PLANETARIUM SHOWS

- Seeing the "what does stuff do in the sky" things we're going to talk about is way easier in the planetarium than in class or the book
- Go to one of the two remaining shows scheduled over the next couple weeks
  - This is a required, if ungraded, assignment
- More info here, next show is today at 4pm

AURORA LAST NIGHT

- Slid more east of us, although after midnight I saw some nice ones. The UK was in the right place:

Photo of Aurora last night in Edinburgh by Paul Baralos, from this BBC article

AURORA LAST NIGHT

- Was here too! Battling full moon and city lights...

Photo of Aurora last night from Spirit Mountain by James Larson of this very class

NEXT UP

- How did we (as a culture) take these confusing motions and come up with answers like:
    - Earth moving around Sun? After all, we see the Sun and Stars moving around us!
    - What about planets, and how do they move?
- What are the rules of the game the universe appears to be playing by?

TIME

- The skies are a way to keep track of time
  - Very handy for agriculture!
- Since the sky does things on a regular basis, early astronomy was all about using this for timekeeping
  - And, of course, for astrology

Archeoastronomy!

CALENDARS

- First widely used* calendar came with the first widely used Empire
  - Julius Ceasar, in 46BC – “Julian Calendar”
  - 365 days
  - One extra Leap Day every 4 years for 365.25 days/year
- But – year is really 365.242199 days long
  - The extra 0.0078 days per year added up (3 extra days/400 years)
  - By the renaissance, the vernal equinox had slipped by two weeks!

*I’m not sure how the Chinese calendar worked

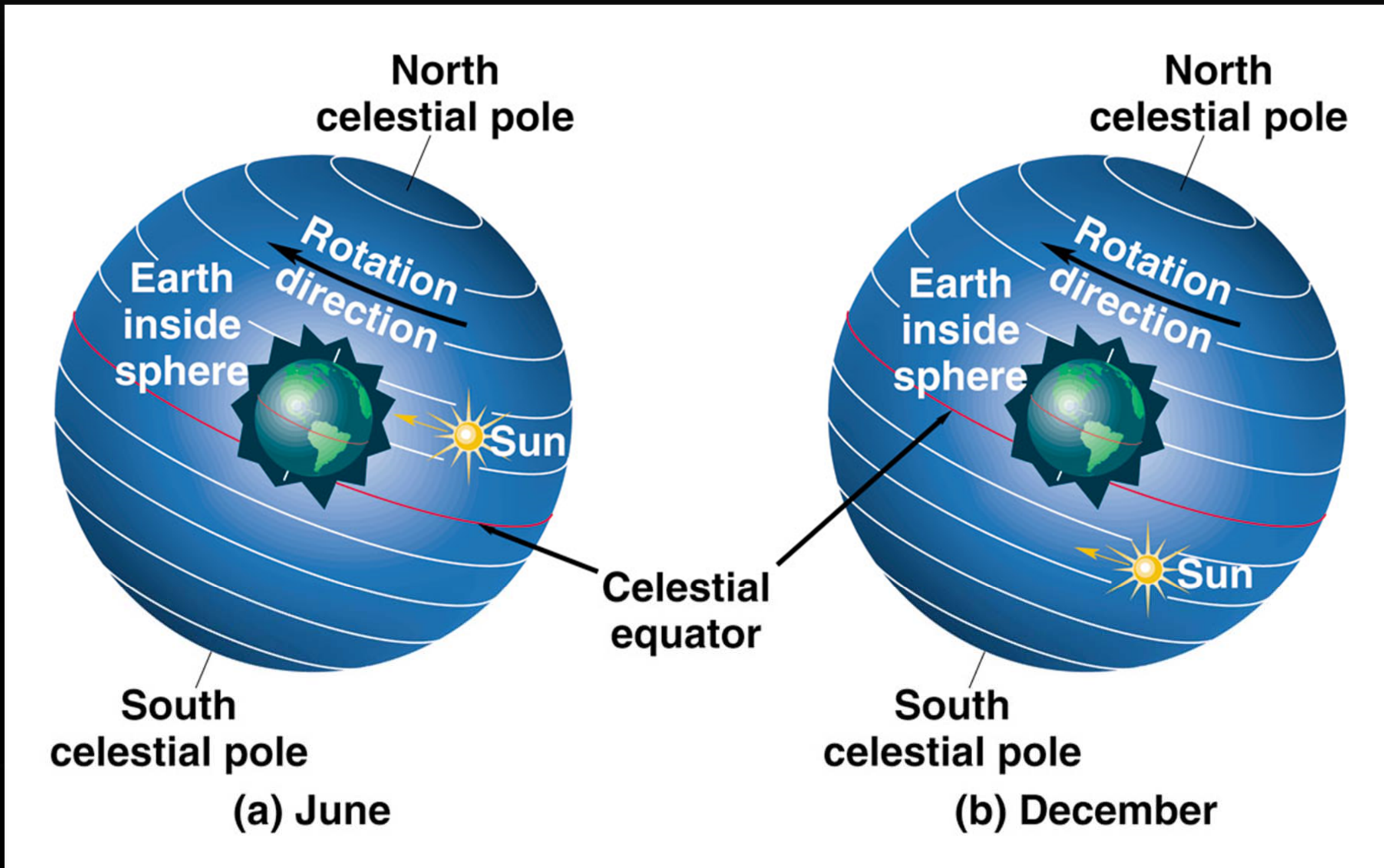
CALENDARS

- Pope Gregory XIII introduces Gregorian Calendar in 1582
  - Drops 10 days (Oct. 5 became Oct 15!)
  - Centuries not divisible by 400 are not leap years
  - Has 365.2425 days/year
  - Non-catholic countries adopt this calendar later (England and thus its American Colonies in 1752)
  - Only off by 0.0003 days/year
- One modern change
  - 4000, 8000, 12000 etc will not be leap years
  - Takes up most of the leftover difference

EARTH CENTERED MODELS

The "Obvious" Point of View

SCIENTIFIC MODELS



THE GREEK GEOCENTRIC MODEL

- Of all the ancient civilizations, the Greeks were most interested in explaining things (all that philosophy)
  - Similar to modern science, they were interested in
    - Symmetry
    - Order
    - Unity
- Other peoples were very good at recording (and even predicting) astronomical events, but didn’t write down thoughts about why things did what they did

EARLY THINKING

- Thales of Miletus (600 BC)
  - Rational thought can lead to understanding of universe
  - Sun & stars not gods but balls of fire
- Pythagoreans (450BC)
  - Spherical Universe
    - Earth, Moon, Sun, 5 planets move about central “fire” or force

ARISTOTLE

- Proposed Earth at center of things:
  - Argues we should see *stellar parallax* if Earth moves
  - Parallax not seen, so Earth must be fixed
  - A great philosopher, views agreed with from 400 BC through 1600's (and on many non-astronomical subjects, is still The Man)

