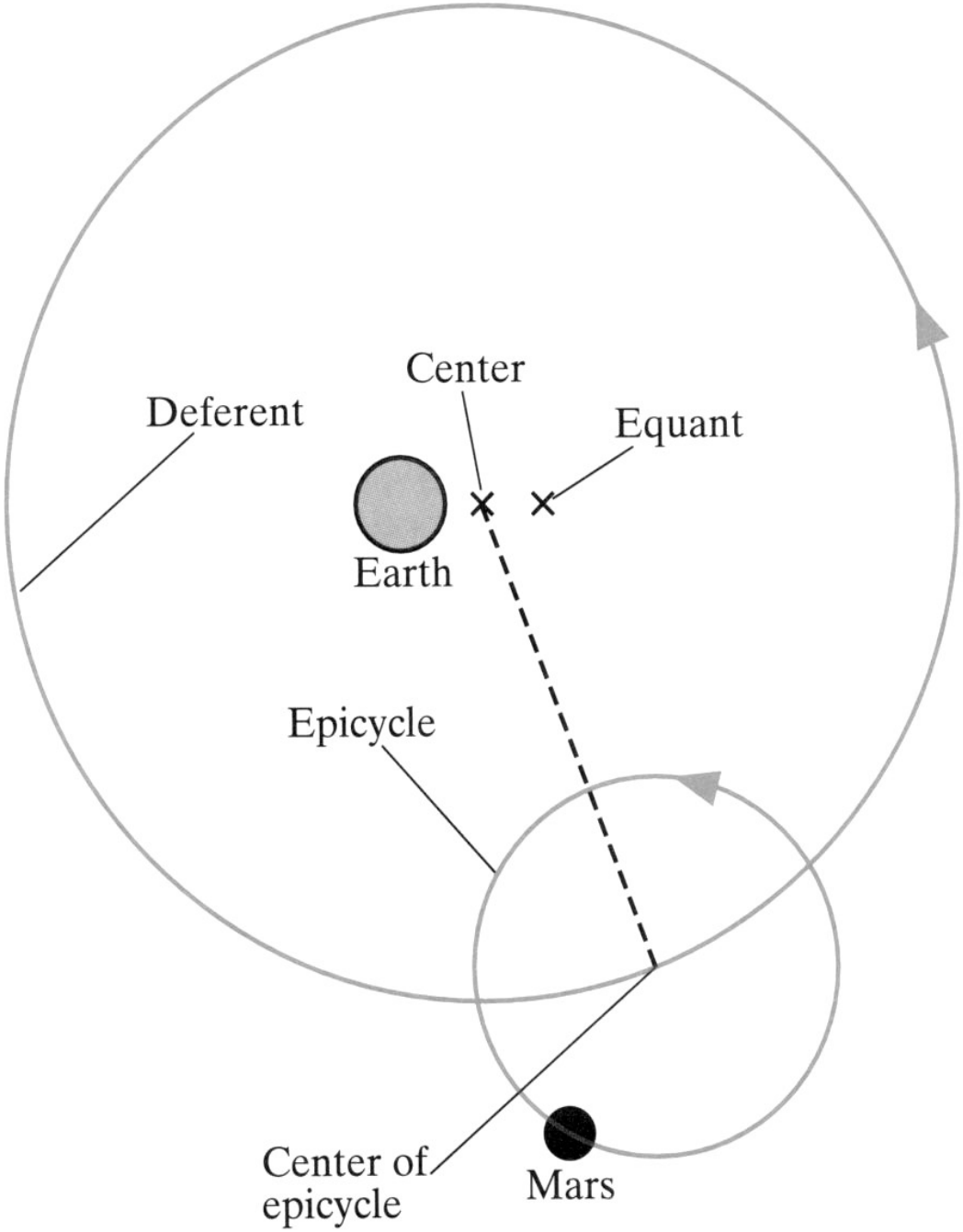
- Synodic period, S
  - time interval between successive conjunctions or oppositions, 1→ 3
- Sidereal period, P
  - Time interval for one complete orbit relative to background stars, 1→2



Relate to Mechanics terms (on board).

Ptolemy's Model -

- Eccentric - displaces Earth from center
- Equant – center of epicycle has uniform angular speed when viewed from this point
- Period of superior planet around epicycle is sidereal period of Earth.
- Period of epicycle center around deferent center is sidereal period for a superior planet, or the Earth's sidereal period for an inferior planet.
- 80+ epicycles, Equants, …
- It works pretty well!

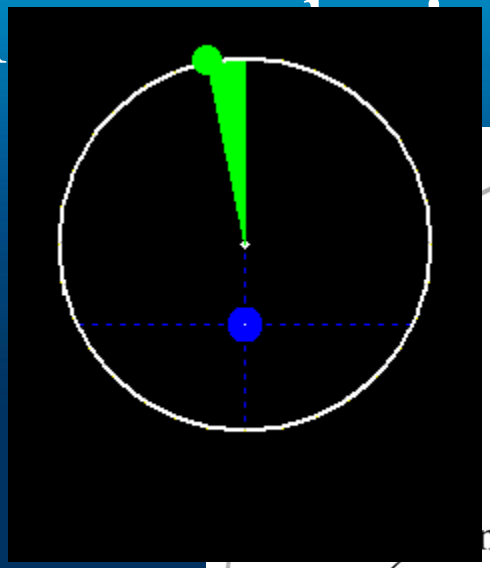


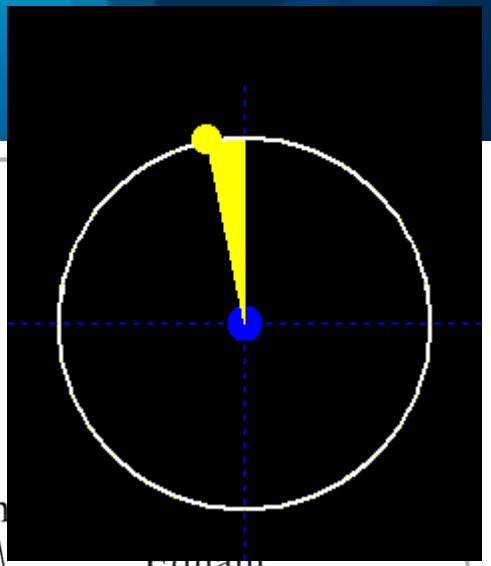
Ptolemy's Model

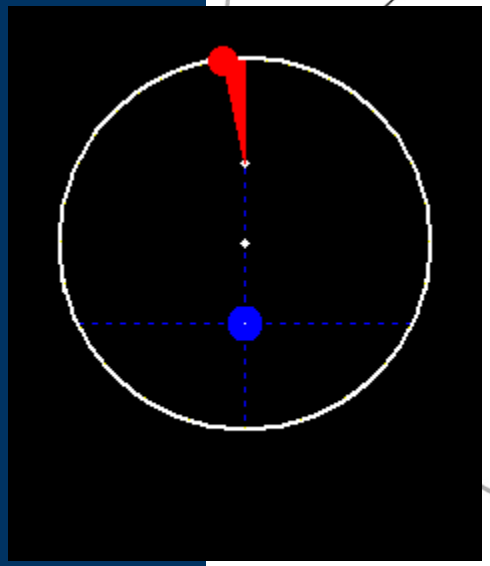
- Eccentric - displaces Earth from center
- Equant – center of epicycle has uniform angular speed when viewed from this point

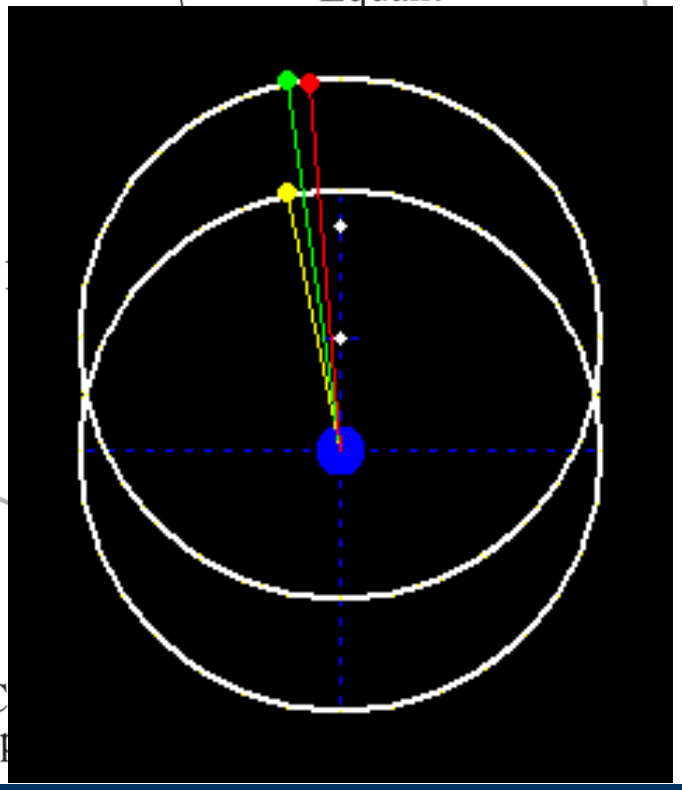
- 80+ epicycles
- It works pretty well!

- But pretty complex and contrived





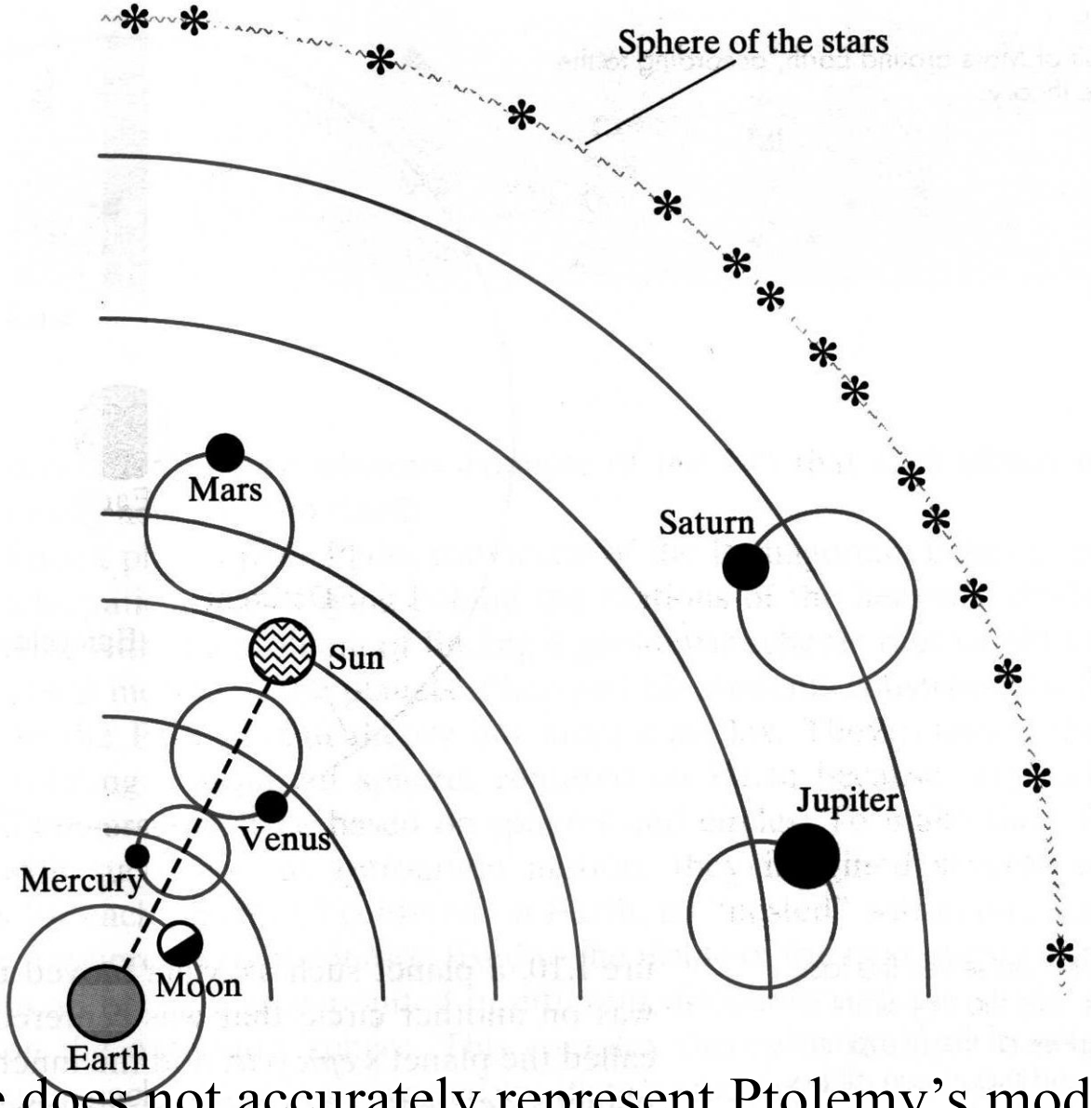




Ptolemy's Model

- Explains retrograde and brightness
- Speed is still a problem

FIGURE 1.12
The ancient astronomer Ptolemy, A.D. 85–165. Using epicycles and many other theoretical devices, he prefected the Earth-centered theory of the layout of the universe.



