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 (distances to Sun clearly not to scale)
Solar System – Orbits
Sun vs Earth. (Moon has about ¼ Earth’s radius)

100 times larger radius \(\rightarrow\) 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

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<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass (kg)</th>
<th>Radius (km)</th>
<th>Density (g/cm³)</th>
<th>Rotation Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sun</td>
<td>(1.991 \times 10^{30})</td>
<td>695,950</td>
<td>1.410</td>
<td>24.66</td>
</tr>
<tr>
<td>2. Mercury</td>
<td>(3.181 \times 10^{23})</td>
<td>2,433</td>
<td>5.431</td>
<td>58.82</td>
</tr>
<tr>
<td>3. Venus</td>
<td>(4.883 \times 10^{24})</td>
<td>6,053</td>
<td>5.256</td>
<td>244.59</td>
</tr>
<tr>
<td>4. Earth</td>
<td>(5.979 \times 10^{24})</td>
<td>6,371</td>
<td>5.519</td>
<td>1.00</td>
</tr>
<tr>
<td>5. Moon</td>
<td>(7.354 \times 10^{22})</td>
<td>1,738</td>
<td>3.342</td>
<td>27.40</td>
</tr>
<tr>
<td>6. Mars</td>
<td>(6.418 \times 10^{23})</td>
<td>3,380</td>
<td>3.907</td>
<td>1.03</td>
</tr>
<tr>
<td>7. Jupiter</td>
<td>(1.901 \times 10^{27})</td>
<td>69,758</td>
<td>1.337</td>
<td>0.41</td>
</tr>
<tr>
<td>8. Saturn</td>
<td>(5.684 \times 10^{26})</td>
<td>58,219</td>
<td>0.688</td>
<td>0.43</td>
</tr>
<tr>
<td>9. Uranus</td>
<td>(8.682 \times 10^{25})</td>
<td>23,470</td>
<td>1.603</td>
<td>0.45</td>
</tr>
<tr>
<td>10. Neptune</td>
<td>(1.027 \times 10^{26})</td>
<td>22,716</td>
<td>2.272</td>
<td>0.66</td>
</tr>
<tr>
<td>11. Pluto</td>
<td>(1.08 \times 10^{24})</td>
<td>5,700</td>
<td>1.65</td>
<td>6.41</td>
</tr>
</tbody>
</table>
### Planetary Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mean Distance from Sun (AU)</th>
<th>Sidereal Orbital Period</th>
<th>Mass ($M_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.241</td>
<td>0.055</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.615</td>
<td>0.815</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000 AU</td>
<td>1.000 year</td>
<td>1.000</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>1.881</td>
<td>0.107</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.203</td>
<td>11.857</td>
<td>317.828</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.537</td>
<td>29.424</td>
<td>95.161</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.191</td>
<td>83.749</td>
<td>14.536</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.069</td>
<td>163.727</td>
<td>17.148</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>FRENCH</th>
<th>ENGLISH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Sunday</td>
</tr>
<tr>
<td>Moon</td>
<td>Monday</td>
</tr>
<tr>
<td>Mars</td>
<td>Tuesday (Germanic)</td>
</tr>
<tr>
<td>Mercury</td>
<td>Wednesday (Germanic)</td>
</tr>
<tr>
<td>Jupiter</td>
<td>Thursday (Germanic)</td>
</tr>
<tr>
<td>Venus</td>
<td>Friday (Germanic)</td>
</tr>
<tr>
<td>Saturn</td>
<td>Saturday</td>
</tr>
</tbody>
</table>
Planetary Motion

- Planets “move” relative to stars (Venus and Mercury always near Sun). Will be in different constellations each year – Assignment #3 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

• “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
• Mars viewed from Earth changes what constellation it 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 Catholic Church adopts as “revealed truth” in 13th Century (when first Universities in Europe began).

• Earth at almost 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). Ptolemy modified this by putting the Earth off center → more accurate predictions

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. See in Assignment #3
Copernican - Heliocentric

- 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)
Locations of known copies of *De revolutionibus* in 1620. From Owen Gingerich *The Book Nobody Read* (also the source of the images in the next few slides).
Nicolaus Copernicus 1473-1543

- Polish monk. Studies canon law, math, astronomy, medicine at Universities of Krakow, Bologna, Padua. Was a student of astronomer Domenico Maria Novara da Ferrara. Practiced medicine when returned to Poland. 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.

- 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.
Copernican - Heliocentric

Copernican model from his book *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 than the Ptolemaic techniques.
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
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. Was also a mystic and “rabble rouser”

• "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
Lecture Feedback

E-mail me a few sentences describing one topic you learned from this set of presentations. Please include the phrase “Copernicus model of the Solar System put the Sun at the center and gave accurate predictions for the future positions of the planets” in your mini-report but do not use that as your “one topic”.