OTHER ARISTOTLEAN IDEAS

- Aristotle also reasoned:
  - Moon is Spherical (watch phases!)
  - Sun further from us than Moon
    - Again, phases of Moon are light from Sun
    - Moves more slowly in sky
    - Earth Spherical! (see next page)

SPHERICAL EARTH

- Objects all fall down
  - Only on a sphere do they all seek the center
- Go south, see more of the sky
- In Lunar Eclipses, Earth's shadow on moon is curved
- Plus, spheres are very symmetrical

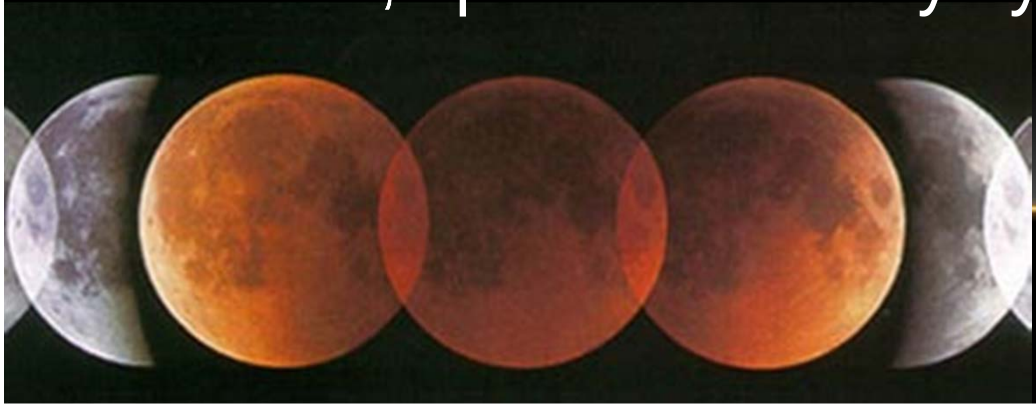


Photo of July 2000 lunar eclipse
by Akira Fujii For *Sky & Telescope*

NATURAL PROPERTIES

- Heavenly things and Earthly things are Naturally Different
- Heavenly –
  - Keep moving on their own, go in circles
  - "Perfect"
    - Lots of spheres, Long-lasting
- Earthly
  - Fall down
  - Come to a stop
  - Imperfect – lots of chaos, blemishes

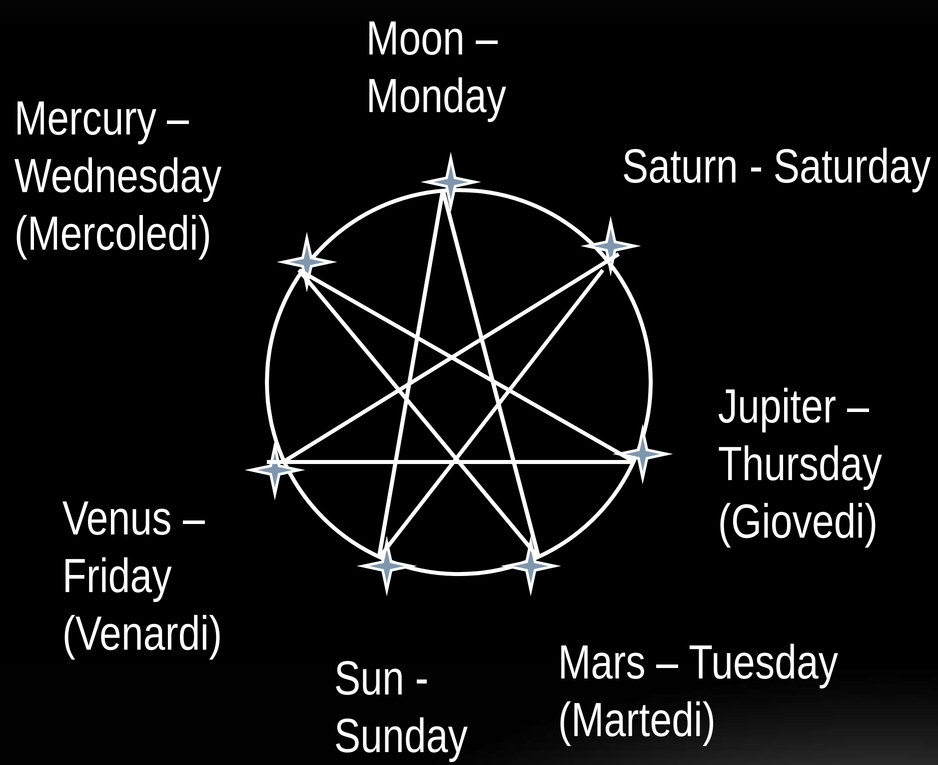
ARISTOTLEAN MODEL

- Sun fixed to a nearby sphere
  - Rotates once per year
- Stars fixed to a further sphere
  - Rotates once per day
  - At an angle of 23.5º from the Sun's sphere
- This model works to explain days, years, seasons, moon phases, eclipses! Most all of the stuff you've been trying to wrap your head around in Ch.2

PLANETARY MOTION

- Five Planets visible to naked eye
  - Mercury
  - Venus
  - Mars
  - Jupiter
  - Saturn
- They also move about with respect to the stars
  - The word “planet” is from the Greek word for “wanderer”

AN EVERYDAY ASTROLOGICAL RELIC



- Place the 7 “wanderers” around a circle, in order of their supposed distance
- Connect the names with the mystic heptagram (7 sided star)
- Follow the lines to get the days of the week
- In our German-influenced language, some day names got co-opted by Norse gods instead