This figure does not accurately represent Ptolemy's model!

The Copernican Revolution ... *matching!*

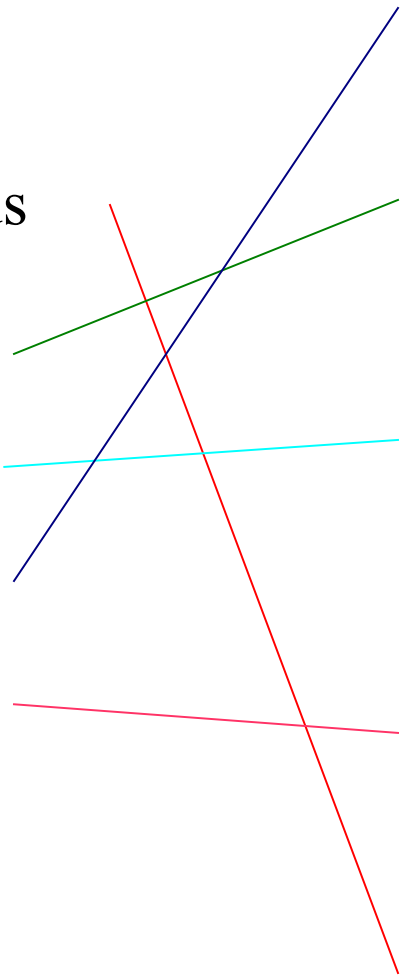
Nicolaus Copernicus

Tycho Brahe

Johannes Kepler

Galileo

Newton



Observed gibbous phase of Venus

Made precision measurements of planets

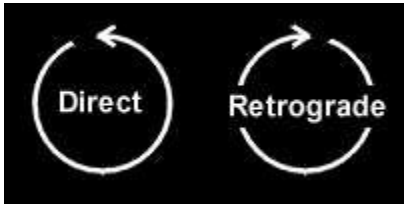
Used ellipses to model solar system

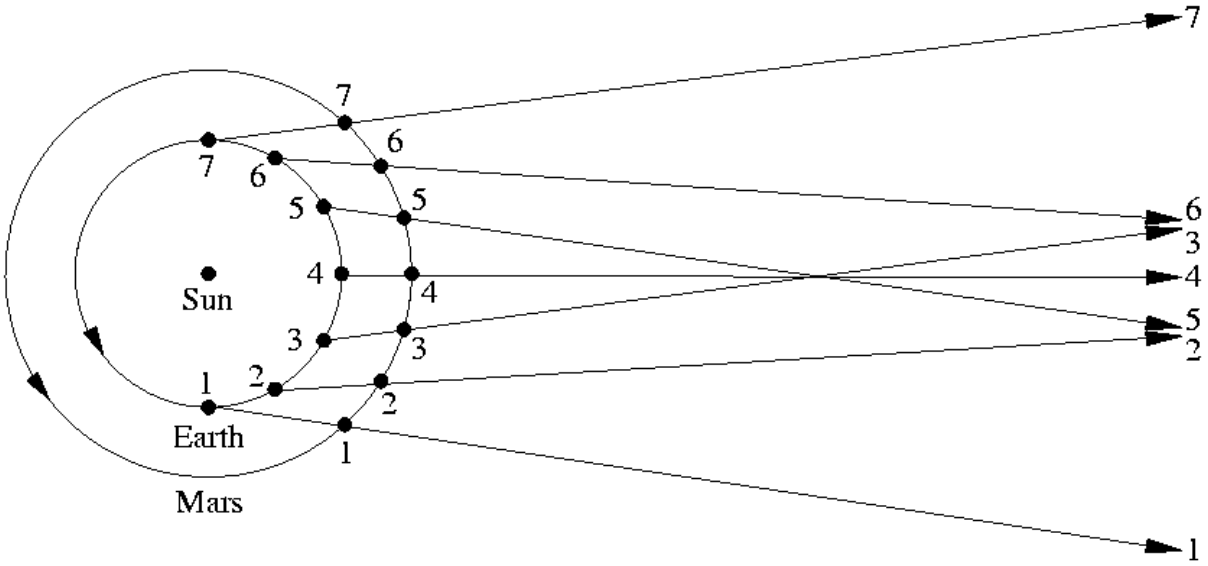
Said gravity accelerates the planets

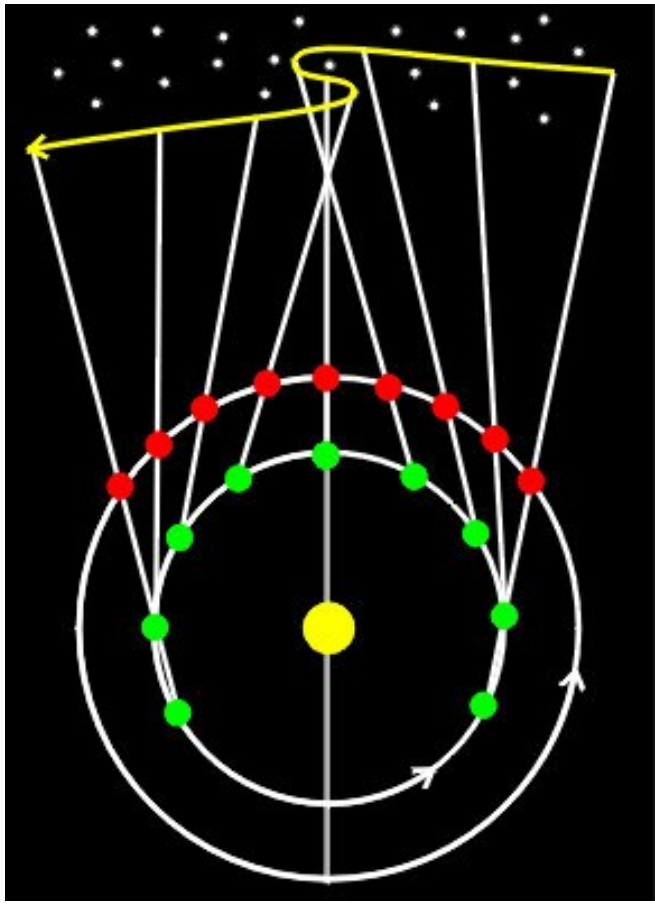
Revived the <u>heliocentric</u> model

Heliocentric Model and Retrograde Motion

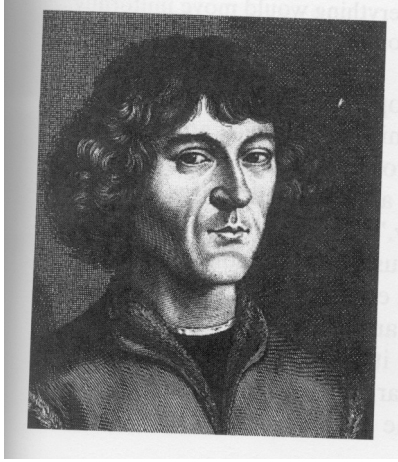
- Different orbital speeds
  - More distant planets have lower speeds
  - Slightly different orbital planes





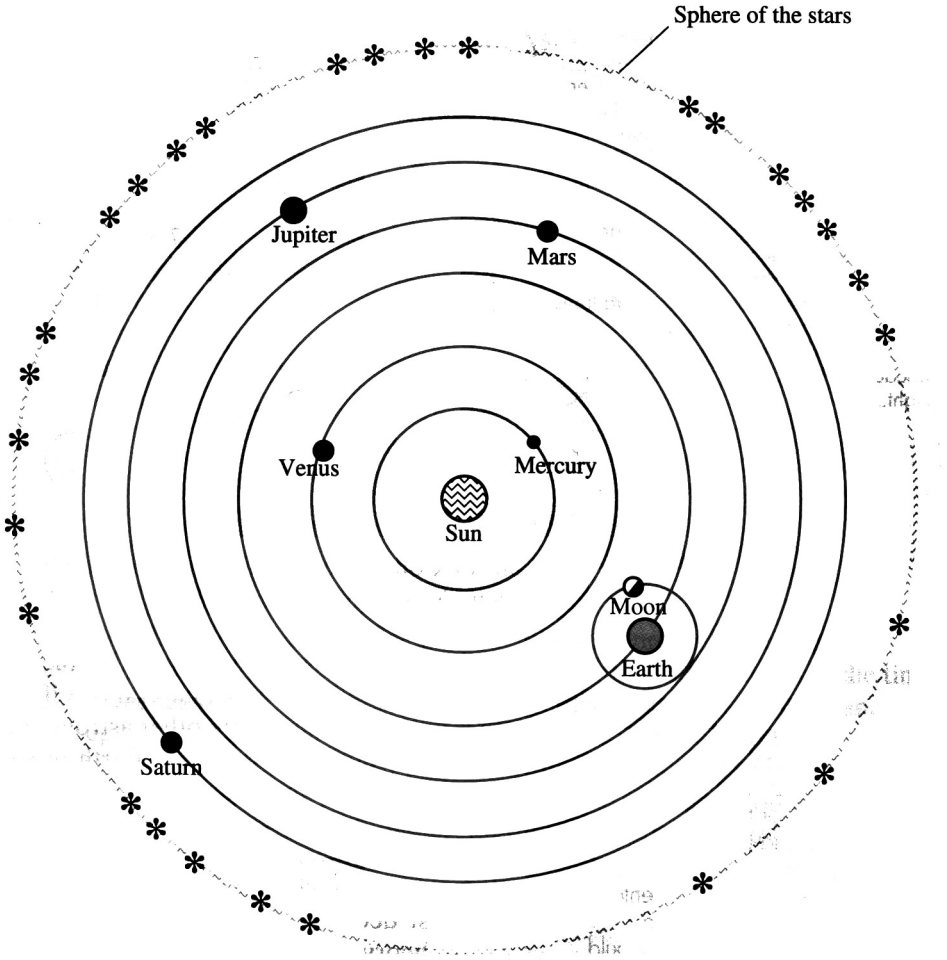


Copernicus



- Is there something simpler?
- Keeps ideas of Pythagoreans
  - Circular deferents and epicycles
  - uniform motion (does away with equants)
- Major Changes
  - Earth centered (heliocentric)
  - Earth rotates
  - Earth is no different from the other planets and stars!
- Established order of the planets
  - Inferior (Mercury and Venus)
    - Morning and Evening Stars
      - Always close to the sun
    - Superior (Mars, Jupiter, Saturn)
- Less complicated explanation for retrograde motion (epicycles not needed)

Occam's Razor (<1347)
Accept the simplest explanation



Copernicus

- Predictions of existing observations are not better than Ptolemy's!!
- Slightly simpler
  - No equants
  - Fewer epicycles (still a lot)
    - remove epicycles
      - Copernicus does okay
      - Ptolemy's is a disaster
- Discriminating observations needed
  - no telescopes
  - Both models survive, Ptolemy's is more widely accepted based on paradigms
  - need better observations

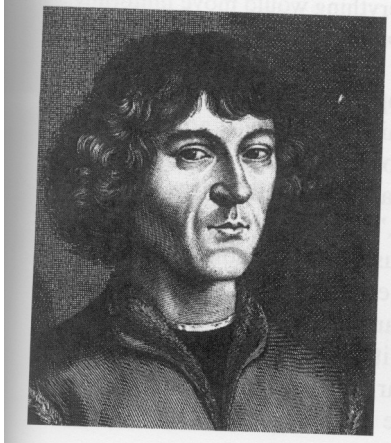


FIGURE 1.14
Renaissance astronomer Nicolaus Copernicus, 1474–1543. Finding Ptolemy's system to be "neither sufficiently absolute nor sufficiently pleasing to the mind," he devised a simpler theory. Copernicus's theory placed the sun at the center of the universe, with Earth moving around it. The odd idea that Earth moved and was a planet like the other planets met with much resistance because it conflicts with the intuitive notion that Earth is at rest at the center of things and because it conflicted with prevailing philosophies.

