Formation of the Solar System

• Any theory of formation of the Solar System must explain all of the basic facts that we have learned so far.
The Solar System

- The Sun contains 99.9% of the mass.
- The Solar System is mostly empty space.
- The Solar System is a flattened disk.
  - All planets revolve in the same direction
  - Most planets also rotate in the same direction
- All objects have similar ages (about 4.6 billion years, when measurable).
- Planets belong in one of two families.
Two Types of Planets

- Terrestrial planets
  - low mass ($\leq 1 \, M_{\oplus}$)
  - high density (rocky, metallic)
  - slow rotators ($P \geq 24$ hours)
  - few satellites
  - close to Sun ($a \leq 1.6$ AU)

- Jovian planets
  - high mass ($\geq 15 \, M_{\oplus}$)
  - low density (gaseous)
  - rapid rotators ($P \leq 18$ hours)
  - many satellites
  - far from Sun ($a \geq 5$ AU)
Lessons in Comparative Planetology

• Lesson 1: Surfaces of planets are a result of competing *internal* mechanisms (volcanism, plate tectonics) and *external* mechanisms (cratering due to bombardment).
  – Internal mechanisms dominate for larger bodies (e.g., Earth, Venus)
  – External mechanisms dominate for smaller bodies (e.g., Moon, Mercury)
The surfaces of the Moon and Mercury are old surfaces with very little modification since the heavy bombardment phase.
• The surfaces of Venus and the Earth have been significantly modified by volcanism.

• Plate tectonics and water erosion are important on Earth.
  – Venus is a little too small and rotates too slowly for plate tectonics to be very important, and too hot for liquid water to exist.
• Mars is an intermediate case
  – evidence of both heavy cratering and volcanism
  – evidence of past water flows
  – clear examples of wind erosion
Lessons in Comparative Planetology

• Lesson 2: More massive, colder bodies will better retain atmospheres.
  – More massive bodies have higher escape velocities.
  – At higher temperatures, atoms and molecules are moving faster.
    • Lightest particles are moving the fastest and are thus hardest to retain.
In order of increasing mass, consider:

- **Pluto**: cold, but too small to retain anything but a thin CH$_4$ atmosphere.
- **Moon**: too small and (periodically) hot to retain anything.
- **Mercury**: too small and hot to retain anything.
- **Mars**: cold, but too small to retain anything but a weak CO$_2$ atmosphere.
- **Venus**: hot, but massive enough to retain a dense CO$_2$ atmosphere.
- **Earth**: warm, but massive enough to retain CO$_2$ atmosphere, which evolved into a thinner N$_2$ + O$_2$ atmosphere on account of liquid water and plant life.
- **Jovian planets**: cold and massive enough to retain H and He atmospheres, which is why they are gaseous, massive bodies.
Lessons in Comparative Planetology

• Lesson 3: Satellites of Jovian planets show patterns consistent with our ideas about formation of the planets.
  – Inner satellites form under warmer conditions
    • Densities imply lower ice content
    • Show evidence of volcanism (in this case driven by tides) and resurfacing
    • Examples: Io, Europa, Enceladus
Low density, geologically active satellites are near their parent planets.

Io (Jupiter)  
Enceladus (Saturn)  
Europa (Jupiter)
– Largest objects form in middle of system
  • Like Jupiter and Saturn in Solar System
  • Examples: Ganymede, Titan, Titania
The largest satellites form near the middle of their respective systems.