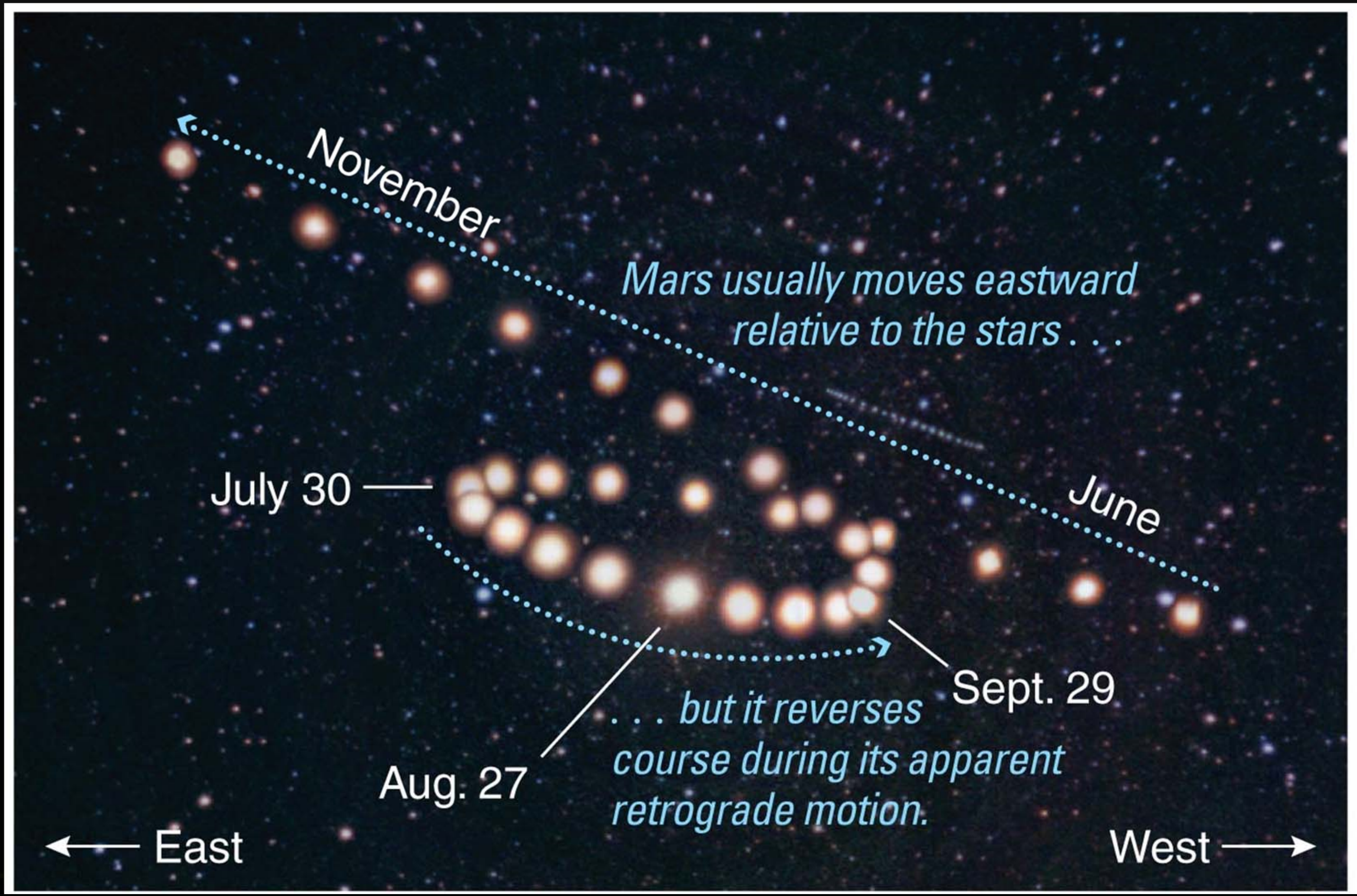
MOTIONS OF INFERIOR PLANETS

- “Inferior” simply refers to those planets in between us and the Sun
- Mercury, Venus swing back and forth near the sun
  - Mercury very close to Sun, hard to see
  - Venus swings further out
    - “Morning Star” or “Evening Star”
    - *Maximum Elongation* of 46^{o}

MOTIONS OF SUPERIOR PLANETS

- "Superior" simply meaning those planets further out than Earth
- Mars, Jupiter, Saturn all show the same basic motion, although each more slowly than the last
- They move from West to East along the ecliptic like the Sun and Moon
- However, they experience *Retrograde Motion* once per year

RETROGRADE MOTION OF MARS



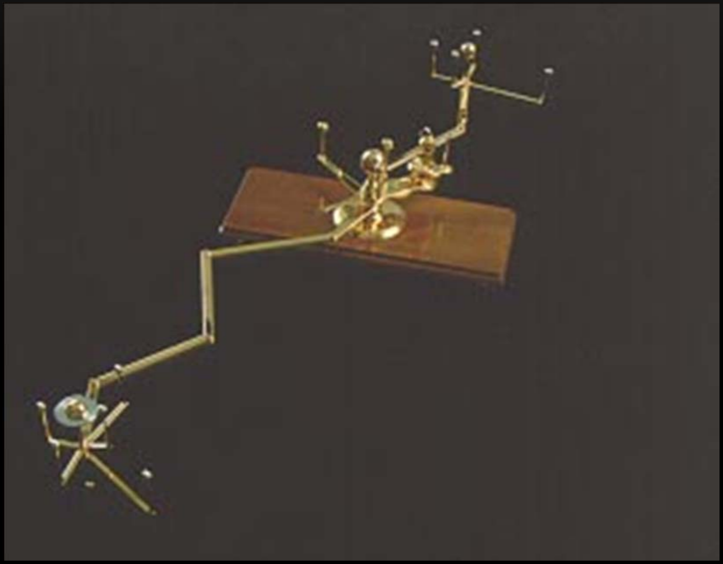
From last chapter

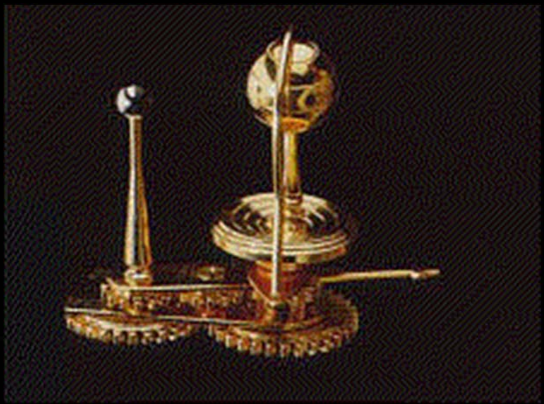
Fig.2.29

PTOLEMY

- Wrote Almagest around 150 AD
  - Elaborates *Ptolemaic* Model
  - Refines Aristotlean ideas
  - Builds a model of the sky's motions using Epicycles to account for planetary motion
  - Helpful to think of an actual model here:
    - Would this make a good *orrery*?

ORRERY

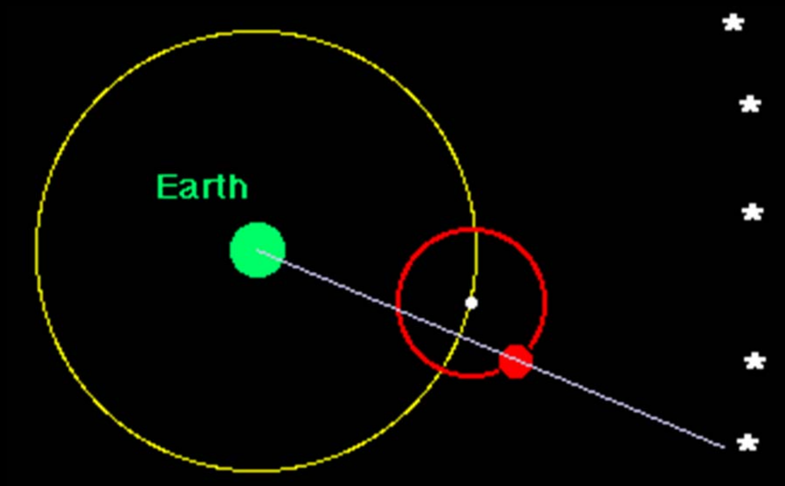




This Orrery from Van Cort Instrument Makers

- A mechanical model of the Solar System
- Shows relative motions of bodies, not their scale
- This one is heliocentric (not geocentric)