Tycho Brahe

- Better observations
  - 5x better
    - 2 arc-minutes (1/30 of a degree) compared to 10 arc-minutes (1/6 of a degree)
    - 20 years of data
  - Both Ptolemy and Copernicus's models are wrong!

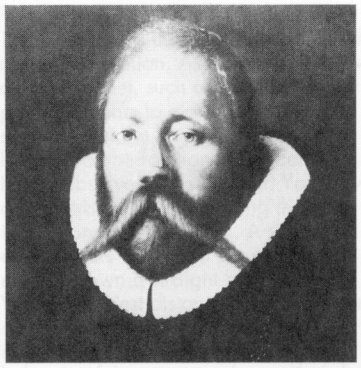


FIGURE 1.18
Tycho Brahe, 1546–1601. By making measurements of the planetary positions that were five times more accurate than were previous measurements, he overthrew two theories of the architecture of the heavens.

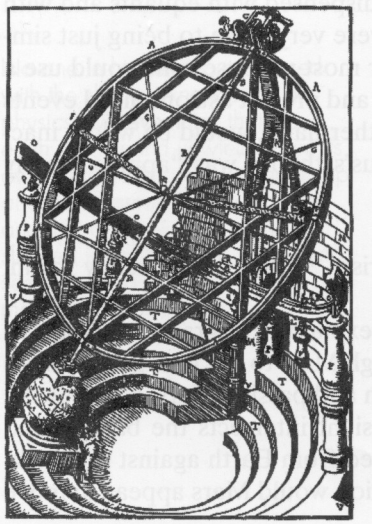


FIGURE 1.19
Brahe's sextant for measuring the positions of the planets. Brahe's work was done without telescopes.

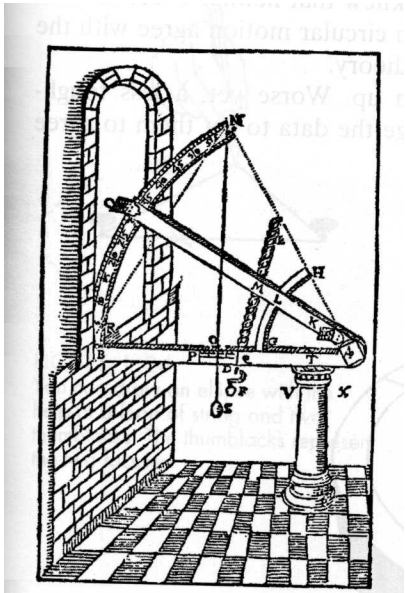


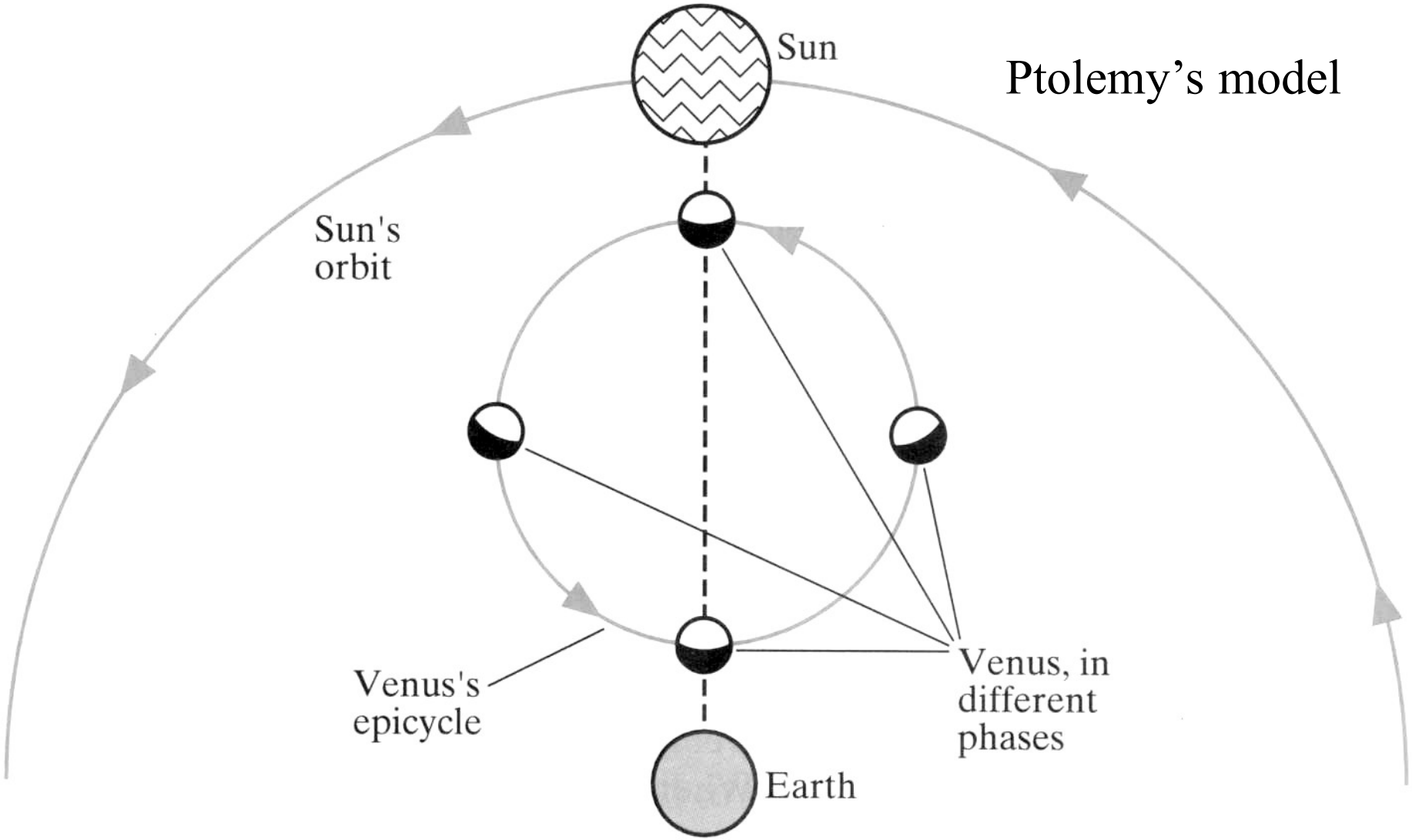
FIGURE 1.20
An instrument that Brahe used for

Galileo

- Used a telescope for astronomical observations
- Supported Copernican and Kepler's models (heliocentric)
  - Moons of Jupiter orbit Jupiter!
    - Earth not the center of all celestial motions!
  - **Phases of Venus include the gibbous phase!**
    - Not predicted with Ptolemy's model
- Experiments with mechanics
  - Free-fall and incline plane experiments
  - Refutes Aristotelian physics

Phases of Venus

Ptolemy's model



The Celestial Sphere

- a conceptual model of the sky.

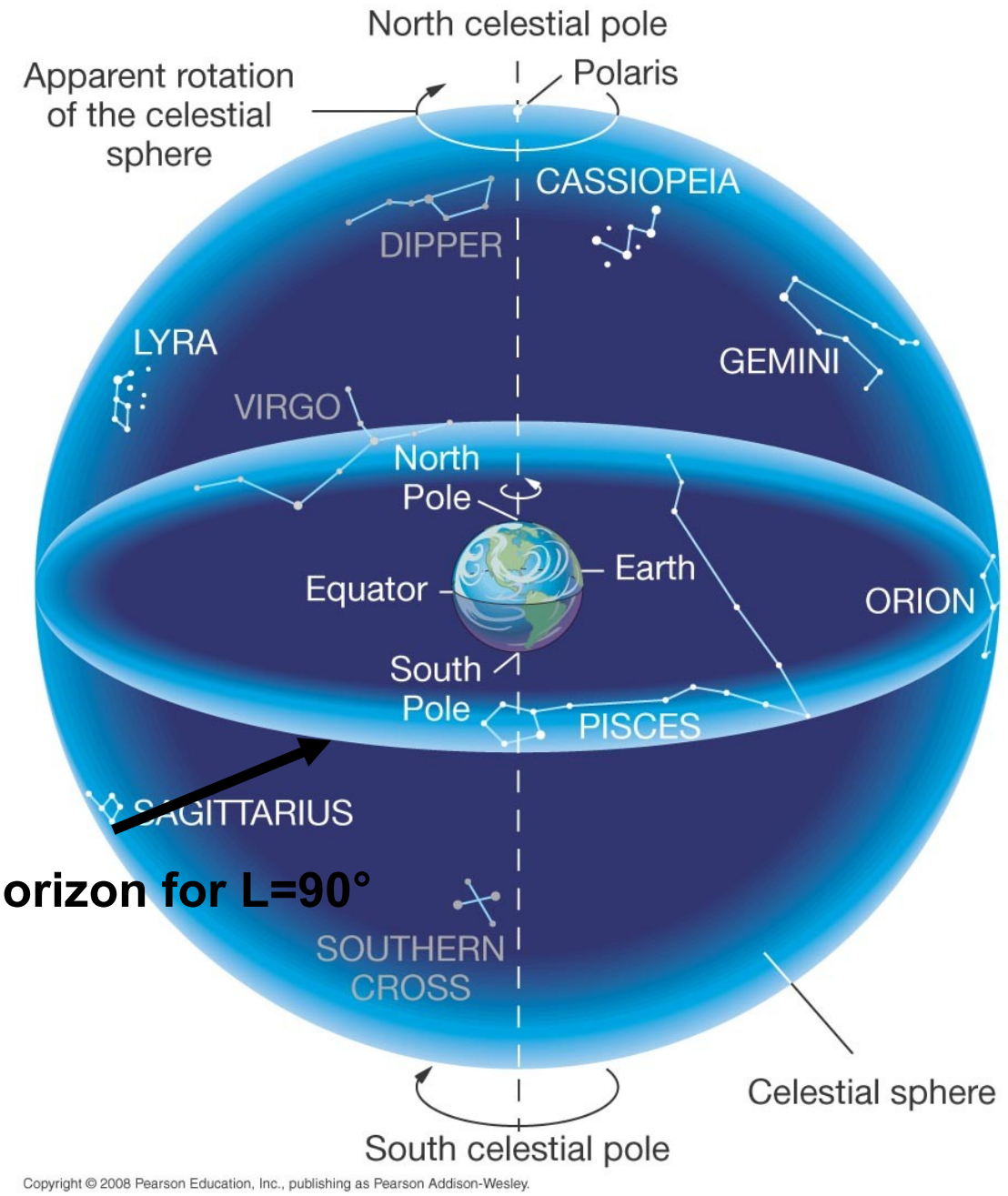
-geocentric (wrong)

-all stars at same distance (wrong)

