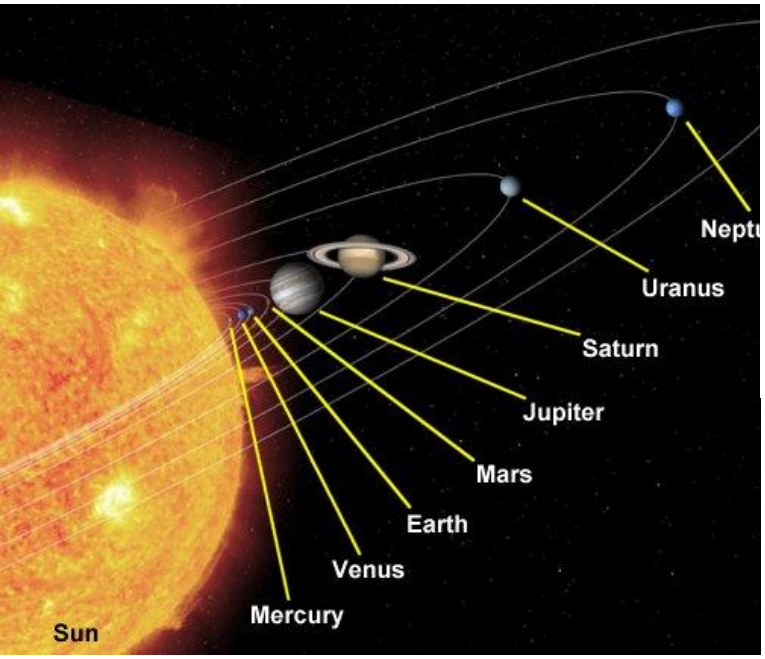
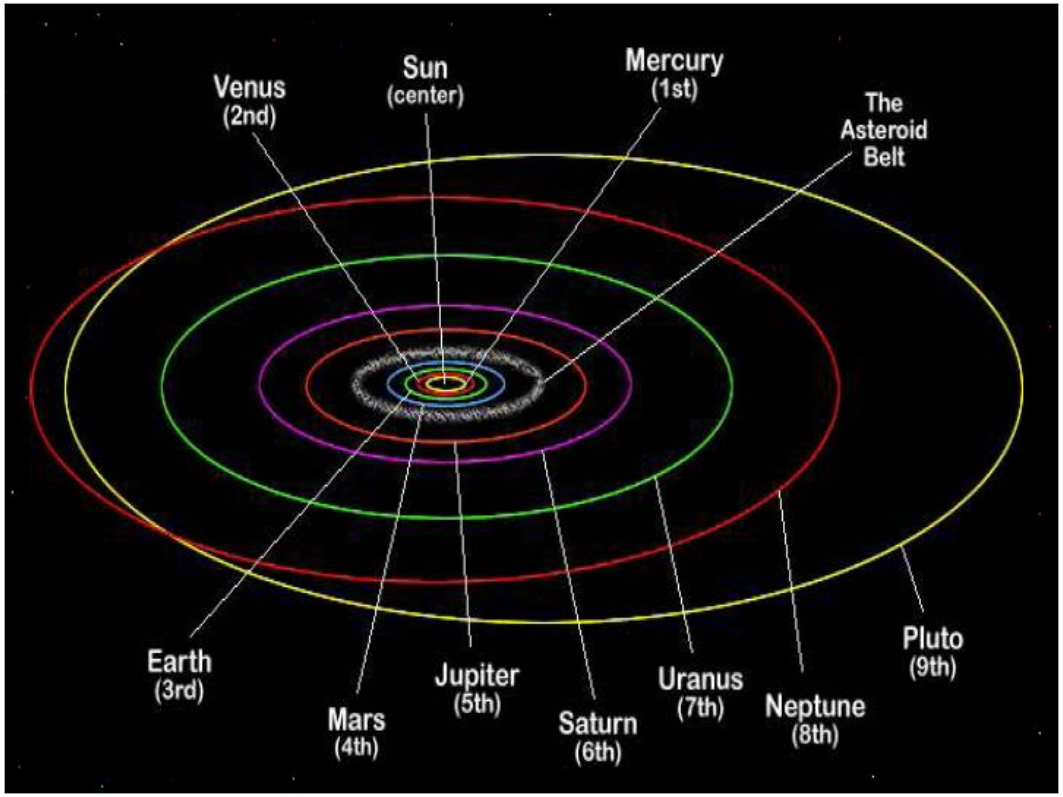
Solar System

- Sun plus 8 (or 9 with Pluto) planets many of which have moons
- plus “debris”: comets, asteroids, meteors, etc
- We’ll go over historical understanding of motion (which is “complicated” when viewed from the Earth) and later in the course look at Solar System formation, planetary atmospheres, and planets discovered in other star systems