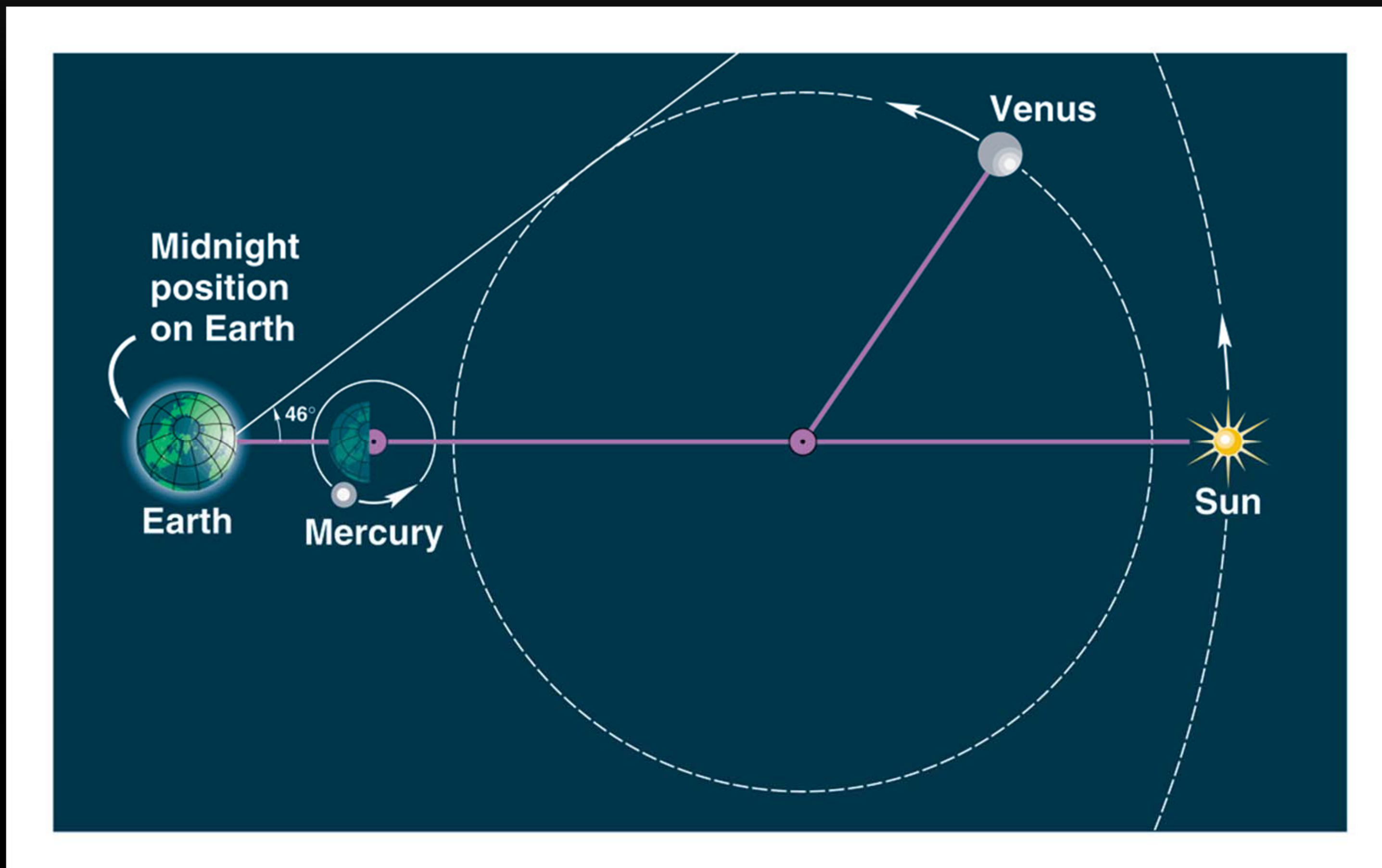
EPICYCLES



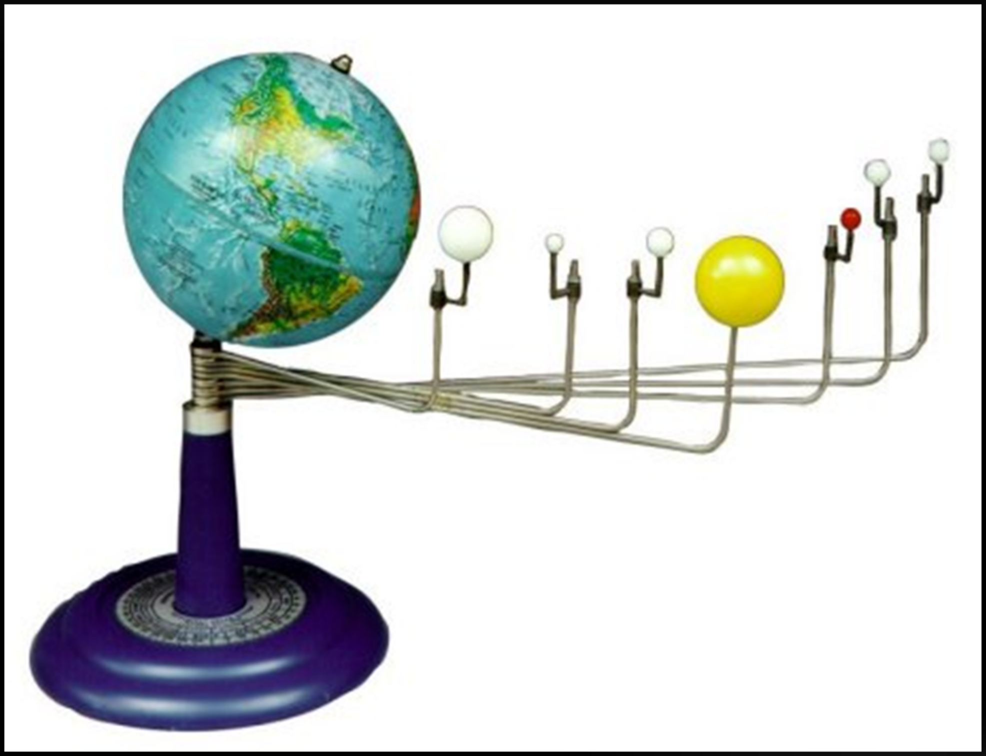
- A model of planetary motion to explain their movement across the sky

Animation from UTK

INFERIOR PLANET EPICYCLES



A PHYSICAL PTOLEMAIC MODEL



This Orrery from Trippensee Planetarium

- Geocentric
- Explains motions of the sky
- Uses only a few circles

PTOLEMY'S SUCCESSES

- Explains complex motions with simple geometry
- It lasts more than 1300 years before observers notice problems
- Quote from Almagest is interesting mixture of science and Aristotlean philosophy:
  - "Having set ourselves the task to prove that the apparent irregularities of the five planets, the sun, and the moon can all be represented by means of uniform circular motions, because only such motions are appropriate to their divine nature, … we are entitled to regard this accomplishment as the ultimate aim of mathematical science based upon philosophy"