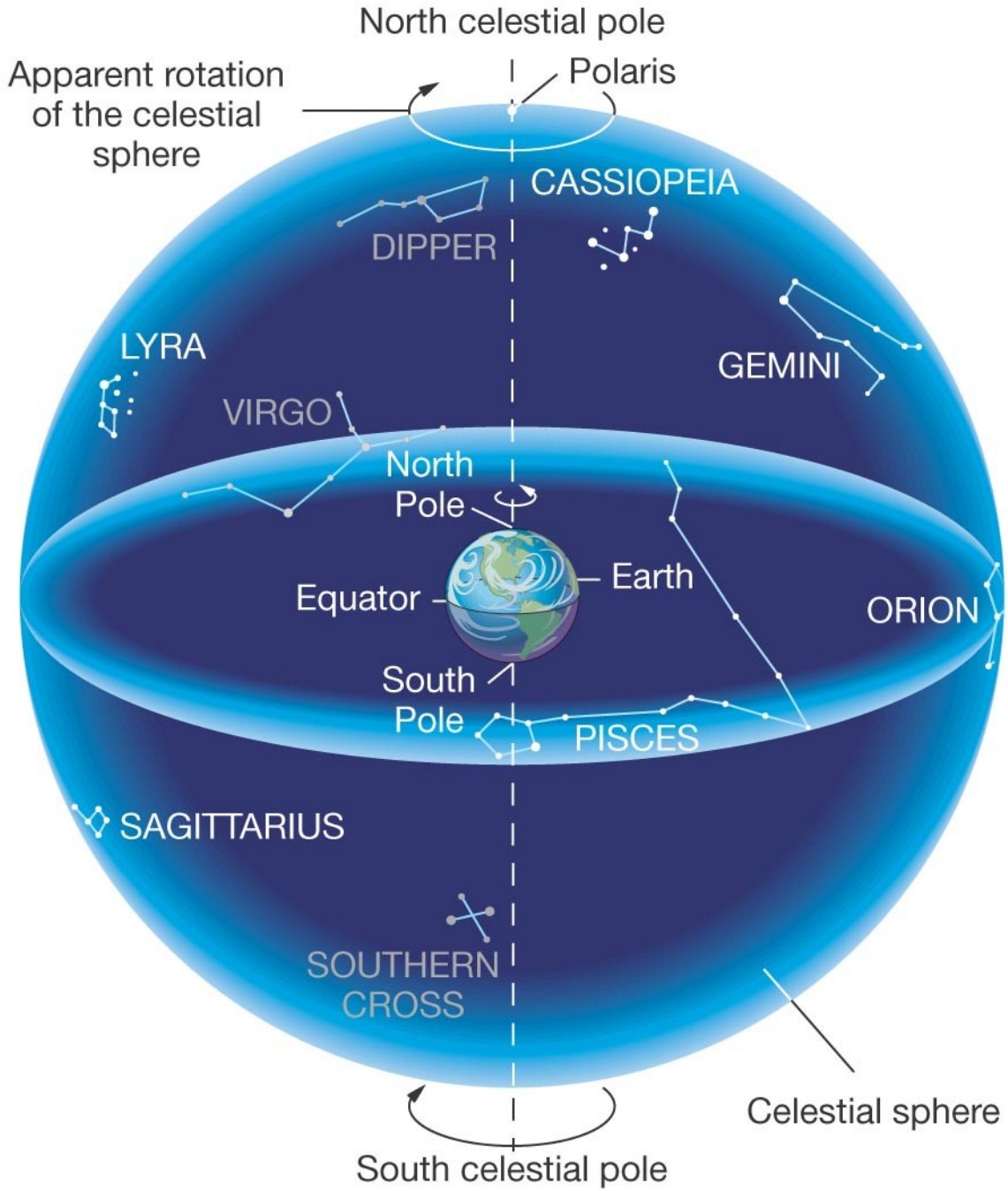
-a distortion-free sky map

-reproduces daily rising and setting motions for any latitude on Earth

-Cel. Sphere is infinitely bigger than the Earth.



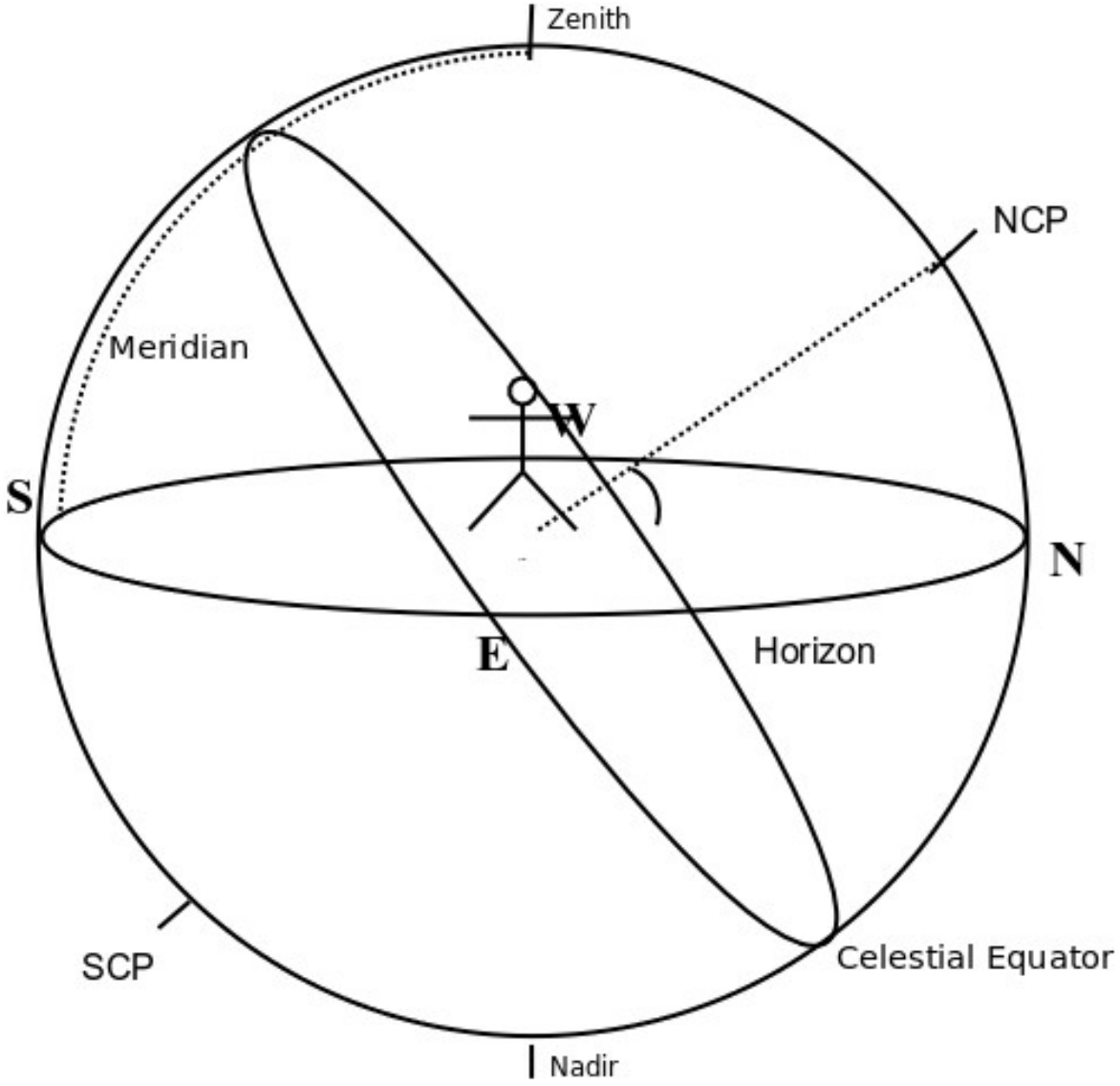
Horizon for L=90°



The Celestial Sphere

Features:

1. stars
2. Earth/observer
3. N. Celestial Pole
4. S. Celestial Pole
5. Celestial Equator

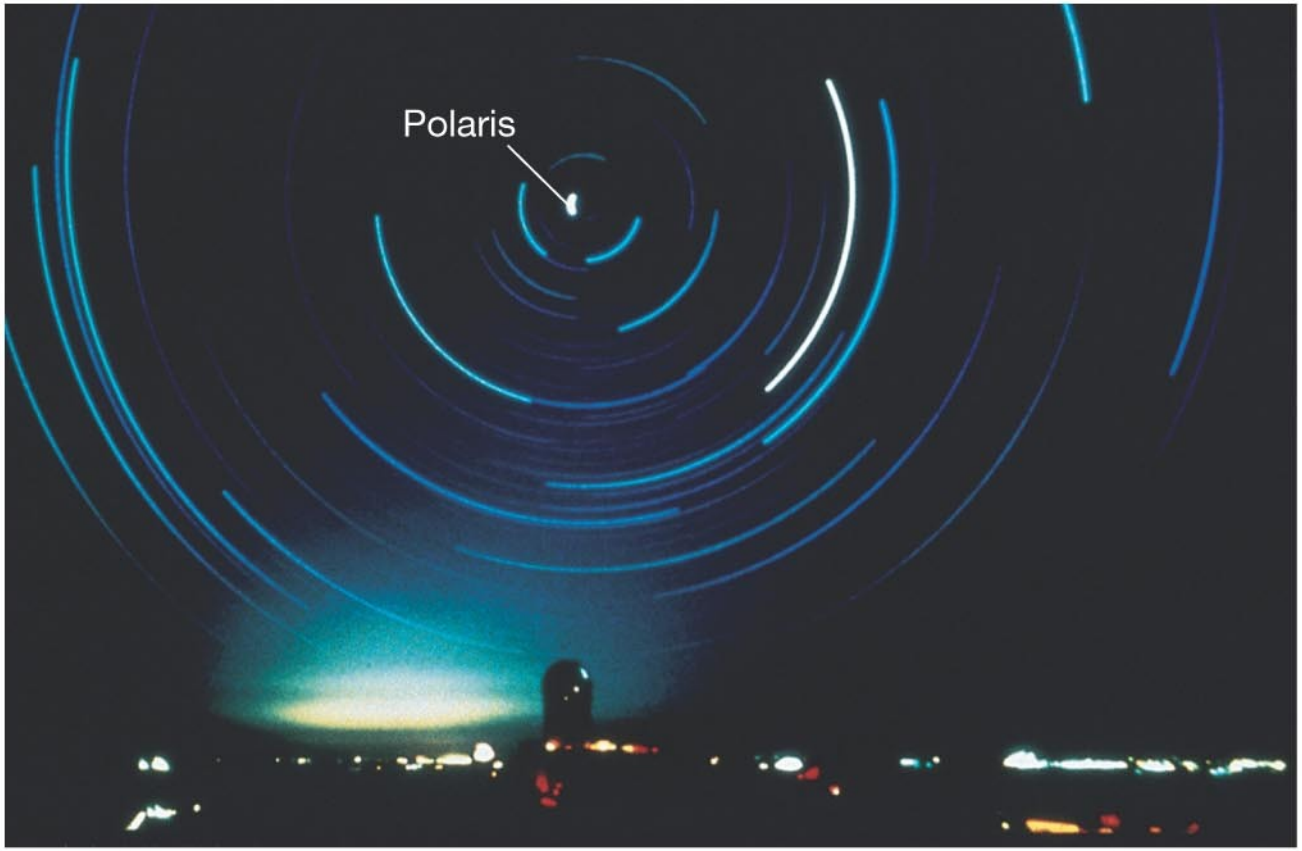


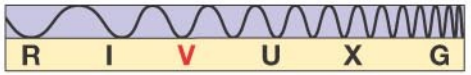
The Celestial Sphere

More Features:

1. stars
2. Earth/observer
3. N. Celestial Pole
4. S. Celestial Pole
5. Celestial Equator
6. Horizon
7. Cardinal points, (N,S,E,W)
8. Zenith
9. Nadir
10. Meridian

Star Trails





The view from inside of the celestial sphere. Stars rise on the right and set on the left.

UNLs: Celestial and Horizons system comparison.

Coordinate Systems for the sky

<u>Altazimuth coordinate system</u>

Uses the horizon for it's zeropoints.