Solar System





	Planet	Mass (kg)	Radius (km)	Density (g/cm^3)	Rotation Period (days)
1.	Sun	1.991×10^{30}	695,950	1.410	24.66
2.	Mercury	3.181×10^{23}	2,433	5.431	58.82
3.	Venus	4.883×10^{24}	6,053	5.256	244.59
4.	Earth	5.979×10^{24}	6,371	5.519	1.00
5.	Moon	7.354×10^{22}	1,738	3.342	27.40
6.	Mars	6.418×10^{23}	3,380	3.907	1.03
7.	Jupiter	1.901×10^{27}	69,758	1.337	0.41
8.	Saturn	5.684×10^{26}	58,219	0.688	0.43
9	Uranus	8.682×10^{25}	23,470	1.603	0.45
10.	Neptune	1.027×10^{26}	22,716	2.272	0.66
11.	Pluto	1.08×10^{24}	5,700	1.65	6.41

Sun vs Earth. (Moon has about ¼ Earth's radius)
100 times larger radius → 1,000,000 times larger volume and 300,000 times larger mass. Note all spin but Mercury and Venus have "long" days, almost with one side always facing Sun

Planetary Characteristics

	Mean Distance from Sun	**Sidereal Orbital Period**	**Mass**
	AU	$\boldsymbol{P_e}$	$\boldsymbol{M_e}$
Mercury	0.387	0.241	0.055
Venus	0.723	0.615	0.815
Earth	1.000 AU	1.000 year	1.000
Mars	1.524	1.881	0.107
Jupiter	5.203	11.857	317.828
Saturn	9.537	29.424	95.161
Uranus	19.191	83.749	14.536
Neptune	30.069	163.727	17.148

Have period=length of time to orbit Sun and mass relative to the Earth

Planets before telescopes

- Five planets can be seen without a telescope.
- As Earth and plants orbit Sun, the relative location of planets will change often with some not being visible during the night.
- Ancients (Babylonia, Hebrew. Not sure if Hebrew independent of Babylonian) included Sun and Moon as "planets" → Romans at time of Augustus gave names to 7 days of week, see in French. Chinese may have independently adopted 7 day week. Egyptians had 10 day week.

	FRENCH	ENGLISH
Sun	Dimanche	Sunday
Moon	Lundi	Monday
Mars	Mardi	Tuesday (Germanic)
Mercury	Mercredi	Wednesday (Germanic)
Jupiter	Jeudi	Thursday (Germanic)
Venus	Vendredi	Friday (Germanic)
Saturn	Samedi	Saturday

Planetary Motion

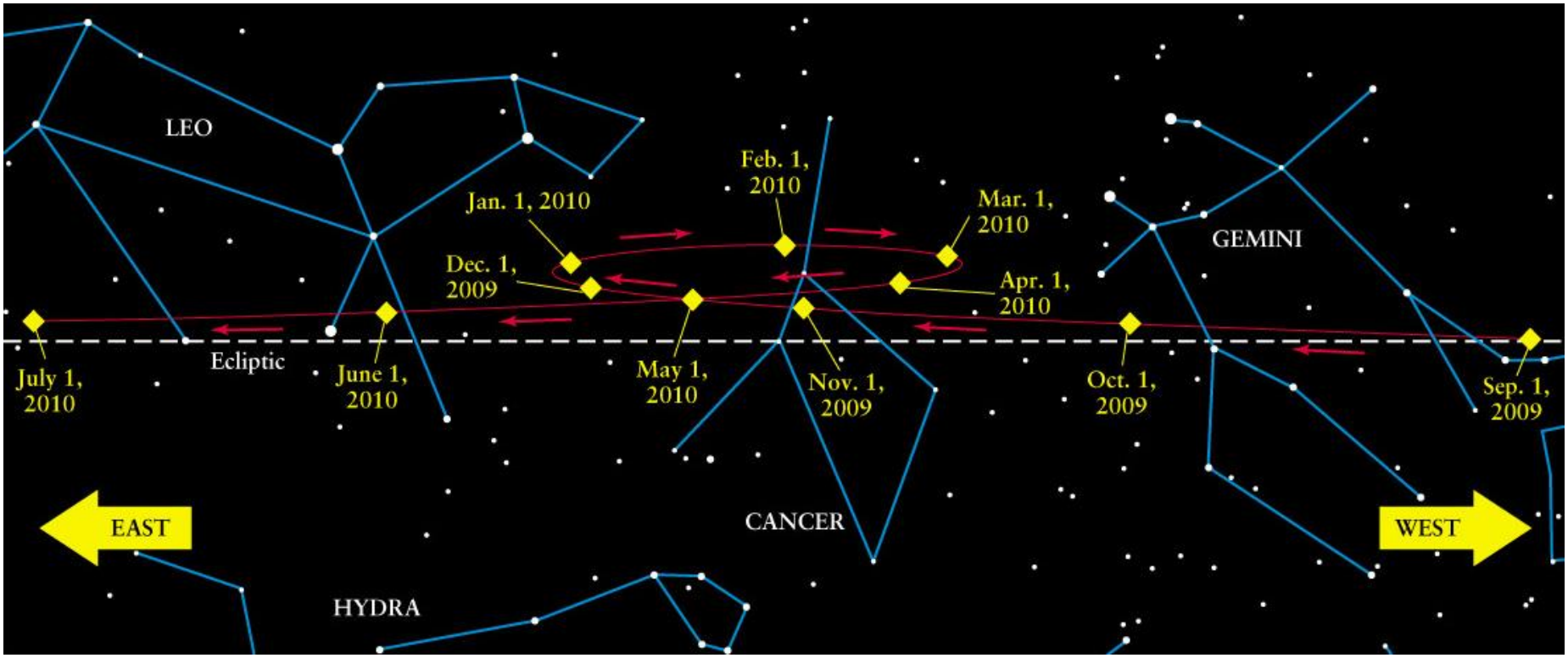
- Planets “move” relative to stars (Venus and Mercury always near Sun). Will be in different constellations each year – Assignment #1 gives examples.
- motion is “odd” as sometimes East to West but mostly West to East against the background of stars (E to W called retrograde motion)
- Historically large problem explaining planets’ motion; reality it is relatively simple: Venus and Mercury clearly orbit Sun as always close to Sun. Mars, Jupiter and Saturn can be close or distant from Sun in the Sky as further away from Sun than Earth and it takes a little bit more work to show they orbit Sun and not Earth