CRITERIA FOR SCIENTIFIC MODELS

- The model must fit the data
  - Ptolemaic model well describes what's going on in the sky, almost to the limits observable with the naked eye
- The model must make predictions which allow it to be tested
  - Ptolemy predicts where objects will be at what time
  - Predicts that the earth is stationary
  - Note that prediction is not some magic future weather forecast – but simply the logical consequence of the model

CRITERIA FOR SCIENTIFIC MODELS

- The model should be aesthetically pleasing
  - This is harder to define and subjective
  - Today, should be simple, symmetric
  - Ptolemy's model *was* simple, symmetric, plus it fit in with Aristotlean and geometric ideals
- Ptolemaic model meets all these criteria, certainly better than alternatives available at the time (although, we will see, less well than later Heliocentric models)
- This model was universally accepted and well tested – a *theory*

A COMPETING MODEL

- Aristarchus (~280 BC) proposes Heliocentric model
  - Similar to today's Copernican model
  - More aesthetic (even Ptolemy said so)
    - Fewer circles, no special cases (inferior vs. superior planets, for instance)
  - Problem – Didn't agree with observations
    - Moving Earth predicts parallax
    - Moving Earth would mean a great wind

PTOLEMY AND PARALLAX

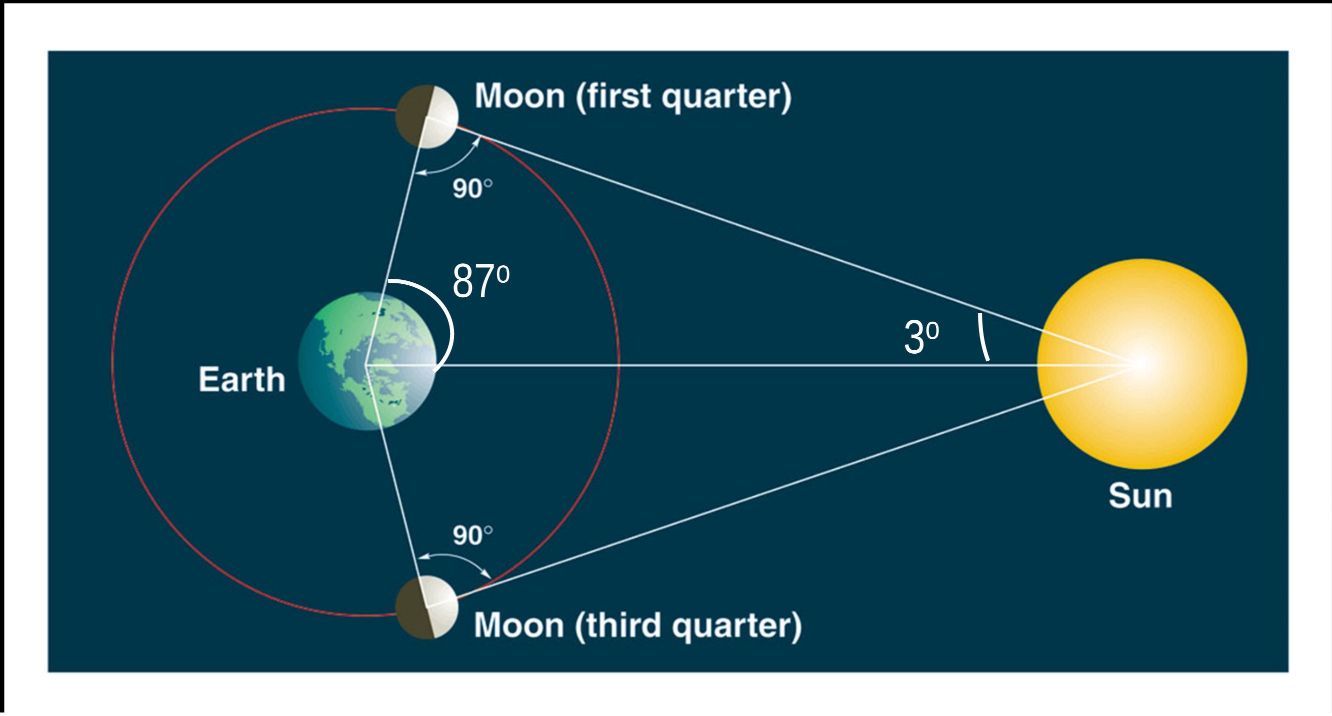
- Ptolemy observed the parallax of the Moon compared to the background stars – so he knew it worked
- How to see this?
  - In this case, it's not the Earth moving
  - It's you moving to a different spot on the Earth!
  - The moon is close enough so this is not hard to see
- But, no parallax of the stars were observed
  - They're further than the moon
  - But if the Earth was moving around the Sun, parallax of the stars should be seen!

EARTH/MOON/SUN SYSTEM

- However, Aristarchus did figure out the comparative sizes of Earth, Moon and Sun, and their distances, starting with the following model:
  - Moon goes around the Earth
  - Moon is lit by light from the Sun
  - Together, these explained phases of the moon
  - It turns out that the positions of Earth/Moon/Sun are the same in both geo- and heliocentric models

RELATIVE DISTANCE TO SUN

- For a half-lit moon, a right triangle is formed
- If you measure the angle between Sun and Moon, you can solve the triangle for distances



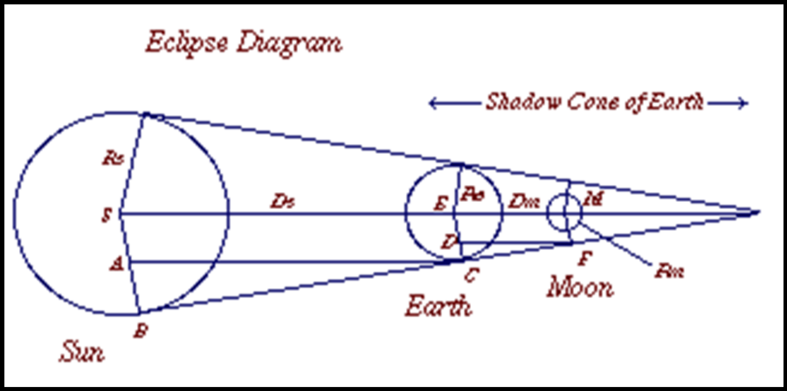
Measured 87°

Leaves 3°

So ratio of distances is sin(3°) or about 20x

Really is 89°50', 10', and 400x

RELATIVE SIZES OF EARTH AND MOON



- In Lunar Eclipse, the moon travels through the shadow of the Earth
- Aristarchus measured the angular size of the Sun to be 0.5^o
- The shadow of the Earth is about twice the size of the Moon (which is also 0.5^o wide)
- Uses diagram and geometry to conclude Earth is 3 times larger than Moon (*actually 3.7*)