A star's coordinates are different for observers on different parts of Earth

Altitude **= angle measured above (or below) the horizon in degrees.**

Azimuth **= angle measured along the horizon in degrees such that 0º azimuth is due North, 90º is due East, etc.**

Ex) Polaris

Altitude = 40.75 degrees (our latitude)

Azimuth = 0 degrees (straight above N on horizon)

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Equatorial (or Celestial) coordinate system

Uses the Celestial equator and ecliptic to define zeropoints.
A star's coordinates are the same for all observers!
***Right Ascension*, RA = distance measured in hours, minutes and seconds along the celestial equator such that RA=0h at the vernal equinox and RA=6h at the Summer Solstice.**
***Declination*, DEC = Angle measured in degrees, arcminutes and arcseconds above the celestial equator such that DEC = 0º on the cel. equator, increasing to +90º at the NCP and -90º at the SCP.**

Coordinate Systems for the sky

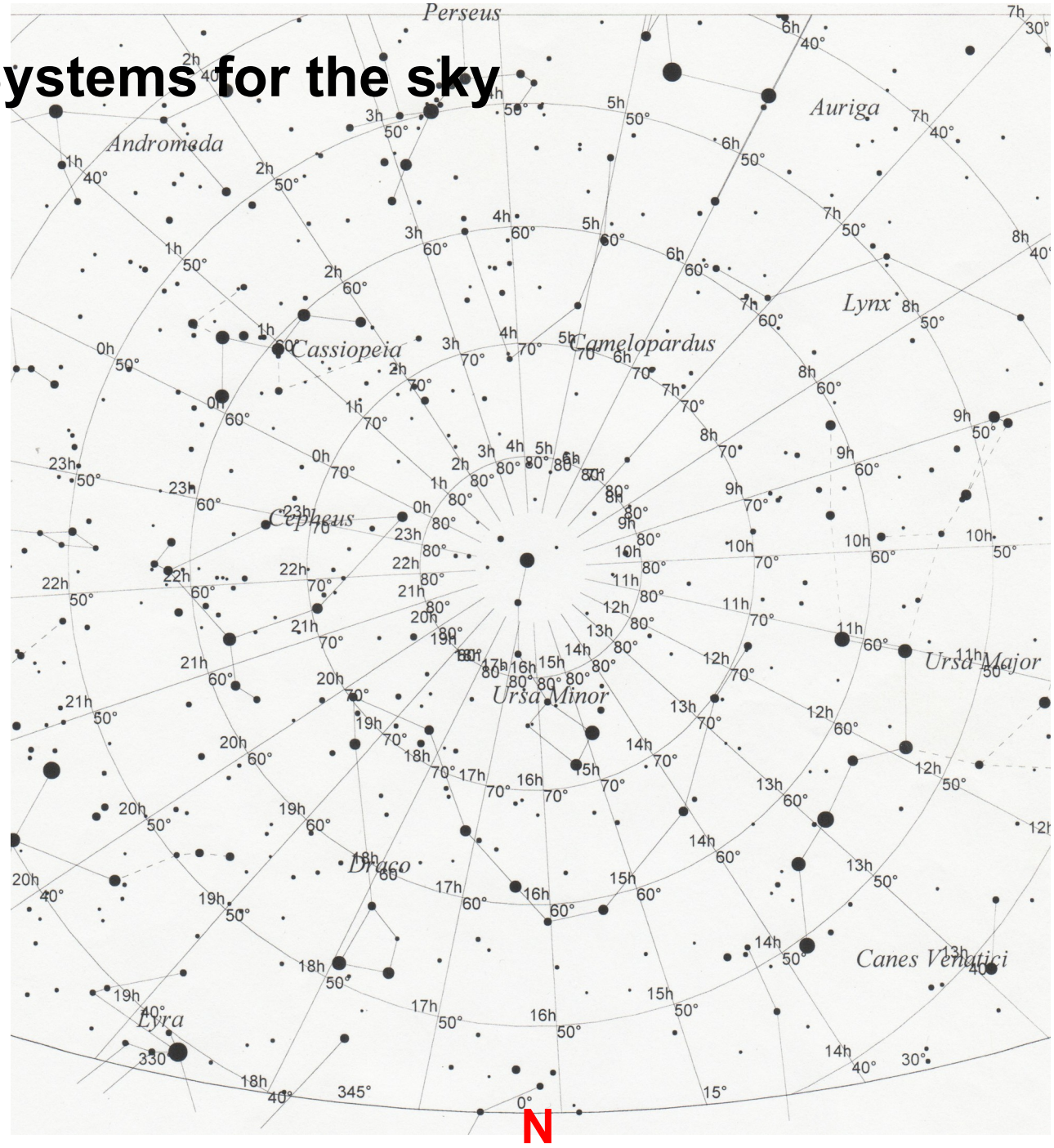
Example: Polaris

Equatorial:

Dec=90º
RA = ~2hr

Altazimuth:

Alt = 46º
Azim = 0º



Coordinate Systems for the sky

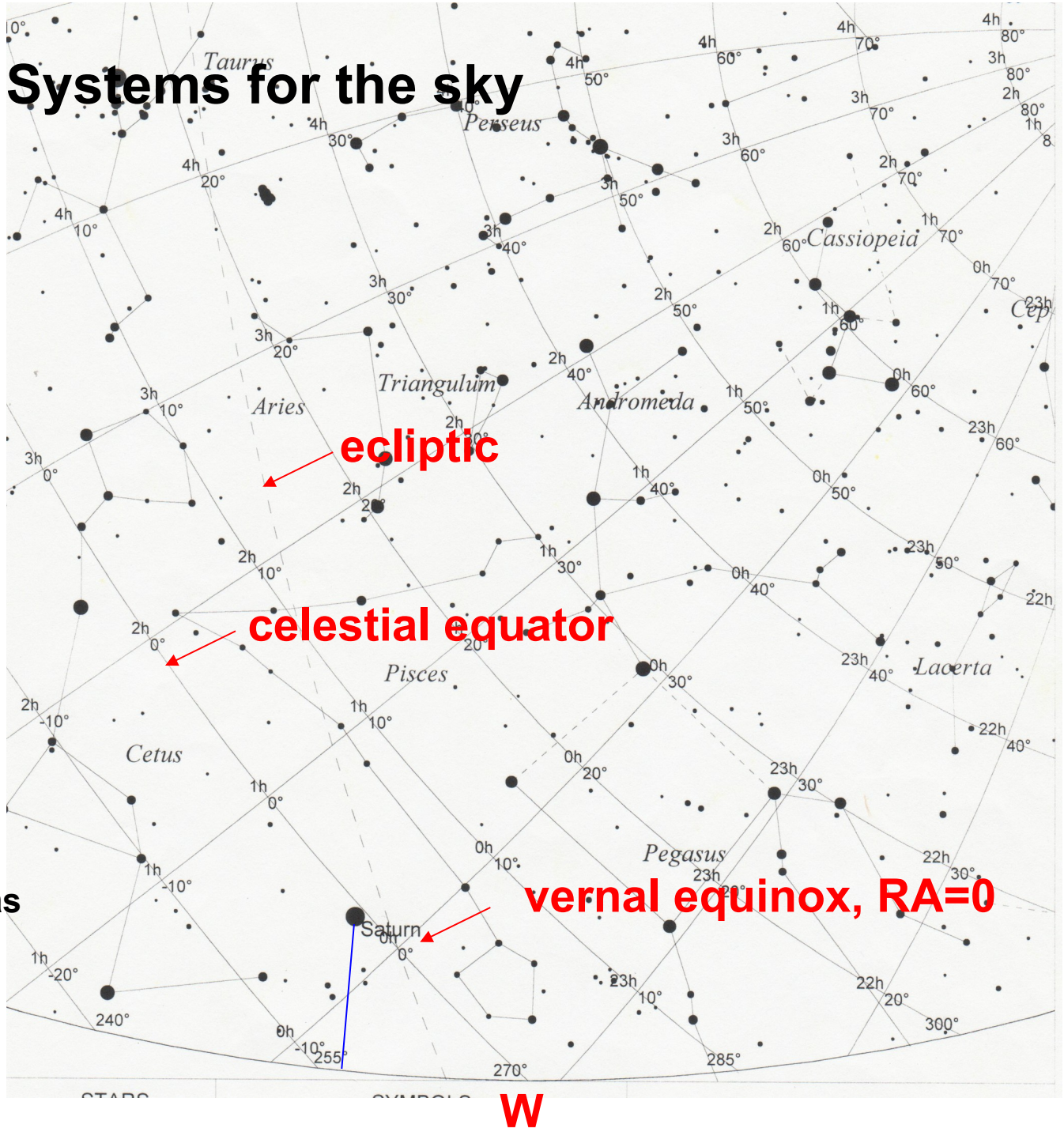
Example: Saturn *

Equatorial:

Dec=-1°
RA = 0h 15m

Altazimuth:

Alt = 13°
Azim = 257°

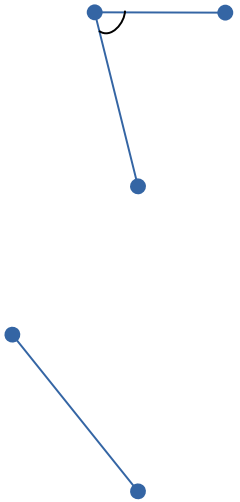


* This is where Saturn was many years ago, not its current position.

Angles, distances and widths

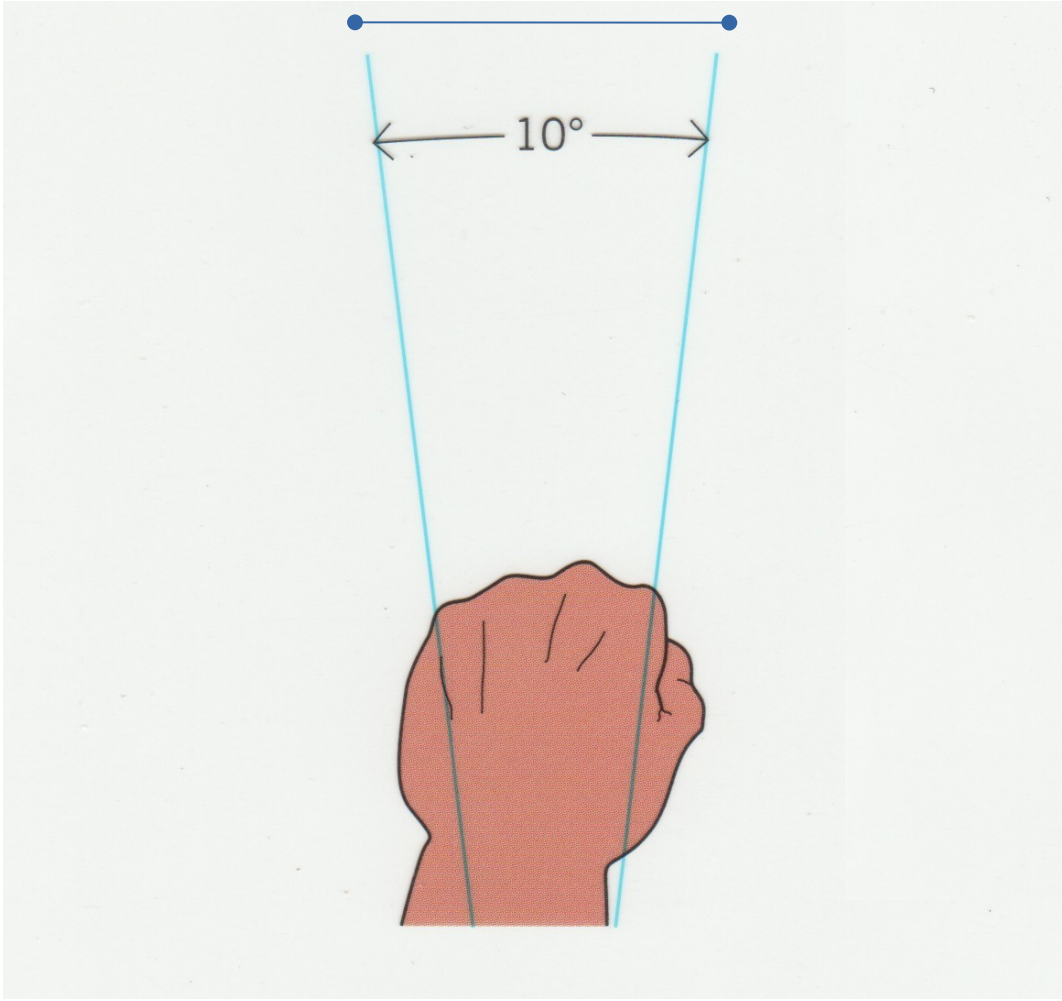
Angles are measured in degrees, arcminutes, and arcseconds.
1 degree (º) is 1/360 of a complete rotation
1 arcminute (') is 1/60 of a degree
1 arcsecond (") is 1/60 of an arcminute