- Ganymede (Jupiter)
- Titan (Saturn)
- Titania (Uranus)
Lessons in Comparative Planetology

• Lesson 4: The most unusual features of the Solar System are likely attributable to “giant impacts”.
  – Relatively large satellites of small planets
    • Earth-Moon: non-equatorial orbit of Moon, gross differences in surface compositions.
    • Pluto-Charon: retrograde motion of system
    • Neptune-Triton: retrograde orbit of Triton
  – Retrograde rotation of large bodies
    • Uranus, Venus
  – Other evidence: impact basins on Moon, Mercury, Callisto
Probable Origin of the Moon

- Theory that best explains properties of Earth and Moon is “giant impact” between early Earth and a Mars-sized object in a similar orbit.
Mare Orientale, formed 3.8 billion years ago, is the youngest of the large lunar impact basins. The outer ring is about 1000 km in diameter. The central part of the basin subsequently flooded with lava, forming the mare.
Caloris Basin on Mercury

• Formed as a result of an enormous direct impact.
Caloris Basin on Mercury

- Impact shattered surface at antipode.
Callisto

- Jupiter’s satellite Callisto also shows the result of a large direct impact.
Miranda: Victim of a Violent Past

- Miranda is fifth largest satellite of Uranus, (diameter 485 km)
- Its surface shows evidence of violent collisions late in its formation history.
Basic Facts that Must Be Explained by a Theory of Origin

- Planetary orbits:
  - Orbits are all in a single plane. ✓
  - The Sun’s equator lies in this plane. ✓
  - Planetary orbits are nearly circular. ✓
  - Planets all revolve in the same direction. ✓
  - Most planets and the Sun rotate in the same direction that the planets revolve. ✓
  - Planets have almost all of the angular momentum of the Solar System. ✓
  - Spacing between planets follows a regular pattern (Bode’s Law). ?
Basic Facts that Must be Explained by a Theory of Origin

• Planetary composition
  – Varies with distance from Sun; metal-rich near the Sun, Hydrogen-rich farther away.
  – Satellite systems show similar patterns: inner satellites are dominated by less-volatile elements.
How Typical Is the Solar System?

• We can’t claim that we understand formation of planetary systems based on one example.

• Unfortunately, detection of extrasolar planets (exoplanets) is difficult.
  – Much fainter than stars and close to them.
Can We Observe Exoplanets?

• Consider problem of detecting Jupiter around the Sun directly from α Cen
  \((d = 270,000 \text{ AU} = 1.3 \text{ pc})\)
  – Angular separation:

\[
\theta = \frac{5.2 \text{ AU}}{270,000 \text{ AU}} = 1.9 \times 10^{-5} \text{ rad} = 4.0''
\]
Can We Observe Exoplanets?

• Consider problem of detecting Jupiter around the Sun directly from α Cen (d=270,000 AU = 1.3pc)
  – Optical brightness contrast: \( L_{\text{Jup}} = \left( \frac{L_\odot}{4\pi a^2} \right) \pi R^2 A \)

\[
\frac{L_{\text{Jup}}}{L_\odot} = \frac{A}{4} \left( \frac{R_{\text{Jup}}}{a} \right)^2 = \frac{0.51}{4} \left( \frac{7.2 \times 10^4 \text{ km}}{7.8 \times 10^8 \text{ km}} \right)^2 \approx 4 \times 10^{-9}
\]

Can We Observe Exoplanets?

- Consider problem of detecting Jupiter around the Sun directly from α Cen (d=270,000 AU = 1.3pc)
  - Far-IR brightness contrast is more favorable:

\[
\frac{L_{\text{Jup}}}{L_\odot} = \frac{4\pi R_{\text{Jup}}^2}{4\pi R_\odot^2} \frac{T_{\text{Jup}}}{T_\odot} \approx 3 \times 10^{-4}
\]
Can We Observe Exoplanets?

- Direct detection is difficult, but not impossible.
- One claim of detection has been made, with *Hubble Space Telescope*.
- Fomalhaut b ($D = 7.7$ pc).
Indirect Detection of Exoplanets

• Reflex Doppler motion of host stars.

![Diagram showing reflex Doppler motion and wavelength shifts](image-url)
Indirect Detection of Exoplanets

- Reflex Doppler motion of host stars.

![Graph of 51 Pegasi with phase, velocity, and RMS values](chart.png)
Indirect Detection of Exoplanets

- Planetary transits
Indirect Detection of Exoplanets

- Planetary transits
Indirect Detection of Exoplanets

• Gravitational microlensing