RELATIVE SIZES OF MOON AND SUN

- Since both Moon and Sun are about the same size,
$$\frac{Radius : Moon}{Radius : Sun} = \frac{Dist : Earth - Moon}{Dist : Earth - Sun}$$
- Gets the Sun as 20x the size of Moon (actually 390, due to error in Earth/Moon distance)

ABSOLUTE SIZES

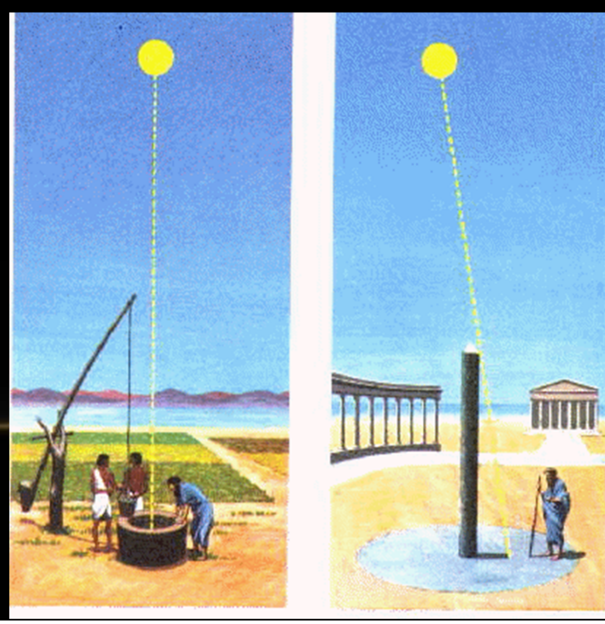
- For Earth/Moon/Sun system, Aristarchus has a good handle on relative sizes and distances
- Eratosthenes (~200 BC) calculates the radius of the Earth
- Compares position of Sun at two different places

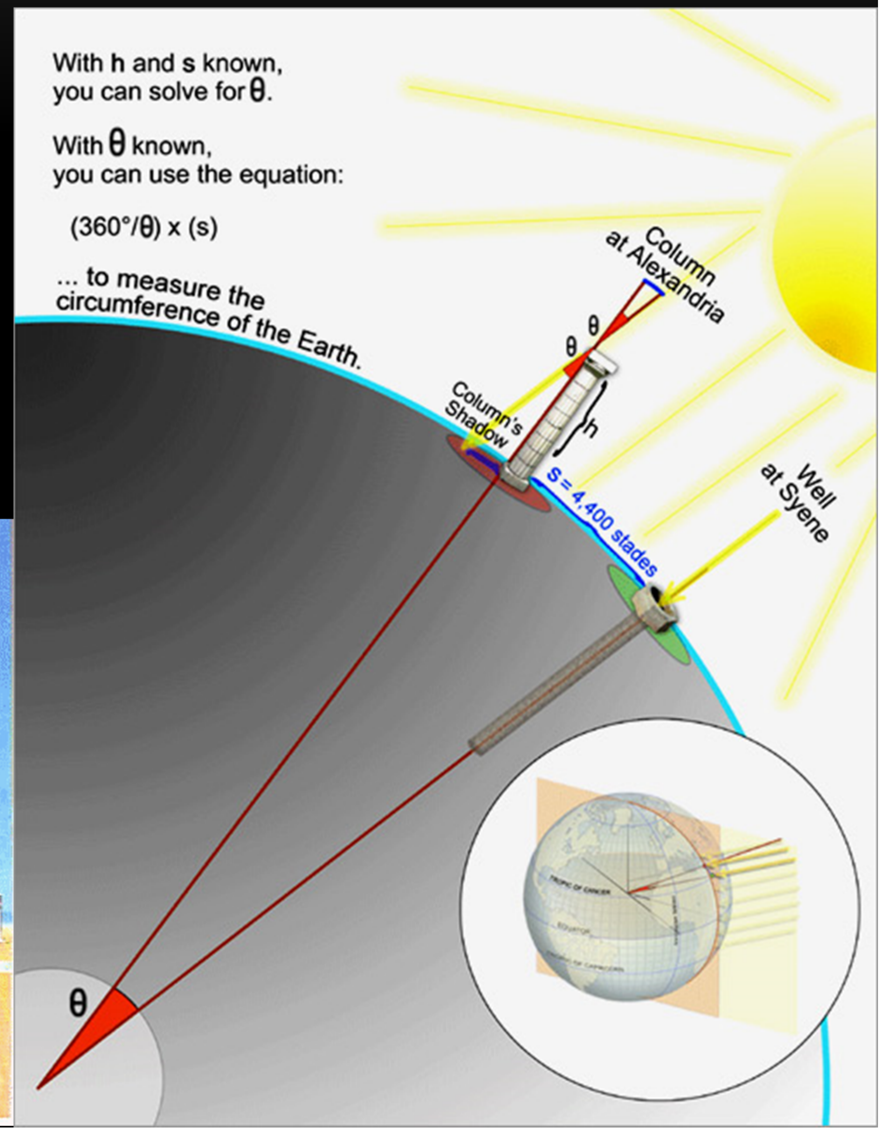
ERATOSTHENES' EXPERIMENT

- At noon during the summer solstice, the Sun shone directly down a well at Syene (*now Aswan, Egypt*) – so the sun was at the Zenith
- He measured that in Alexandria, the Sun was 7.2º away from the Zenith at the same time
- Applying more Geometry (the ancient Greeks were really into this):

ERATOSTHENES' EXPERIMENT

- 7^{o} is to 360^{o} as the distance between Syene and Alexandria (4400 stadia, or 830 km) is to the circumference of the Earth





Gets
Circ.=41,500 km
Or R=6600 km
(really 6378!)

THEM GUYS WEREN'T DUMB

- Ancient Greeks had a pretty good idea of what was going on in the solar system
  - Knew comparative sizes, distances
  - Knew Earth was round, and about how big
  - Had a model which worked well (Ptolemy's geocentric universe!)
    - Circles (orbits, epicycles) predict heavenly motions

COULD YOU DO BETTER?