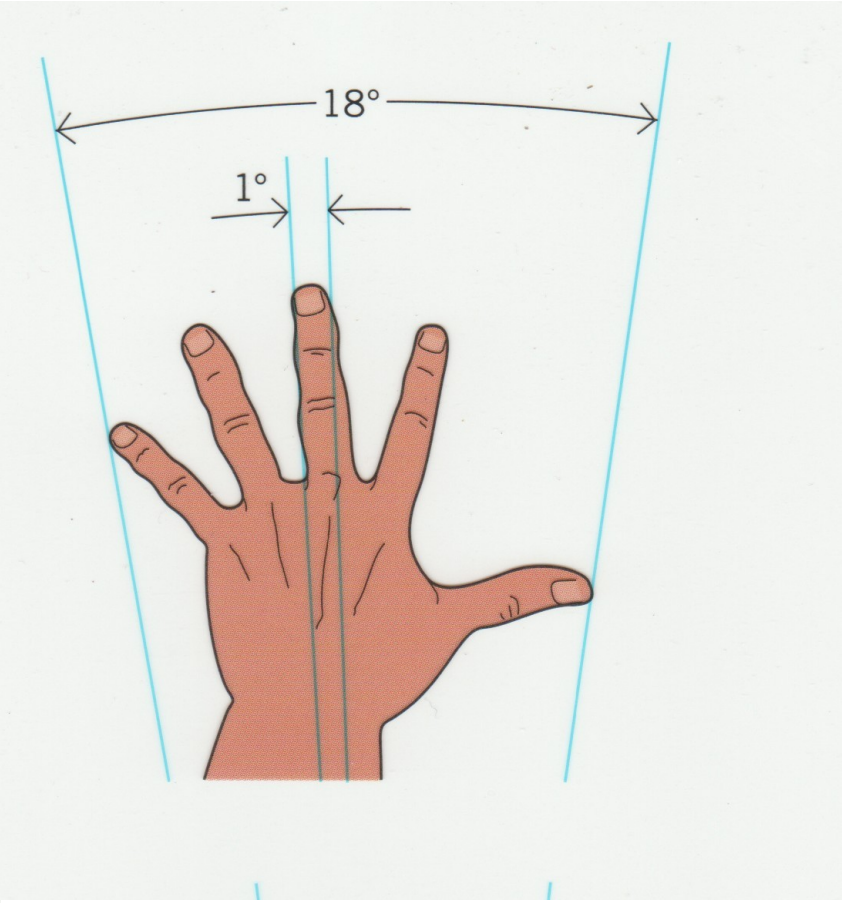
Angles on the sky can be measured in two ways:
1) Think of the sky as a flat paper with lines connecting one star to two others. An angle can be drawn between those two lines where they intersect.
2) The angle between two rays extending from your eye to two points in the sky. This is called the "angular separation" of those two stars and it can be estimated using your fist at arm's length.



Mostly we use #2.

Angles, distances and widths



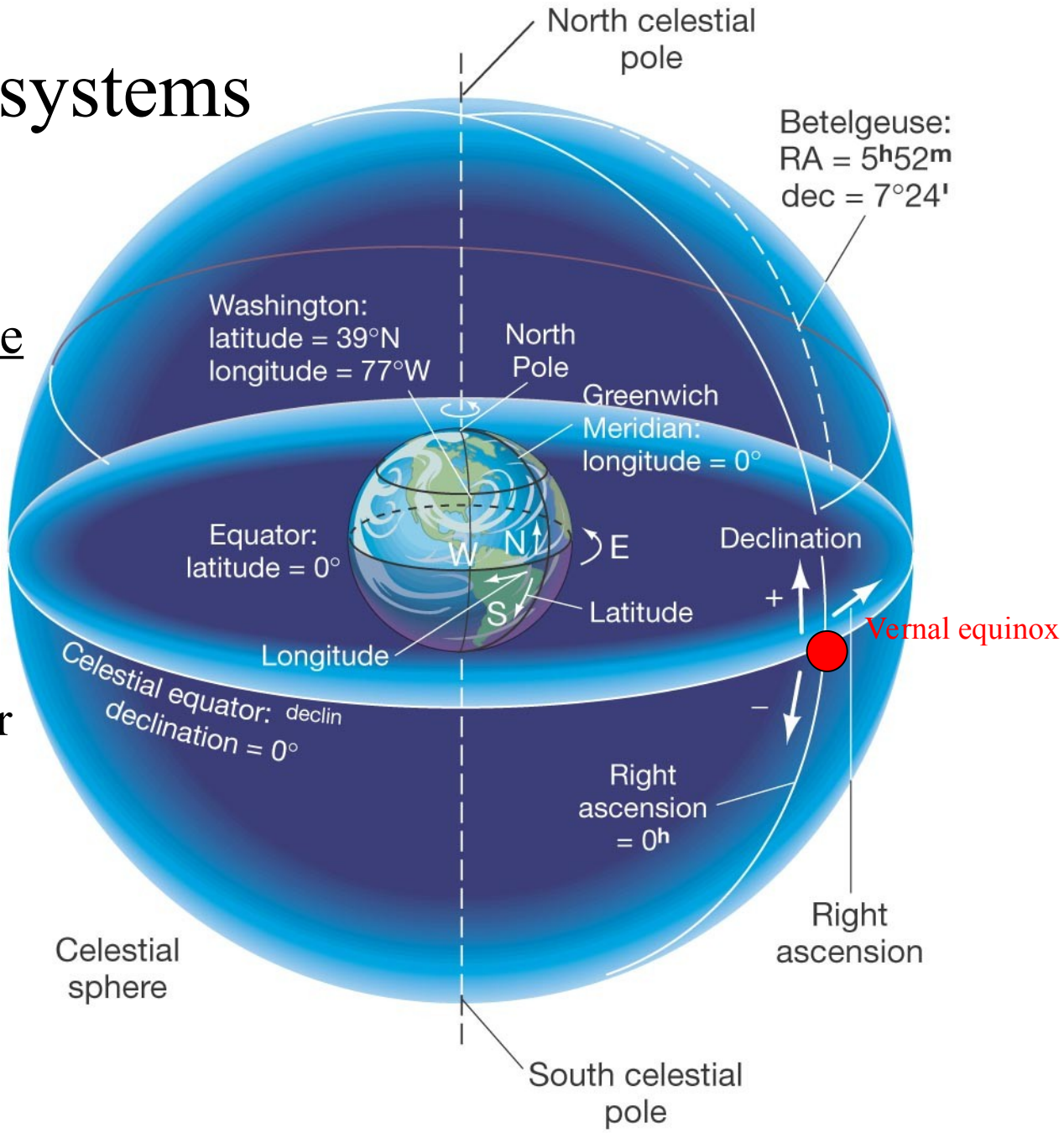


Coordinate systems

<u>Equatorial Coordinate System</u>

Right Ascension
Declination

* Uses celestial equator and vernal equinox as references
* Analogous to longitude and latitude



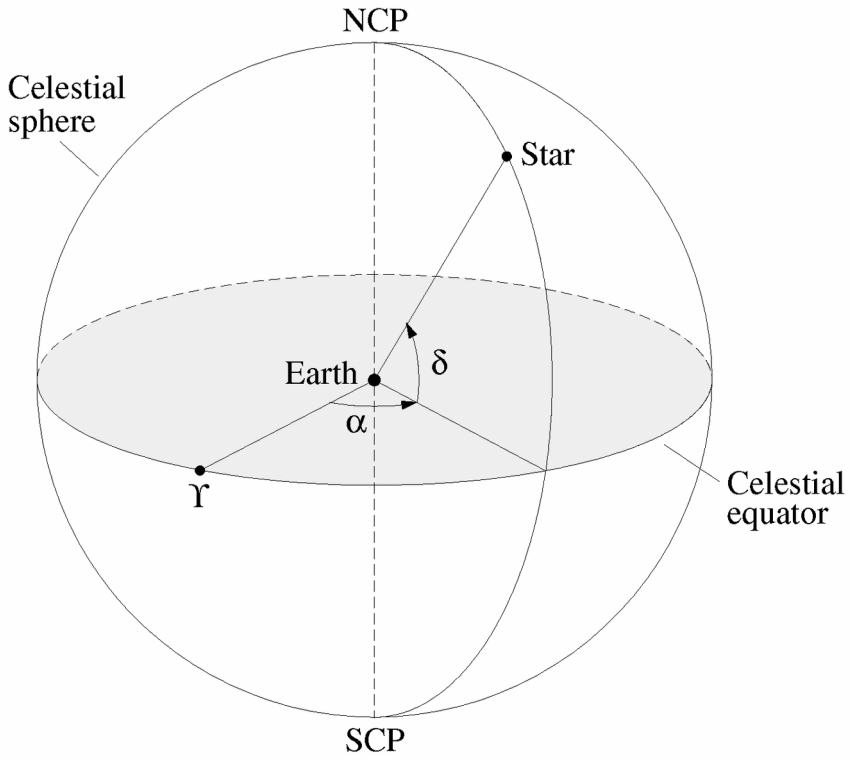
Equatorial Coordinate System

- A location-independent system
- Also doesn't depend on date or time of day. (Just year or "epoch".)

δ – declination (latitude)
α – right ascension (longitude)
♈ – vernal equinox (origin)

α and δ gradually change as Earth Precesses (25,770 year period)

"North Pole" moves 47° in 13,000 years

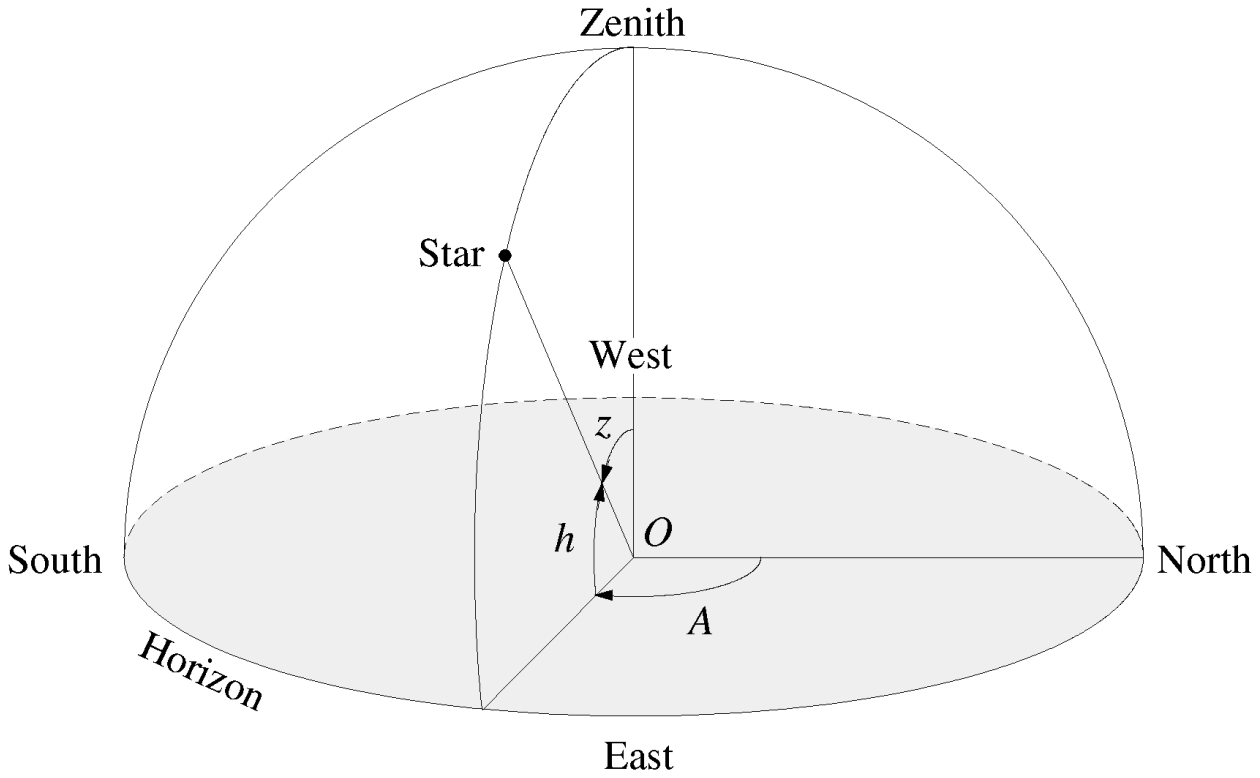


See UNL's RA/Dec Demonstrator.

Note: this simulator gives the impression that Greenwich is fixed under the 0h circle, but the Earth rotates relative to this equatorial coordinate grid.