Planetary Motion - Historical

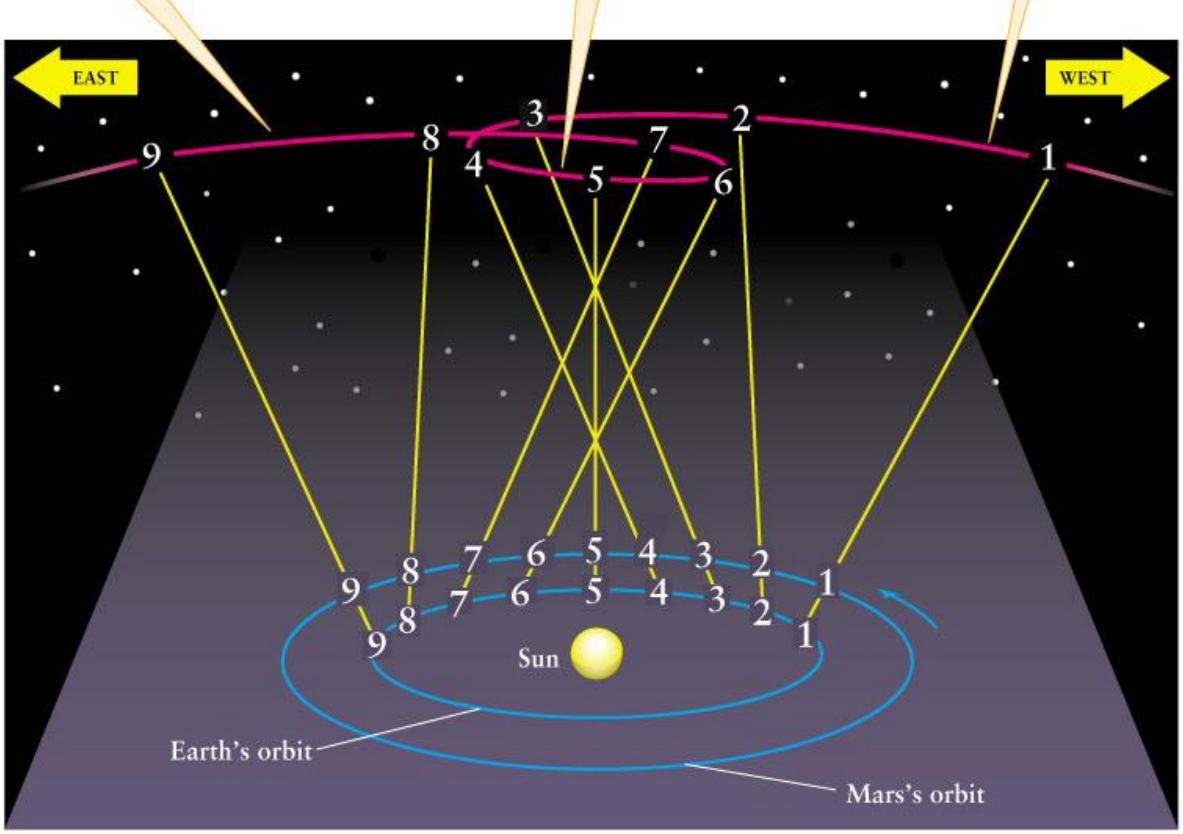
Archimedes

- "Classical" natural philosophers put philosophy/theology first and dismissed science/observations
  → obsessed by Earth being at center
  → obsessed by "perfect" objects like circles
- Perfectly symmetric Universe → **lifeless void**
- It is the asymmetries that allow our existence
- Confused by the physics of motion. Thought if the Earth were spinning we would all be "flung off" as didn't understand gravity and inertia until Galileo and Newton

Planetary Motion - Retrograde



- Mars (red line): Sept 2009 through June 2010. “moves” through constellations.



