Early History of Astronomy

• We will follow the historical development of astronomy. Motivation:
  – Natural way to learn the subject
  – Demonstration of the method
  – Shows what we can learn without telescopes
Greek Astronomy

• Greeks were the first to recognize that the sky is three-dimensional. The sky has depth. This explains:
  – Phases of the Moon
Greek Astronomy

- Greeks were the first to recognize that the sky is three-dimensional. The sky has **depth**. This explains:
  - Phases of the Moon
  - Eclipses

Solar eclipse  Lunar eclipse
Solar Eclipse

Moon

Earth

sunlight
Lunar Eclipse

sunlight

Earth

Moon
Greek Astronomy

• Aristotle (384 – 322 BC) understood that the Earth is spherical
  1 Earth’s shadow during a lunar eclipse is always round
The Earth’s Shadow

Only a sphere produces a shadow that is always round.
Greek Astronomy

• Aristotle (384 – 322 BC) understood that the Earth is spherical
  1 Earth’s shadow during a lunar eclipse is always round
  2 Stars move towards southern horizon as you move north
Greek Astronomy

• Aristotle (384 – 322 BC) understood that the Earth is spherical

  1 Earth’s shadow during a lunar eclipse is always round

  2 Stars move towards southern horizon as you move north

  3 Elephants are found only in Morocco and India (they must be close together!)
African and Indian Elephants
Greek Astronomy

• Aristarchus (310 – 230 BC) measured the relative distances of the Sun and Moon and their relative sizes
Greek Astronomy

- Measure angle $\theta$ between Sun and first-quarter Moon.

\[
\cos \theta = \frac{A}{C}
\]
Greek Astronomy

• \( \theta = 89.85^\circ \); therefore \( \frac{C}{A} = 382 \).

\[
\cos \theta = \frac{A}{C}
\]
Greek Astronomy

The Sun and Moon have about the same angular diameter: they both subtend approximately $\frac{1}{2}^\circ$.

\[ \frac{a}{b} = \frac{A}{B} \]
Greek Astronomy

• By similar triangles,

\[ \frac{b}{a} = \frac{B}{A} = 382 \]
Greek Astronomy

- Aristarchus also determined that the Earth is about 4 times larger than the Moon.
  - This can be done by comparing the size of the Moon to the Earth’s shadow during a lunar eclipse.
Moon passing through Earth’s Shadow
Greek Astronomy

• Aristarchus thus knew:
  – The Sun is bigger than the Earth (his measurement said 10 times bigger; actual value closer to 100 times bigger).
  – Earth is about 4 times as large as the Moon
  – The Sun is much farther away than the Moon (his measurements said 40 times farther away; actual value closer to 400 times farther away).
  – First to propose a *heliocentric* system
Greek Astronomy

• Eratosthenes (276 – 195 BC)
  – Measured the size of the Earth to an accuracy of a few percent.
  – He did this by measuring the length of shadows at two places on the same day.
Tropic of Cancer
Syene
Tropic of Cancer

- At summer solstice, Sun passes through zenith on the Tropic of Cancer.

A vertical column casts no shadow when Sun at zenith.

To constellation Cancer
Eratosthenes Measurement

- At Alexandria, Sun is $7^\circ$ from zenith when Sun is overhead at Syene.
- Measure distance from Syene to Alexandria.
- Multiply by $360^\circ/7^\circ$ to get circumference of Earth.
- Answer correct to a few percent (though some uncertainty about units he used).
Greek Astronomy

- Hipparchus (160 – 125 BC) was the greatest of the Greek astronomers.
- He made several important and lasting contributions to astronomy:
  - catalogued star positions
Hipparchus

- Discovered *precession* by comparison of his measurements with older Babylonian measurements
- Precession causes nearly a 3° change in position of vernal equinox in 200 years

Period of precession is about 26,000 years
Hipparchus

- Established the magnitude system
  - brightest visible stars are first magnitude
  - faintest visible stars are sixth magnitude
- Refined the distance to the Moon
- Measured the length of the year (to within 6 minutes)
Hipparchus