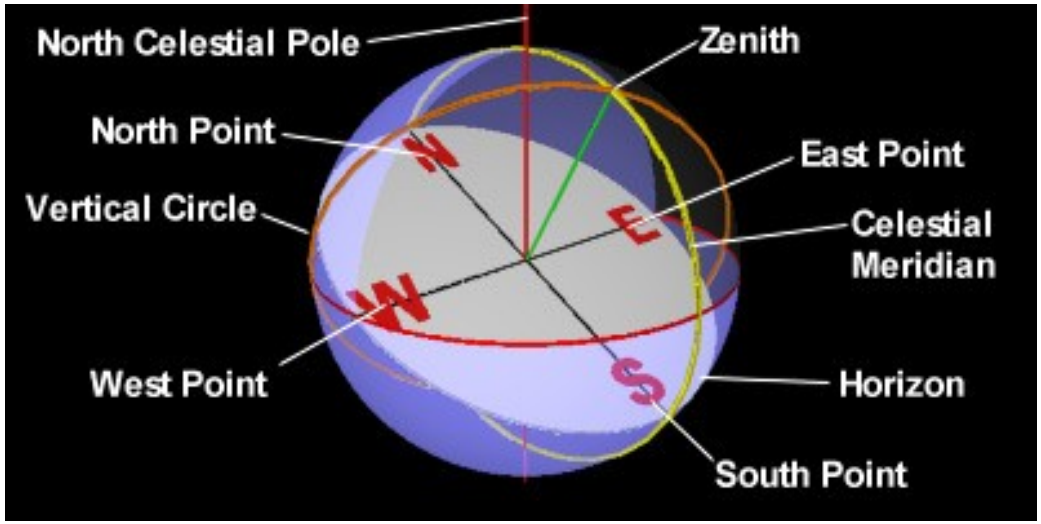
The Celestial Sphere & coordinates

- Altitude-azimuth coordinate system
- A "location-dependent" system
  - Altitude, h
  - Azimuth, A
- Also, z = zenith angle (h + z = 90^{o})

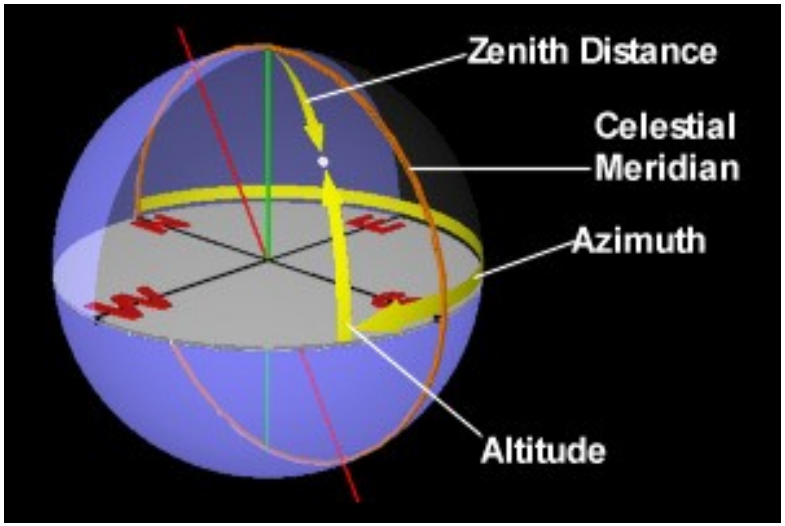


Altitude – azimuth coordinate system

NCP pointing up

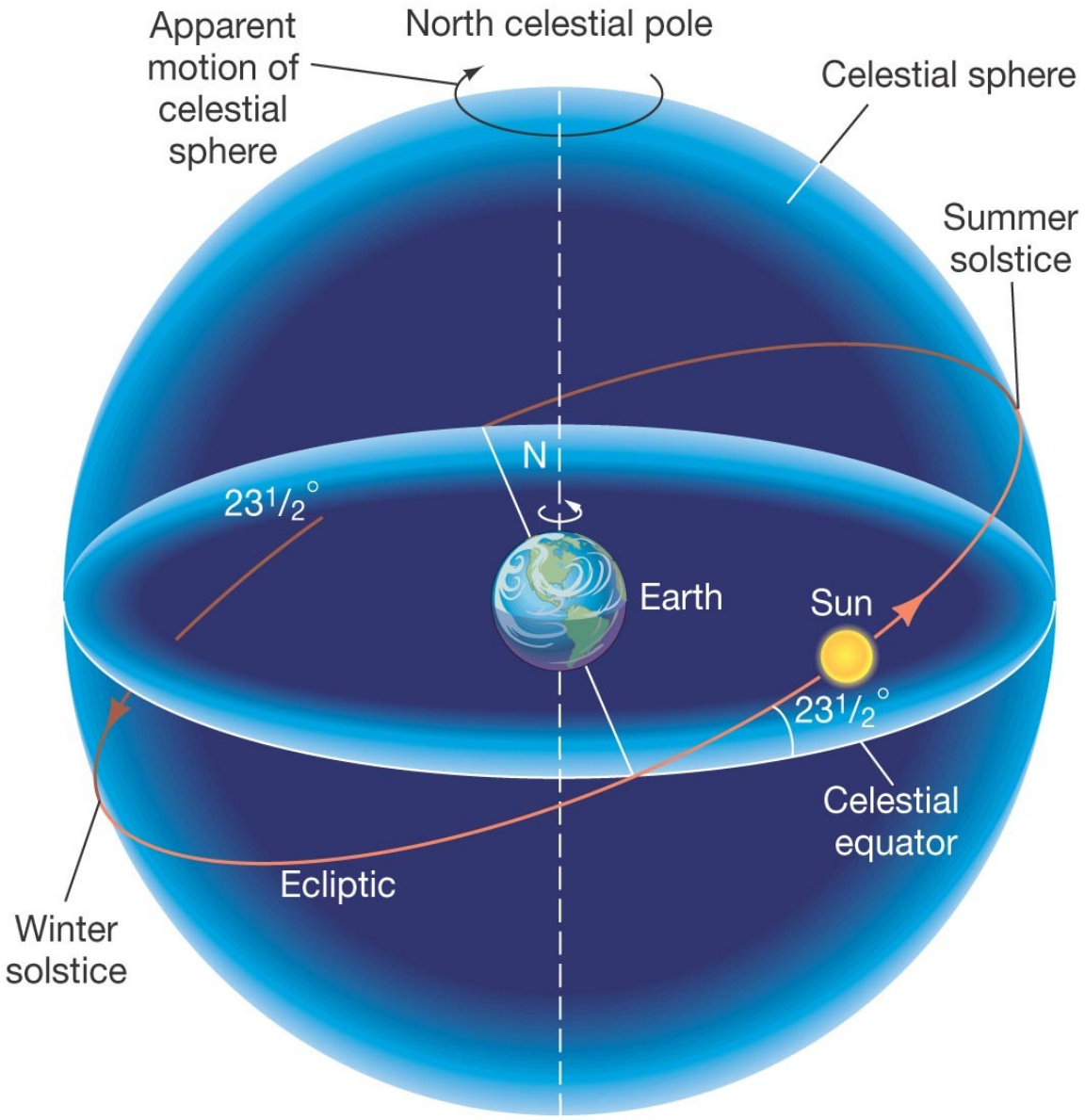


Zenith pointing up



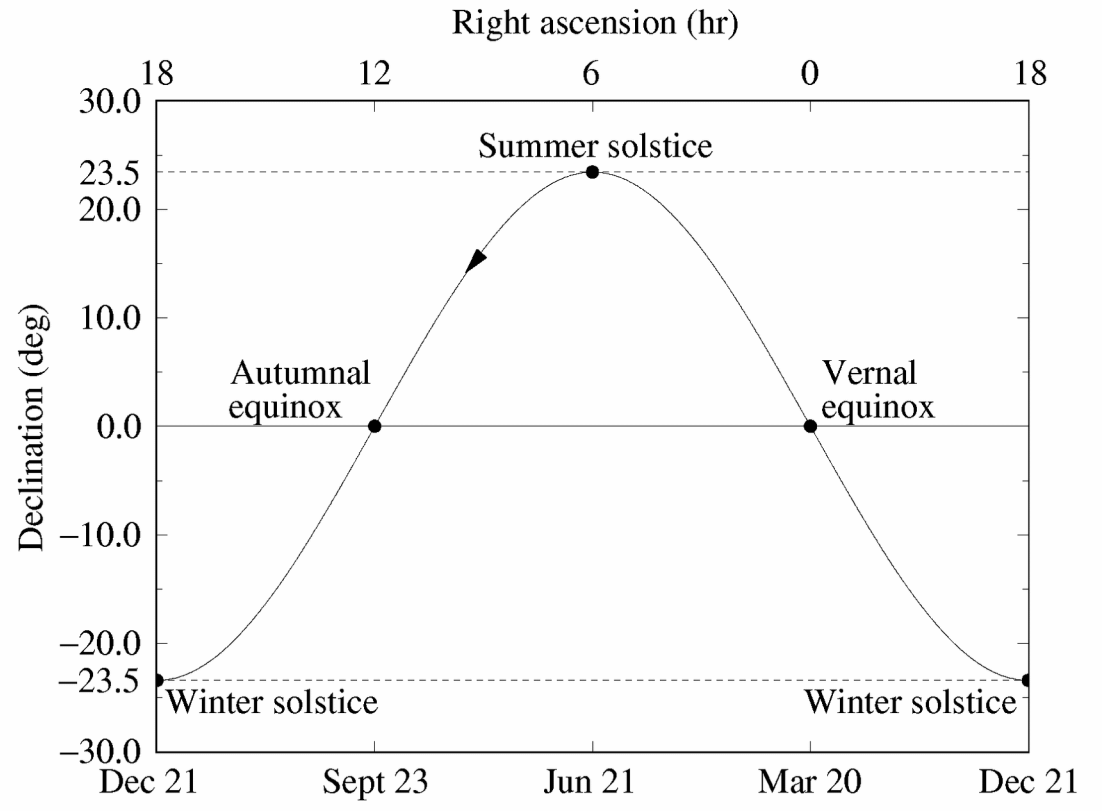
- Good for communicating a location to someone close to you.
- Problems
  - Alt and Az of a star depend on observer's location!
  - Alt and Az of a star depend on time of day.
  - Alt and Az of a star depend on date.
- To understand how the "NCP up" point of view relates to the "zenith up" point of view, see: Celestial and Horizons system comparison

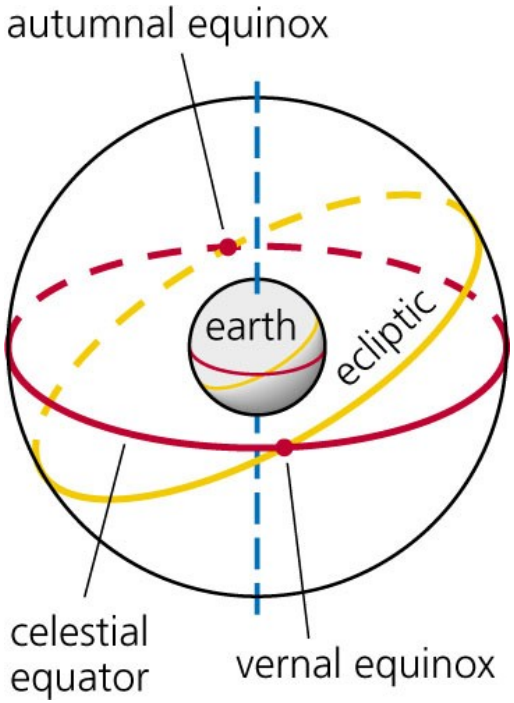
Celestial Sphere and the ecliptic



Ecliptic

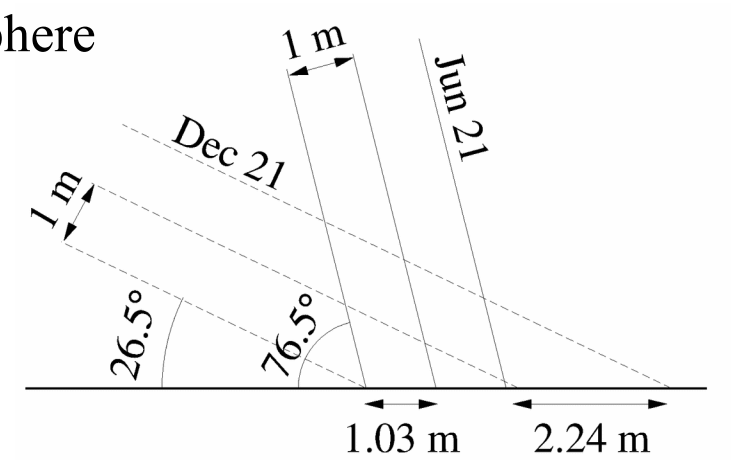
- Seasonal variations due to orbital motion and the 23.5° tilt of Earth's rotational axis