- With the tools available to the ancients
  - Your eyes
  - No good clock other than the sky
  - No satellites etc.
- How could you test Ptolemy's theory?
- The answer – very precise observations
  - See if things keep holding up
  - Tycho Brahe was the last of a long line of astronomers who did this
  - Uncovered many small deviations from circularity which kept adding more and more epicycles

THE HELIOCENTRIC MODEL

Or, “Build a Better Mousetrap”

(err, “Model”)

ADJUSTMENTS TO PTOLEMAIC MODEL

- Predictions of planetary positions using the model would be off after a few centuries
  - Much like the Julian calendar!
- More epicycles were added (circles upon circles) and planetary positions reset to bring predictions in line with observations
  - Sort of like the tinkering with the leap-years and resetting calendars done by Pope Gregory

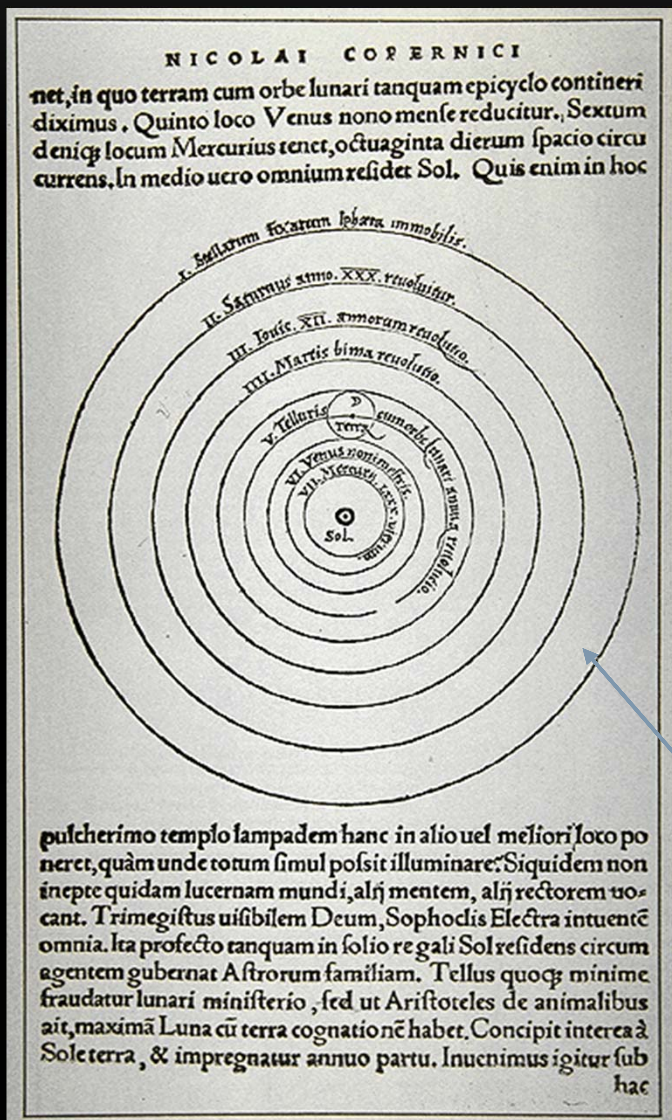
ASTRONOMICAL PROBLEMS IN 1500

- Predictions, such as eclipses, conjunctions, etc. were not precise enough
- New seafaring explorations needed better astronomical navigation
- The Julian Calendar was getting pretty far off

NICOLAUS COPERNICUS

- Polish scholar, Bologna alum, consulted for the Vatican on calendar reform
- Worries about the Ptolemaic Model:
  - Mars changed in brightness too much
  - Needed tweaking to stay accurate
  - Different setups for inferior/superior planets not very aesthetically pleasing
  - Religious reasons – Sun was source of light and life, so is more logically centered
- Read about Aristarchus' work, and spent 40 years refining it

THE COPERNICAN MODEL


NICOLAI COPERNICI

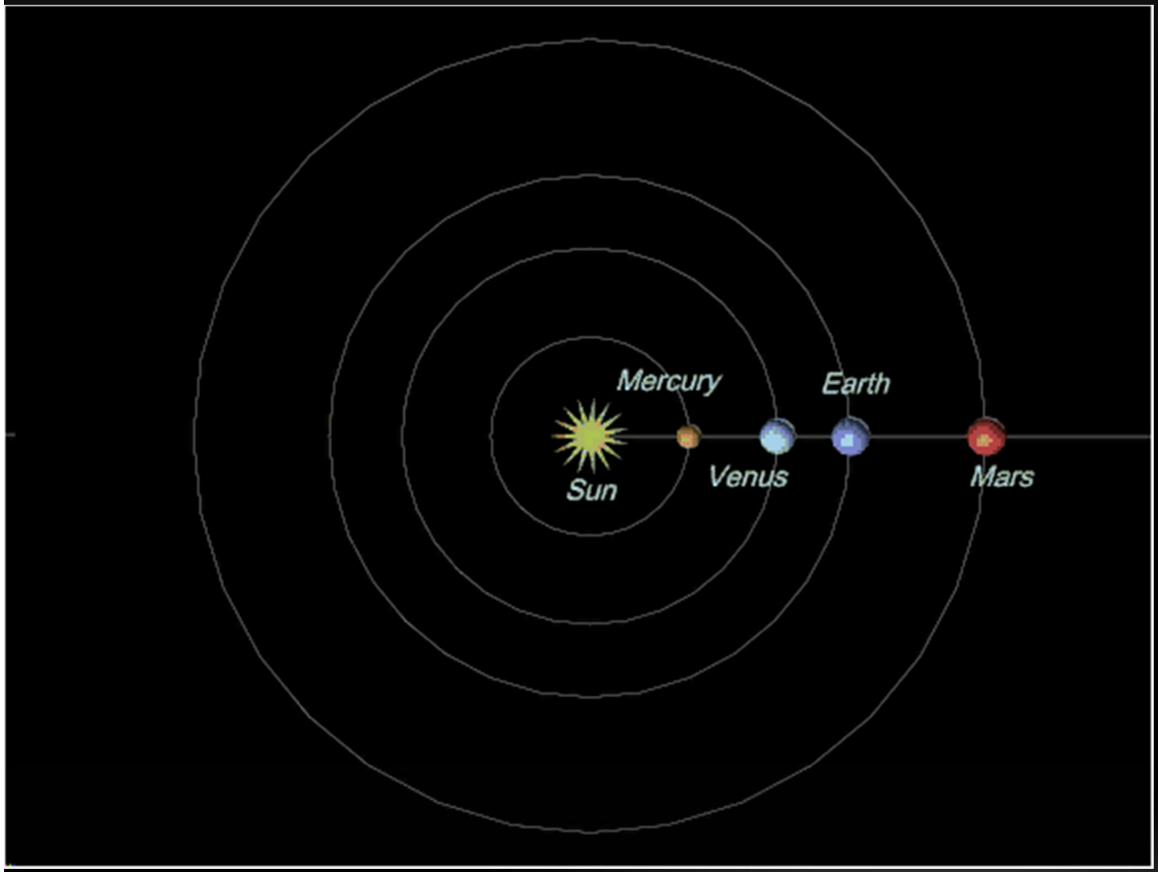
net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circu currens. In medio uero omnium residet Sol. Quis enim in hoc

pulcherimo templo lampadem hanc in alio uel meliori loco po neret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uo cant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

- <u>De Revolutionibus Orbium Coelestium</u> *("On the Revolutions of the Celestial Orbs")*
  - Published shortly before his death in 1543, and caused little controversy until 70 years later
  - Is Heliocentric (sun-centered)

