The size of our solar system, galaxy, and Universe
• The Light Year \(10^{13}\) km as a fundamental distance unit
• Universe is mostly empty space (density = \(10^{-23}\) g/cm³)
• Composition: 75% hydrogen; ~24% helium; < 1% “impurities”
• we are mostly “star stuff” produced in stars and supernovae
• Time scales of the Universe (age ~ 13.6 billion years)

Composition:
75% hydrogen; ~24% helium; < 1% “impurities”

Astronomy as a catalyst for modern Science
• by watching the skies, humankind eventually uncovered the basic laws that govern the motions of the planets, stars, and galaxies
• Using Newton’s laws, we can measure the most fundamental property of things in the Universe - their mass
• Gravity and light are the two ‘messengers’ that astronomers use to learn about the Universe

Occam’s Razor:
William of Occam, 1340(!)
“We take as Truth the simplest explanation that fits all of the data.”
This is the fundamental principle of all modern science

The Early Days...
• Prehistoric Discoveries
  • Motivation: Calendar = survival
    Cosmology = order = higher being
  • Ecliptic + Zodiac paths of planets and Sun
  • Solstice seasons
  • Saros cycle eclipses
• Early Science: The (500 BCE - 150 CE)
  • spherical Earth (Pythagoras)
  • model of celestial motion (Aristotle)
  • relative dimensions of Sun, Moon, Earth (Aristarchus)
Ancient Calendars and Calculators

- Ecliptic / Equinox / Eclipse marker: Stonehenge

- Chichen Itza, Yucatan (Mexico): Annual

Philosophy + some observation culminated in

- Ptolemy’s computational scheme for celestial motion
  - Earth -centered
  - Uniform, circular Motion
  - Epicycles

1200s: Ptolemy’s method off by several degrees
  - response: add more epicycles . . .

1543: Copernicus
  - moved sun to center ----> Revolutionary!

1580: Tycho Brahe
  - precise positions of planets
  - stars are fixed, therefore very distant
  - sky is not immutable

1609: Galileo
  - astronomer: telescopic studies show Copernicus was right
  - physicist: experiments with Gravity
Looping Planets

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Brahe’s Tools and Ideas
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1610 - Johannes Kepler
mathematician and klutz

used Tycho’s data on the motion of Mars:
with no circular motion bias
to discover

Kepler’s Laws
of Planetary Motion

These are simple empirical laws explaining
planetary motion, derived from data only,
with no preconceptions.
Kepler’s Law #1
• Planets orbit the sun in **ELLIPtical** orbits around the sun, with the sun at one ‘focus’ of the ellipse.
  • non-circular motion

Kepler’s Law #2
• A line joining the planet to the Sun sweeps out **equal areas in equal times**... so planet moves faster when closer to the Sun
  • non-uniform motion

Kepler’s 3rd Law

<table>
<thead>
<tr>
<th>Planet</th>
<th>P[y]</th>
<th>a[a.u.]</th>
<th>$p^2$</th>
<th>$a^3$</th>
<th>$P^2/a^3$</th>
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</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.241</td>
<td>0.387</td>
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<td>0.3779</td>
<td>1.0008</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
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<td>1.524</td>
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<td>5.203</td>
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<tr>
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<td>865.54</td>
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<td>7057.7</td>
<td>7066.8</td>
<td>0.9987</td>
</tr>
<tr>
<td>Neptune</td>
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<td>30.06</td>
<td>27159</td>
<td>27162</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

Kepler’s Law #3
• **The Law of Periods:**

\[ \text{Period}^2 = (\text{semimajor axis})^3 \]
\[ P^2 = a^3 \]

($P$ in years, $a$ in A.U.)

Bigger orbit (larger $a$) $\rightarrow$ longer **Period**

---

1666: **Isaac Newton**

mathematician: Invented calculus as a youth . . .

**SYNTHESIZED:**

Galileo’s Experiments

Kepler’s Laws

Calculus

into Physical Laws;
the basis of Modern Science

Apple falls $\rightarrow$ Earth and apple attract each other
Moon and Earth attract each other, too

If moon moves sideways as it falls, it could forever circle the Earth...
Newton’s Laws of Motion

- **Newton #1**: (the law of inertia)
  - bodies move at constant velocity unless acted upon by an unbalanced force

- **Newton #2**: (fisma)
  - Force = mass x acceleration \((F=ma)\)

- **Newton #3**: for every force on a body, there is an equal force acting in the opposite direction on another body --- recoil

Newton’s Law of Universal Gravitation

**Gravity** is

- a **central** force: strength drops with distance\(^2\)
- a **universal** force: same form everywhere
- a **cosmic** force: inherent property of matter

Apple falls -> Earth and apple attract each other
Moon and Earth attract each other, too

If moon moves sideways as it falls, it could forever circle the Earth...

- **Force** of gravity pulls planets towards Sun
  \((\text{Newton’s 2nd law})\)
- without gravity, planets would fly away in straight lines
  \((\text{Newton’s 1st law})\)

Newton’s Derivation of Kepler #3

- Gravitational force pulling planets **toward** sun
  \[
  F_{\text{toward}} = \frac{GMm}{a^2}
  \]
  (Newton’s law of Universal Gravitation)

- centrifugal “force” pulling planets **away** from sun

  \[
  F_{\text{away}} = \frac{mv^2}{a}
  \]

  or, since \(v = \frac{2\pi a}{P}\)

  \[
  F_{\text{away}} = \frac{m4\pi^2a}{P^2}
  \]

- If forces equal, then distance between doesn’t change!

  \[
  \frac{GMm}{a^2} = \frac{m4\pi^2a}{P^2}
  \]

  \[
  P^2 = a^3 \times \left(\frac{4\pi^2}{GM}\right)
  \]

  this is Kepler’s Third Law - with benefits!