- Explained the visibility of eclipses
  - why doesn’t everyone see a Solar Eclipse when it occurs?
Ptolemaic Astronomy

• Claudius Ptolemy (90 – 168 AD) : the first authoritative compilation of Western astronomy with the “Almagest” (“The Greatest”).
• Introduced a sophisticated *geocentric* (Earth-centered) model to account for retrograde motion of the planets.
  – Note: Uranus, Neptune, Pluto unknown to pre-telescopic astronomy
Sun and Moon move around equant at constant angular speed.
Planets move on epicycles, which move on deferents.

Apparent motion on inner part of epicycle is retrograde.
The Ptolemaic Universe
Ptolemaic Astronomy

• Motivation for geocentric models
  – Cannot feel the motion of the Earth.
  – Philosophical reasons, sense of Earth’s importance and centrality.
  – *Stellar parallax not observed.*
The Birth of Modern Astronomy

- Flaws in the Ptolemaic system
  - Uniform circular motion only approximates motions. Over centuries, errors accumulate.
  - Position of Earth away from center compromises geocentrism.
  - Planets circle around imaginary points in space: what holds them there?
The Copernican Revolution

- Nicolaus Copernicus (1473 - 1543) introduced a *heliocentric* (Sun-centered) model.

- Uniform circular motion led to same accuracy problems as Ptolemy, but a simpler description.
Retrograde Motion in the Copernican Model

Ptolemaic model

Copernican model

Retrograde Motion in the Copernican System
The Copernican Revolution

• In Copernican model, observer moves as well. Relative positions of planets occur in certain important configurations.

• These configurations are important to understand because they allow us to determine the sizes of planetary orbits by using simple geometry.
Copernican Definitions

- **Inferior planets**: those with smaller orbits than the Earth’s
  - Mercury and Venus
- **Superior planets**: those with larger orbits than the Earth’s
  - Mars, Jupiter, Saturn
  - later Uranus, Neptune, and Pluto
Configurations of Superior Planets

• *Opposition*: Earth lies between Sun and planet. From Earth, Sun and Planet are 180° apart.
Opposition

Observer on Earth sees planet transit meridian at midnight
Configurations of Superior Planets

• **Opposition**: Earth lies between Sun and planet. From Earth, Sun and Planet are 180° apart.

• **Conjunction**: Sun lies between Earth and planet. From Earth, Sun and Planet are 0° apart.
Conjunction

Planet is not actually observable, since it is in the daytime sky.
Configurations of Superior Planets

• **Opposition:** Earth lies between Sun and planet. From Earth, Sun and Planet are 180° apart.

• **Conjunction:** Sun lies between Earth and planet. From Earth, Sun and Planet are 0° apart.

• **Quadrature (eastern or western):** Planet and Sun 90° apart as seen from Earth.
Western Quadrature

Planet is high in the sky at sunrise.
Planet is high in the sky at sunset.
Configurations of Inferior Planets

• Two conjunctions with the Sun:
  – *inferior conjunction*
    • planet lies between Sun and Earth
Inferior Conjunction

Planet is usually not observable, but sometimes can be seen transiting the face of the Sun.
Transit of Mercury
2003 May
Configurations of Inferior Planets

- Two conjunctions with the Sun:
  - *inferior conjunction*
    - planet lies between Sun and Earth
  - *superior conjunction*
    - Sun lies between planet and Earth
Superior Conjunction

Earth

Planet is not observable.
Configurations of Inferior Planets

- Angle from Sun is called *elongation*
  - Maximum value is *greatest elongation*
Western Elongation

Earth

$\theta$

Elongation
Greatest Western Elongation

Line of sight to planet is tangent to planet’s orbit
Greatest Eastern Elongation

Earth
Planetary Periods in the Copernican Model

- **Sidereal period**: The period of a planet’s rotation or revolution relative to the fixed stars.
- **Synodic period**: The period of a planet’s rotation or revolution as seen from Earth. Motions in the sky are measured relative to the position of the Sun.
Jupiter at opposition