- Mars viewed from Earth changes what constellation is seems to be in
- easy to explain as it takes Earth 1 year to orbit Sun but Mars 1.9 years → sometimes Mars is "ahead" and sometimes "behind" Earth as they both move around the Sun

Models of the Solar System

Ptolemaic – Geocentric – Earth centered

- Earth at center and motionless. WRONG
- Sun and other planets orbit the Earth on circles within circles.

Copernican - Heliocentric – Sun centered

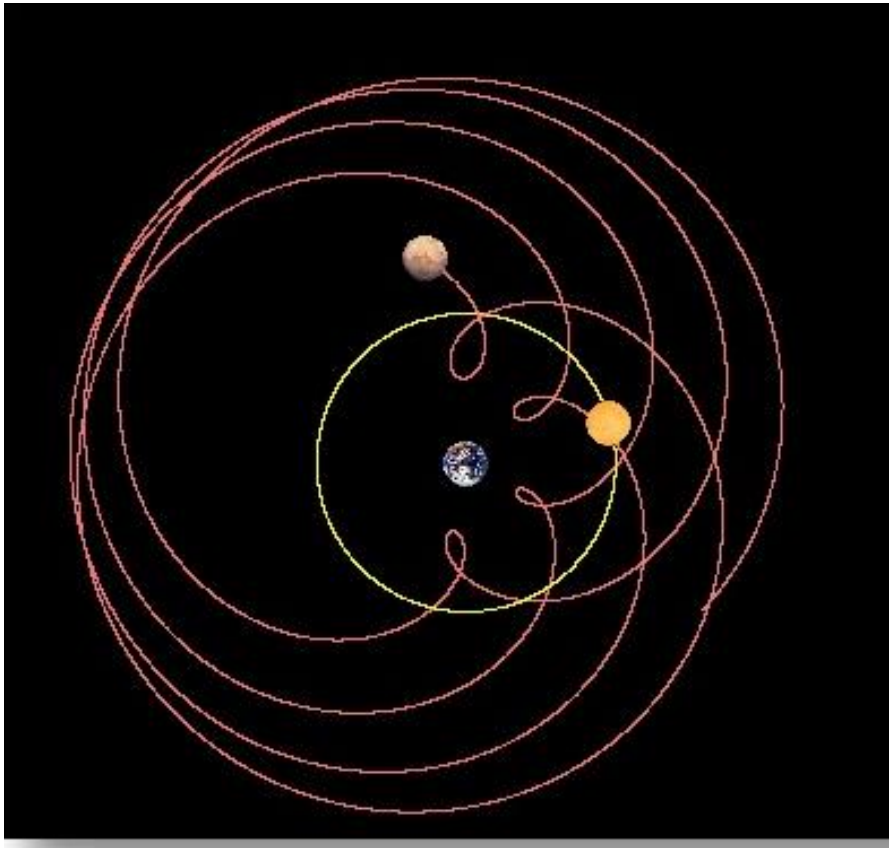
- Sun at center and motionless. Not quite right as Sun rotates/moves
- Earth and other planets orbit Sun. Still circles within circles but the secondary circles are smaller

Both models were considered by Greeks 2200 years ago - Aristarchus of Samos ~250 BC sun-centered, also guessed stars are like the Sun but just further away. Ptolemaic most familiar to Europeans in 1200s as it had survived and was relatively accurate in predicting where the planets would be. Use of experimental observations to resolve about 400 years ago helped start modern science

Models of the Solar System

Ptolemaic - Geocentric

- Earth at center and motionless. Picture shows Sun and Mars
- Sun and other planets orbit the Earth on circles within circles. (in modern eyes sort of wacky)