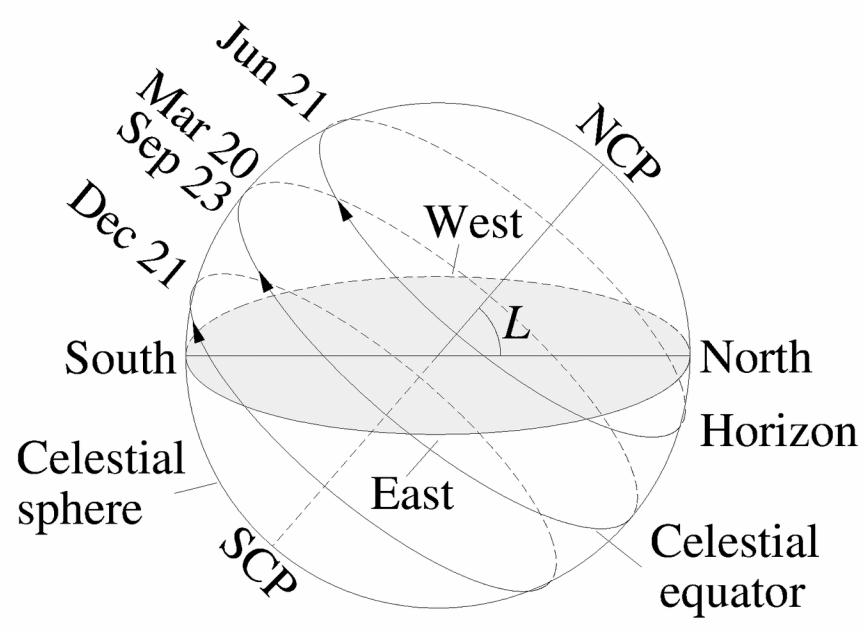


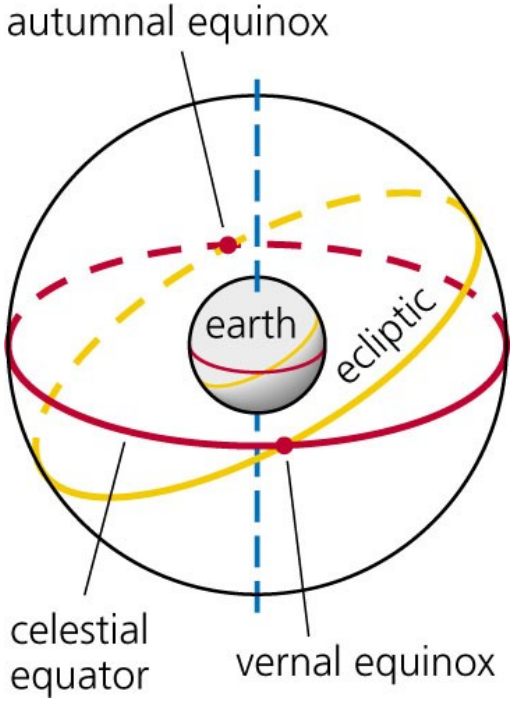


Ecliptic

- Annual path the sun takes across the celestial sphere
- Vernal and autumnal equinox
- Summer and winter solstice







General philosophy of science

Karl Popper: Logic of falsification

Theories can never be verified by observation.

Theories can be falsified by observation, and so discarded.

The only acceptable theories are those which are falsifiable.

Thomas Kuhn: Paradigms and paradigm shifts

"Normal science" -- investigation within a paradigm

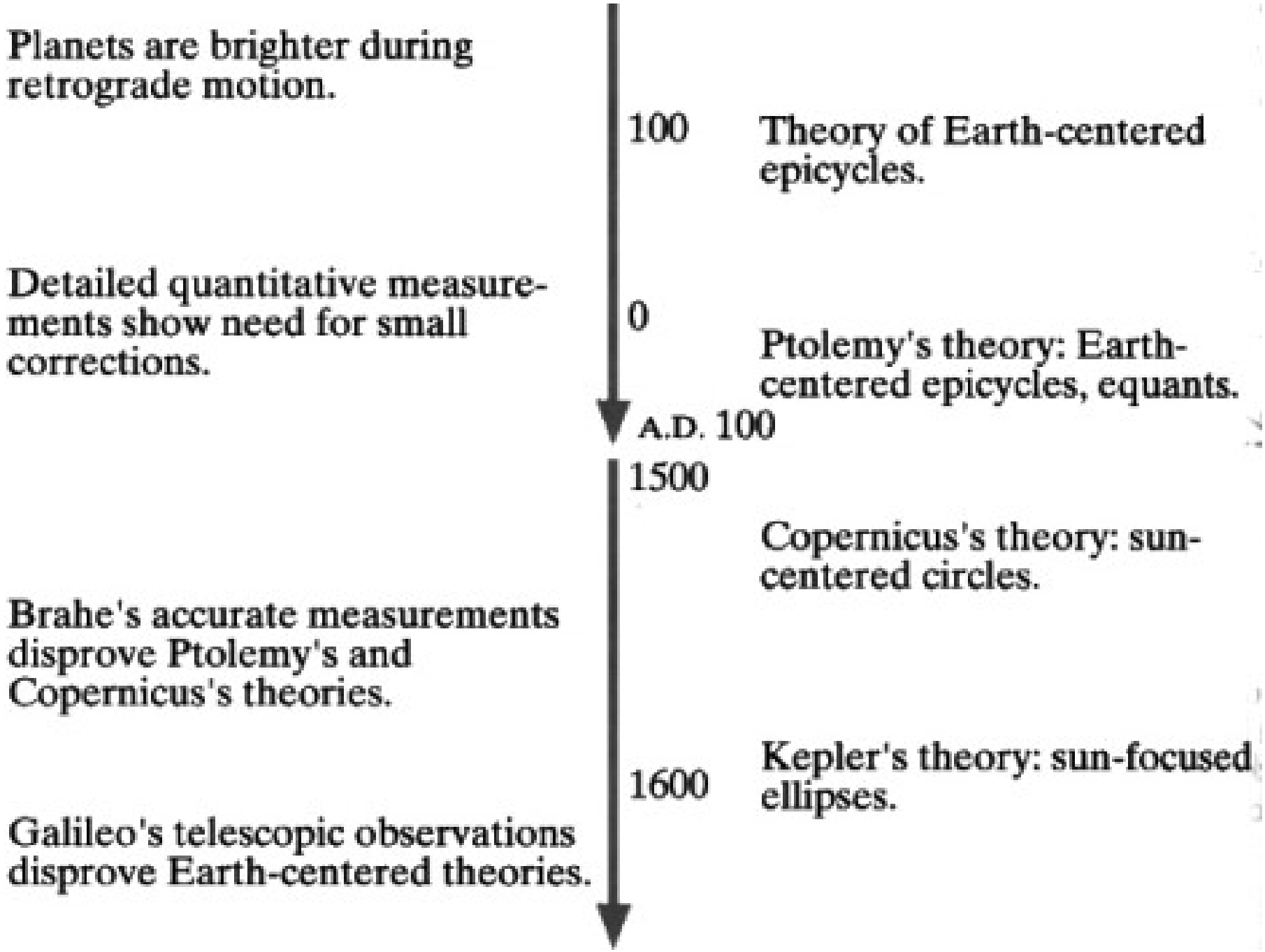
Revolutions -- paradigm shifts driven by anomalous data

Niels Bohr: Correspondence principle

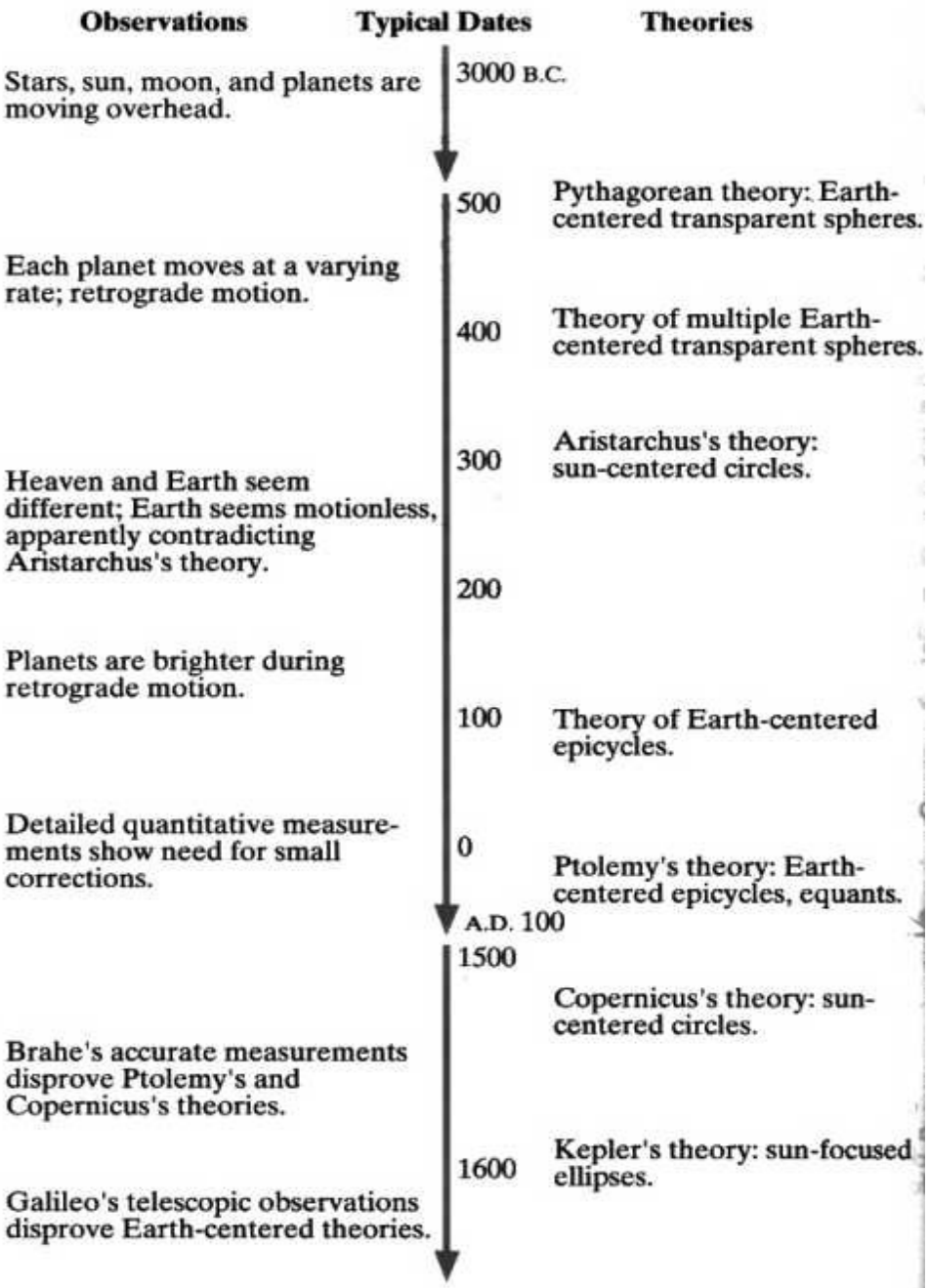
New theories must reduce to good old theories in some limit.

A Summary of the Early History of Astronomy

Observations	Typical Dates	Theories
Stars, sun, moon, and planets are moving overhead.	3000 B.C.	
	500	Pythagorean theory: Earth-centered transparent spheres.
Each planet moves at a varying rate; retrograde motion.		
	400	Theory of multiple Earth-centered transparent spheres.
	300	Aristarchus's theory: sun-centered circles.
Heaven and Earth seem different; Earth seems motionless, apparently contradicting Aristarchus's theory.		
	200	
Planets are brighter during retrograde motion.		


Planets are brighter during retrograde motion.
100
Theory of Earth-centered epicycles.
Detailed quantitative measurements show need for small corrections.
0
Ptolemy's theory: Earth-centered epicycles, equants.
A.D. 100
1500
Copernicus's theory: sun-centered circles.
Brahe's accurate measurements disprove Ptolemy's and Copernicus's theories.
1600
Kepler's theory: sun-focused ellipses.
Galileo's telescopic observations disprove Earth-centered theories.

A Summary of the Early History of Astronomy



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Star Motion

- Radial velocity
- Transverse velocity
  - Angular velocity → proper motion