Six months later

One year later

Jupiter returns to opposition after one synodic period, about 13 months
Relationship Between Sidereal and Synodic Periods
Orbits and Orbital Periods

<table>
<thead>
<tr>
<th>Planet</th>
<th>Semi-major axis (AU)</th>
<th>Orbital Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.241</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.615</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>1.881</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.202</td>
<td>11.867</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.539</td>
<td>29.461</td>
</tr>
</tbody>
</table>
Galileo: The First Modern Scientist

- Galileo Galilei (1564-1642)
  - First modern *experimental* physical scientist
  - Carried out experiments to study nature rather than appealing to authority (i.e., Greek philosophers, especially Aristotle)
  - Invented the field of mechanics (the science of moving bodies)
  - First to use telescope as a scientific instrument
Discoveries of Galileo

- Four brightest moons of Jupiter
  - Io, Callisto, Europa, and Ganymede are still known as the “Galilean moons”
Discoveries of Galileo

- Craters, mountains, and plains on the Moon
  - Called the lowlands “maria” (seas)
Discoveries of Galileo

- Phases of Venus
  - Venus undergoes the same phases as the Moon.
Discoveries of Galileo

- The “Milky Way” is comprised of faint stars
Discoveries of Galileo

- Planets are disks, stars are points

Mars through a small telescope
Discoveries of Galileo

- **Sunspots**
  - These are known to be regions of high magnetic activity and relatively lower temperature.
  - Showed that the Sun is a fluid body, not a solid.
Discoveries of Galileo

- Irregular shape of Saturn
  - His telescope was not high enough quality to show the extensions are rings.
Discoveries of Galileo

• Some of Galileo’s work undermined the Ptolemaic model
  – Moons of Jupiter
    • Jupiter moves, and its satellites move with it. Earth is not the center of the satellite’s motion (at odds with the Aristotelian view).
  – Phases of Venus
    • Venus must orbit the Sun for all phases to be visible from Earth
Ptolemy vs. Copernicus

• Both the Ptolemaic and Copernican model could explain the motions of the Sun, the Moon, and the planets.
• The Ptolemaic model could even be modified to let Venus (and Mercury) go around the Sun.
• Why should one believe that the Earth is in motion rather than the Sun?
Ptolemy vs. Copernicus

• The great virtue of the Copernican model is its simplicity.
The Principle of Occam’s Razor

The simplest description of Nature is most likely to be most nearly correct.
The Principle of Occam’s Razor

• Corollary: Every description of Nature should be as simple as possible.
• As noted by Einstein: “not too simple”
  – some things shouldn’t be oversimplified
The Conflict Between Science and Religion: The Galileo Affair

• Some of Galileo’s work placed him at odds with the Church.
  – While neither Aristotelian nor Ptolemaic thought were Catholic dogma, both were generally accepted and had been incorporated into a world view.
  – Galileo is sometimes portrayed as a “martyr for science”, which is a naïve interpretation.
The Galileo Affair

- The confrontation between Galileo and the Catholic Church was unnecessary and entirely avoidable.

- Why did it happen?
  - Galileo: confrontational personality, arrogant. Would bait other scholars, who might often be clergy.
  - Church: in the midst of the “counter Reformation”, defending itself against both criticism and heresies.
The Galileo Affair

• In 1611, after publication of his telescopic discoveries in “De Revolutionibus”, Galileo was initially received warmly at the Vatican, notably by Pope Paul V.