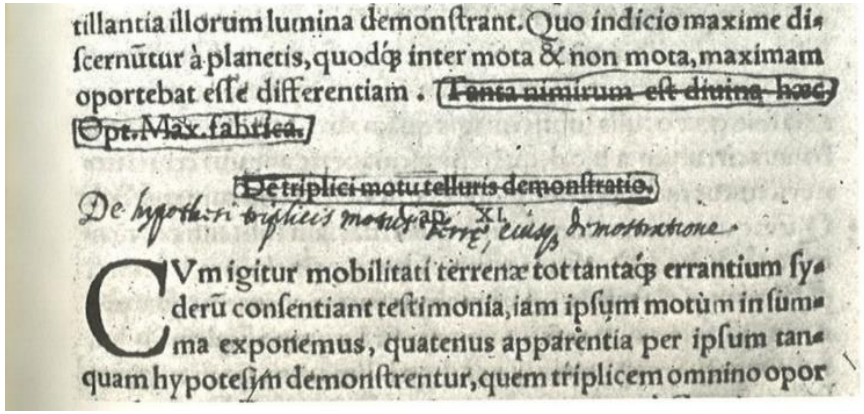
Think Tilt-a-Whirl at Cornfest

Venus and Mercury clearly orbit Sun. They are “circles within circles” about the Earth but their circles coincide with the Sun moving around Earth.

Copernican - Heliocentric

- Nicolaus Copernicus 1473-1543. Polish monk, Sun at center. Planets move about Sun on epicycles (circles on circles)
- Earth revolves on axis once per day
- Copernican model published in 1543 *De revolutionibus* with detailed comparisons to observations. Became well-known during the next 80 years, with many (~15) influential astronomers of the time accepting Sun-centered (Kepler, Galileo, Bruno, Rheinhold) though not completely accepted until Newton..

De revolutionibus is one of the most influential books in history (not just in science) Catholic Church placed on Index of Forbidden Books in 1616 and then censored in 1620. The parts with Sun at center needed to be inked over while the part that gave planet predictions could remain.
This is from Galileo's copy with the "forbidden" text inked over by Galileo himself.


tillantia illorum lumina demonſtrant. Quo indicio maxime di-
ſcernũtur à planetis, quodq; inter mota & non mota, maximam
oportebat eſſe differentiam. ~~Tanta nimirum eſt diuina hæc,~~
~~Opt. Max. fabrica.~~

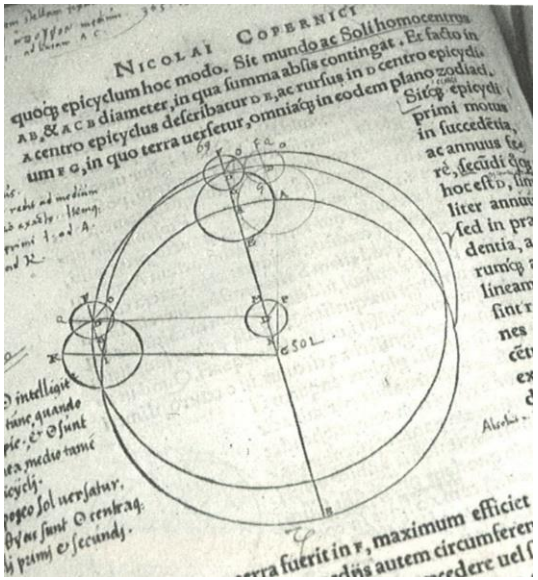
~~De triplici motu telluris demonſtratio.~~

De hypothesi triplicis motus terræ, eiusq; de motoxtione.

CVm igitur mobilitati terrenæ tot tantaq; errantium ſy-
derũ conſentiant teſtimonia, iam ipſum motũ in ſum-
ma exponemus, quatenus apparentia per ipſum tan-
quam hypoteſim demonſtrentur, quem triplicem omnino opor

Nicolaus Copernicus 1473-1543

- Polish monk. Studies canon law, math, astronomy, medicine at Universities of Krakow, Bologna, Padua. Exposed to Sun-centered ideas while in Italy (Nicole Oresme, Leonardo da Vinci who said “The sun does not move....the earth is not in the center of the circle of the sun, not in the center on the universe.”)
- Made some observations of Sun, Moon, planet locations and compared to Ptolemaic model predictions. Especially “easy” when plants were close to each other. Could do so with errors less than a degree. Moved to heliocentrism in about 1510, distributed a pamphlet, and others referenced in the 1530s. In 1541 he gave a copy of his major work *De revolutionibus* to Georg Rheticus (German astronomy professor) who arranged it to be printed in Nuremberg.



Copernican model from De revolutionibus . Sol is the Sun and one sees the circles needed to give the non-circular orbits of the planets.
Copernicus also included tables of planet locations and techniques to calculate their positions at future/past times which were more accurate then the Ptolemaic techniques.

Astrology vs astronomy vs astrophysics

- Astrology is a pseudoscience which claims to explain a person's personality and make predictions based on the positions of the planets, Moon, and Sun relative to the stars at different times (conception, birth, marriage). Deemed "real" until modern times by many.
- Astronomy is the science which marks where objects (stars, planets, etc) are and provides techniques to know where the objects were in the past or will be in the future. Both Ptolemy and Copernicus produced tables (using trig functions) on planet positions and techniques to calculate at different times. Astrologers used that information. Also in 1500s did medical doctors who learned their astronomy while at university.
- Astrophysics gives the underlying reason why planets, stars, etc have the motion observed by astronomers. Kepler was the first astrophysicist.