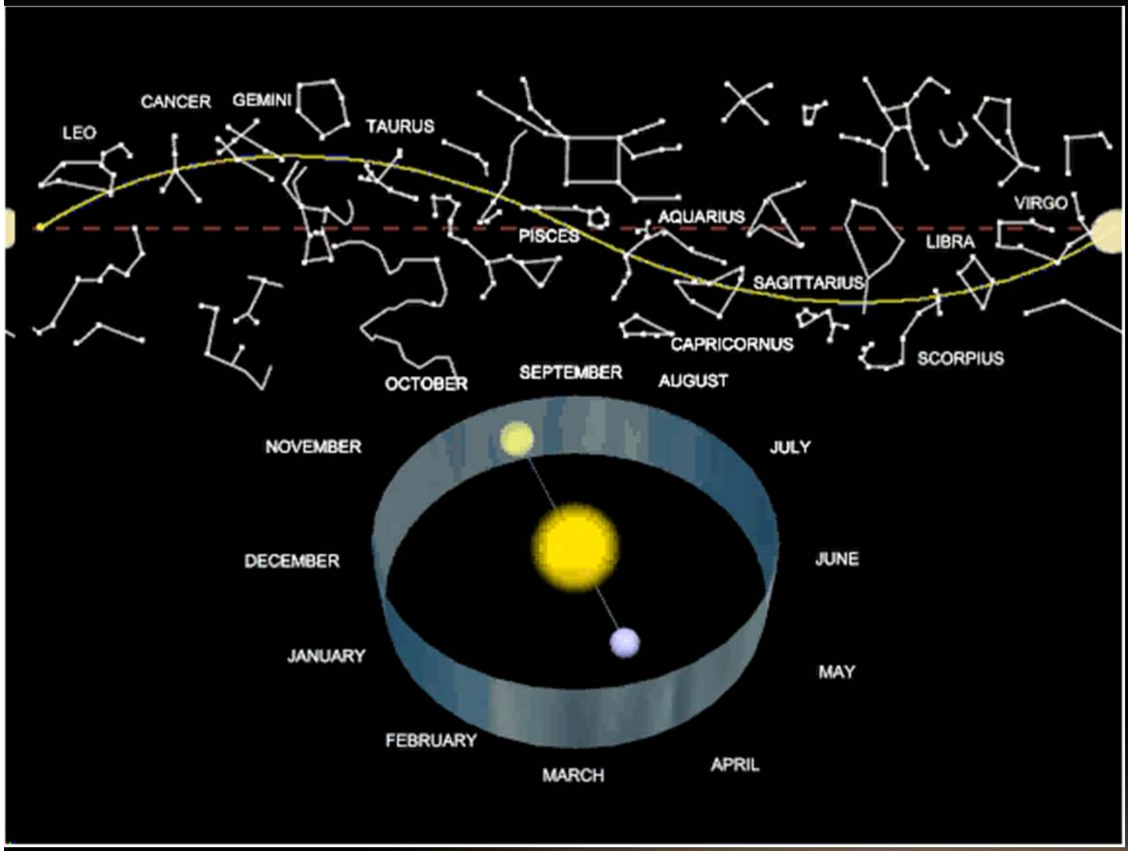
Note that the stars are still fixed on the celestial sphere!

THE COPERNICAN MODEL



- Earth rotates under stationary celestial sphere
  - Looks the same to us
  - No wind if the air is coming along for the ride
- Planets including Earth all revolve around stationary Sun in circular orbits

FEATURES OF THIS MODEL



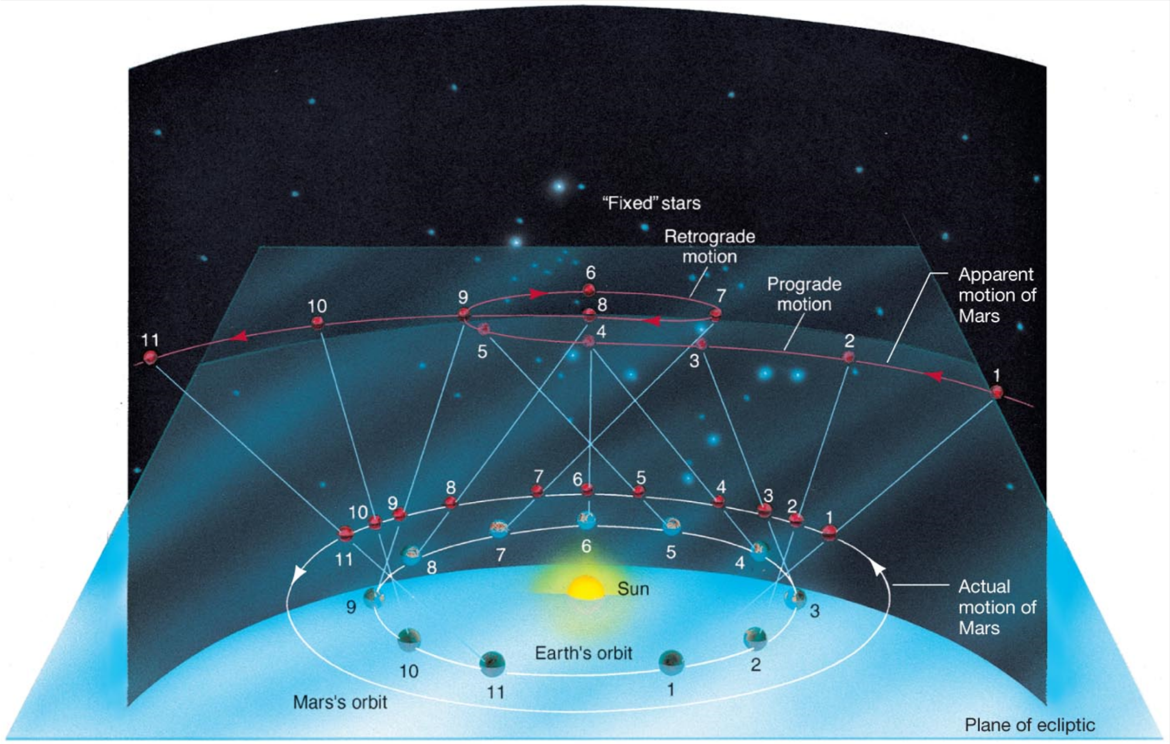
- Planets all revolve in same direction around sun
- Closer planets move faster
- Sun’s motion along zodiac seen to left, just a projection as Earth moves around
- Like Ptolemy, Copernicus makes specific calculations for future planet positions

TILT OF THE ECLIPTIC?

- Projected on the celestial sphere:
  - http://www.youtube.com/watch?v=2-TtcfmbrkI

- If Earth's rotation axis is tilted 23.5^{o} compared to the plane of its orbit, the solstices and equinoxes are explained

HOW ABOUT RETROGRADE MOTION?



- Ptolemy used epicycles to explain the backtracking
- Copernicus' model predicts retrograde motion as planets pass each other

HOW WELL DOES THIS WORK?

- Compare the three things a good model should have, first: <u>accuracy</u>
- The major motions are all there
- How about the precision?
  - Not much better than Ptolemy, actually
  - Circular orbits moved planets at constant rates, but in the sky they change speeds
  - Copernicus used small, slow epicycles to make it work better