• Not everyone was convinced; some even refused to look through his telescope.
  – Virtually all scholars were clergy, and their education in physics was Aristotelian.
  – Relative to the business of saving souls, the nature of the Universe seemed unimportant.
The Galileo Affair

• In 1616, Galileo again went to Rome for an audience with Robert Cardinal Bellarmine.
  – Leading Church official and Aristotelian scholar
  – Named “Doctor of the Church” for his defense of the Church against Protestant challenges.
  – Articulated the Church’s position on science, which essentially drew on St. Augustine (354 – 430).
The Galileo Affair

• Cardinal Bellarmine ordered Galileo not to “hold or defend” the Copernican theory, though it might be discussed as a “mathematical supposition”.
The Galileo Affair

- Galileo openly defied this with the 1632 publication of “Dialog on the Two Chief World Systems”
  - Church leaders saw this as a challenge to their authority.
  - Pope Urban VIII saw it as a personal affront
The Galileo Affair

- In 1633, Galileo was summoned to Rome by the Inquisition.
  - Issue was not the Copernican theory, but whether Galileo had disobeyed Bellarmine’s instruction not to “hold or defend” or to teach it in any way whatsoever (note difference from previous position).
  - Charges: disobeyed Bellarmine (died 1621) and misled censors who published his book.
  - Evidence: a document that showed the order.
The Galileo Affair

• Pope John Paul II reopened the Galileo case and in 1992 declared that the Church had erred in condemning Galileo.

• Why did it take so long?
  – Issue was of authority and obedience, not science
  – The document in evidence against Galileo, still in the Vatican archives, was determined to be a forgery. Neither Bellarmine nor Galileo had signed it.
The Galileo Affair

• The bottom line was that Galileo was framed by his enemies.
• Bellarmine in fact probably protected Galileo from worse harm from his enemies.
• The Church’s error was not in refusing to accept the Copernican theory, but in allowing itself to be used by Galileo’s enemies.
Beyond the Copernican Model

• Tycho Brahe (1546-1601)
  – Made accurate positional observations of stars and planets to accuracy of about 1 arcminute (1/30 the diameter of the full Moon).
  – Did not detect stellar parallax, so did not believe in Copernican model.
• Stellar parallax was not detected until about 1860 because it is so small (< 1 arcsecond) even for nearest stars.
Beyond the Copernican Model

- Johannes Kepler (1571-1630)
  - Tycho’s assistant
  - Used Tycho’s observations to formulate laws of planetary motions
Kepler’s Laws

• First Law: Planets travel in elliptical orbits, with the Sun at one focus.
Kepler’s Laws

- Second Law: A line drawn between the Sun and a planet sweeps out equal areas in equal time intervals.
  - Planets move faster in the orbits near perihelion
Kepler’s Second Law
Kepler’s Laws

• Kepler’s Third Law
  – $P$ = sidereal period of revolution
  – $a$ = semimajor axis of orbit
  – $k$ = a constant that depends on the mass of the system

\[ P^2 = ka^3 \]
Kepler’s Laws

• In the Solar System, we measure $P$ in years, and $a$ in Astronomical Units, and thus $k = 1$.

\[ P^2 = a^3 \]
## Orbits and Orbital Periods

<table>
<thead>
<tr>
<th>Planet</th>
<th>Semi-major axis (AU)</th>
<th>Orbital Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.241</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.615</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>1.881</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.202</td>
<td>11.867</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.539</td>
<td>29.461</td>
</tr>
</tbody>
</table>
Proof of the Earth’s Motion

1. Rotation ($P = 23^h 56^m$)
   - Earth rotates *eastward* (i.e., west to east) on its axis.
   - Proof:
     • Foucault pendulum
     • Coriolis forces
Foucault Pendulum

- A large mass suspended by a wire oscillates in a single plane (Newton’s First Law).
- The Earth rotates underneath the Foucault Pendulum
Coriolis Forces

- Coriolis forces cause deflections to the right in the northern hemisphere (counterclockwise hurricanes), and to the left in the southern hemisphere.
Proof of the Earth’s Motion

2. Revolution \( (P = 1 \text{ year}) \)
   - The Earth revolves around the Sun, counterclockwise as seen from above the North Pole.
   - Proof:
     - Aberration of starlight
     - Stellar parallax
     - Periodic Doppler shifts of stars
Aberration of Starlight
Stellar Parallax

- **Parallax** is the apparent motion of nearby stars due to the motion of the Earth around the Sun.
Annual Periodicity in Doppler Shifts of Stars