Copernican vs Geocentric vs Catholic Church

- Bruno was burned at the stake in 1600 in Rome partially for stating Copernicus was correct
- *"Innumerable suns exist; innumerable earths revolve around these suns in a manner similar to the way the seven planets revolve around our sun. Living beings inhabit these worlds."* — Giordano Bruno

Statue of Bruno

Campo d'Fiore Rome

also has farmer's market and 4 nice restaurants

Other Models

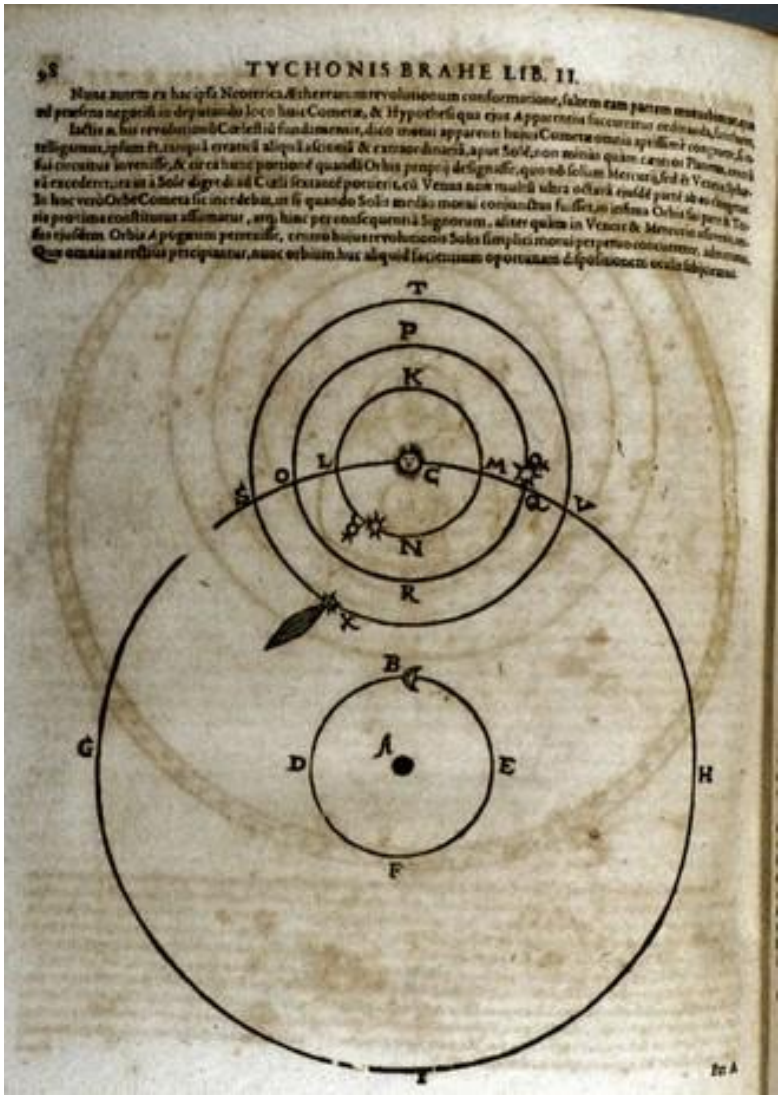
- Tycho Brahe's - Earth at center but other planets orbit the Sun →

Originally developed by Paul Wittich. Essentially the same as Copernicus except the Earth doesn't spin

- Kepler's - Sun at center with planets orbiting the Sun in elliptical paths CORRECT
- Differentiate models by comparing predictions with observations

SCIENTIFIC METHOD

need best observations as possible



A=Earth, B=Moon, C=Sun

Understanding Planetary Motion

- Use experimental observations (made prior to telescopes) to understand motion of the planets

- Leads to Kepler's 3 laws of planetary motion

- Provides experimental observations which are later explained by physics developed by Galileo, Newton and others

Brahe and Kepler →

statue in Prague

- Brahe led team which collected data on position of planets (1580-1600 no telescopes). "commuted" between observatory in Denmark and Prague. Died in 1601.
- Kepler (mathematician) hired by/succeeded Brahe to analyze data. Determined 3 Laws of planetary motion (1600-1620). Mostly funded by Holy Roman Emperor to provide horoscopes (astrology)
- Input - 20 years of data on:

angular position of planets

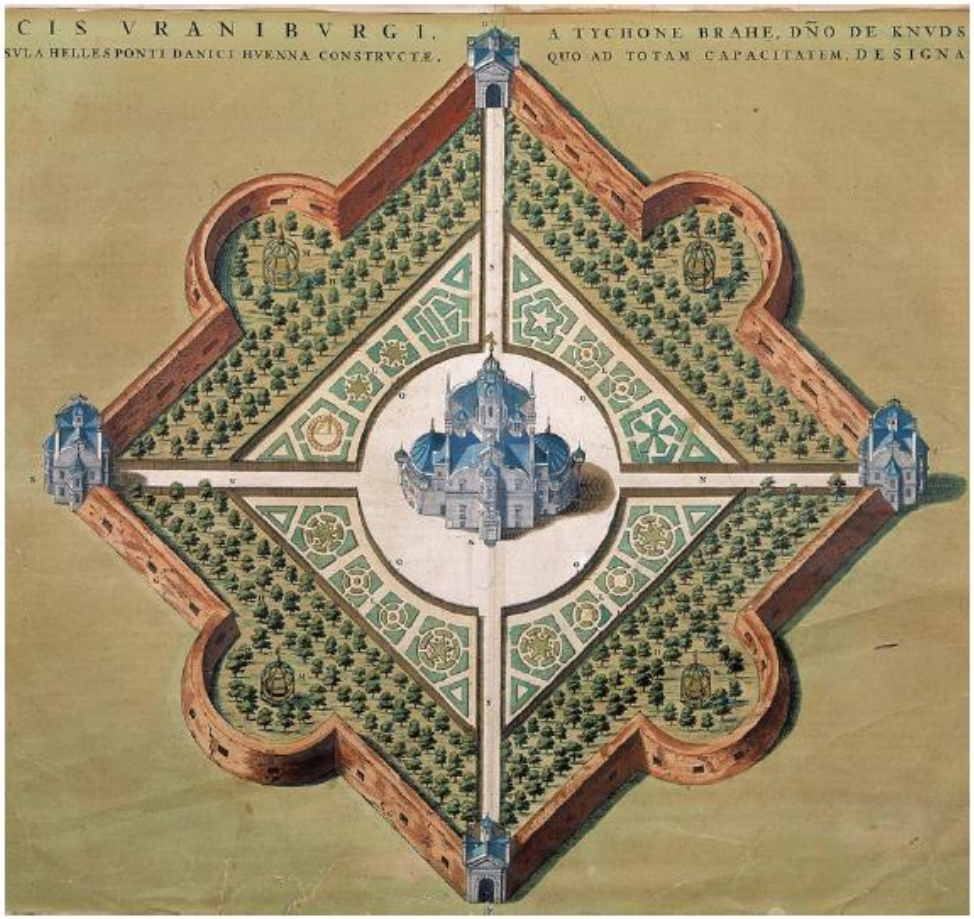
approximate distances from Earth (accurate relative distances)

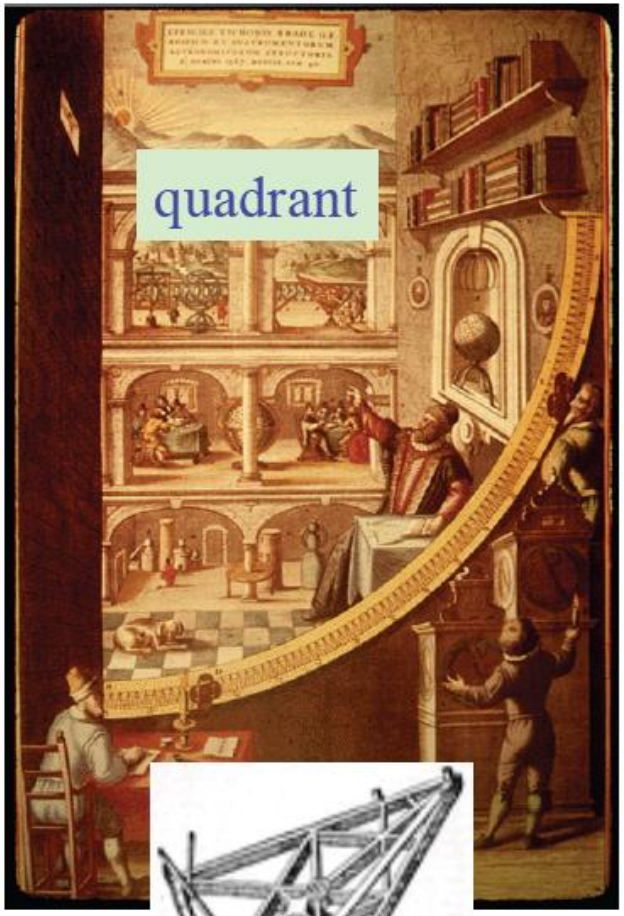
- Few "modern" tools (no calculus, no graph paper, no log tables) but we now know that repeated data taking improves accuracy by sqrt(N)

Observations of Brahe 1580-1600

- Brahe was a Danish nobleman who became famous after observing a supernova and showing it was “far away”
- Danish king provided funding and an island where Brahe set up an observatory – no telescopes just (essentially) sextants - that is long sticks to measure planet and star angles (positions in sky) which could be flipped to measure both E-W and N-S angle at same time

Brahe's Observatory



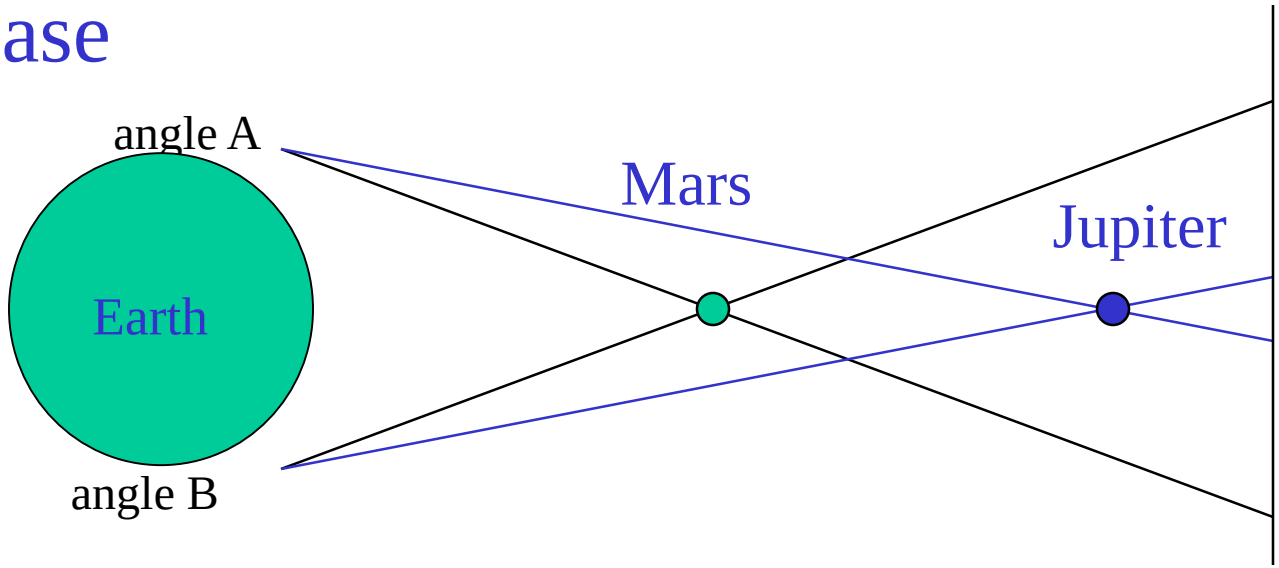


Apparent Shift = Parallax

- A moving observer sees fixed objects move.
- Near objects appear to move more than far objects
- The effect is due to the change in observation point, and is used by our eyes for depth perception.

Geocentric parallax-
Earth as base

Heliocentric parallax-use orbit about Sun as base. Use for stars as need telescope



Sources of Parallax

- Human eyes. Extend thumb out and have right eye open/left close and vice-versa. See how thumb “moves” compared to distant object
- Heliocentric parallax uses the sun as a base.
- Take a photo with telescope at two different seasons → come back to later for stars
- Geocentric parallax uses the earth as a base.
- Make a measurement two or more times in one night.
- Use for planets → Brahe’s data had (after analysis) distances to planets plus their position in sky

Extra Slides

Reaction to Copernicus

Michael Maestlin 1550-1631, German astronomer and mathematician primarily known for being the mentor of Johannes Kepler. In his copy of De revolutionibus he wrote: "the arrangement presented in this book is the sort of structure in which all the sidereal motions and phenomena are explained very exactly. Therefore the hypothesis recommends itself to the intellect." and "When he [Copernicus] noticed that the common hypotheses were insufficient, he [again Copernicus] eventually accepted the idea of the Earth's mobility, since indeed, it not only satisfied the phenomena very well but it didn't lead to anything absurd……Therefore, I think that unless the common hypotheses are reformed (a task I am not up to because of my inadequate abilities), I will accept the hypothesis and opinion of Copernicus – after Ptolemy. The prince of all Astronomers." From Gingerich, The Book Nobody Read.

The "common hypothesis" was the earth-centered Ptolemaic system. Note "inadequate abilities". Trigonometric functions are needed for these calculations and Ptolemy developed accurate tables for the chord function, which were improved by Copernicus. Copernicus' student Rheticus was probably the first in Europe to define trigonometric functions directly in terms of right triangles instead of circles, with tables for all six trigonometric functions. Wikipedia