Guiding Questions

1. Are all the other planets similar to Earth or very different?
2. Do other planets have moons like Earth’s Moon?
3. How do astronomers know what the other planets are made of?
4. Are all the planets made of basically the same material?
5. What is the difference between an asteroid and a comet?
6. Why are craters common on the Moon but rare on the Earth?
7. Why do interplanetary spacecraft carry devices for measuring magnetic fields?
8. Do all the planets have a common origin?
There are two broad categories of planets: Earthlike (terrestrial) and Jupiterlike (jovian)

- orbit the Sun in the same direction and in almost the same plane
- Most of the planets have nearly circular orbits
Density

- The average density of any substance depends in part on its composition.
- An object sinks in a fluid if its average density is greater than that of the fluid, but rises if its average density is less than that of the fluid.
- The terrestrial (Earth-like) planets are made of rocky materials and have dense iron cores, which gives these planets high average densities.
- The Jovian (Jupiter-like) planets are composed primarily of light elements such as hydrogen and helium, which gives these planets low average densities.
The Terrestrial Planets

• The four innermost planets are called terrestrial planets

<table>
<thead>
<tr>
<th>Characteristics of the Planets</th>
<th>The Inner Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (10^6 km)</td>
<td>57.9</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>0.387</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>0.241</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.206</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>7.00°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>4880</td>
</tr>
<tr>
<td>Equatorial diameter (Earth = 1)</td>
<td>0.383</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$3.302 \times 10^{23}$</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>0.0553</td>
</tr>
<tr>
<td>Average density (kg/m^3)</td>
<td>5430</td>
</tr>
</tbody>
</table>
Jovian Planets are the outer planets EXCEPT for Pluto

- Jupiter, Saturn, Uranus and Neptune are Jovian planets

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
<th>Pluto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (10^6 km)</td>
<td>778.3</td>
<td>1429</td>
<td>2871</td>
<td>4498</td>
<td>5915</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>5.203</td>
<td>9.554</td>
<td>19.194</td>
<td>30.066</td>
<td>39.537</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>11.86</td>
<td>29.46</td>
<td>84.10</td>
<td>164.86</td>
<td>248.60</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.048</td>
<td>0.053</td>
<td>0.043</td>
<td>0.010</td>
<td>0.250</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>1.30°</td>
<td>2.48°</td>
<td>0.77°</td>
<td>1.77°</td>
<td>17.15°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>142,984</td>
<td>120,536</td>
<td>51,118</td>
<td>49,528</td>
<td>2300</td>
</tr>
<tr>
<td>Equatorial diameter (Earth = 1)</td>
<td>11.209</td>
<td>9.449</td>
<td>4.007</td>
<td>3.883</td>
<td>0.180</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$1.899 \times 10^{27}$</td>
<td>$5.685 \times 10^{26}$</td>
<td>$8.682 \times 10^{25}$</td>
<td>$1.024 \times 10^{26}$</td>
<td>$1.3 \times 10^{22}$</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>317.8</td>
<td>95.16</td>
<td>14.53</td>
<td>17.15</td>
<td>0.0021</td>
</tr>
<tr>
<td>Average density (kg/m^3)</td>
<td>1326</td>
<td>687</td>
<td>1318</td>
<td>1638</td>
<td>2000</td>
</tr>
</tbody>
</table>

- Jupiter, Saturn, Uranus and Neptune are Jovian planets
Pluto – Not exactly terrestrial nor jovian

- Pluto is a special case
  - Smaller than any of the terrestrial planets
  - Intermediate average density of about 1,900 kg/m$^3$
  - Density suggests it is composed of a mixture of ice and rock
Seven largest satellites are almost as big as the terrestrial planets

<table>
<thead>
<tr>
<th></th>
<th>Moon</th>
<th>Io</th>
<th>Europa</th>
<th>Ganymede</th>
<th>Callisto</th>
<th>Titan</th>
<th>Triton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parent planet</strong></td>
<td>Earth</td>
<td>Jupiter</td>
<td>Jupiter</td>
<td>Jupiter</td>
<td>Jupiter</td>
<td>Saturn</td>
<td>Neptune</td>
</tr>
<tr>
<td><strong>Diameter (km)</strong></td>
<td>3476</td>
<td>3642</td>
<td>3130</td>
<td>5268</td>
<td>4806</td>
<td>5150</td>
<td>2706</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>(7.35 \times 10^{22})</td>
<td>(8.93 \times 10^{22})</td>
<td>(4.80 \times 10^{22})</td>
<td>(1.48 \times 10^{23})</td>
<td>(1.08 \times 10^{23})</td>
<td>(1.34 \times 10^{23})</td>
<td>(2.15 \times 10^{22})</td>
</tr>
<tr>
<td><strong>Average density (kg/m³)</strong></td>
<td>3340</td>
<td>3530</td>
<td>2970</td>
<td>1940</td>
<td>1850</td>
<td>1880</td>
<td>2050</td>
</tr>
<tr>
<td><strong>Substantial atmosphere?</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

(JPL/NASA)
Spectroscopy reveals the chemical composition of the planets

- The spectrum of a planet or satellite with an atmosphere reveals the atmosphere’s composition.
- If there is no atmosphere, the spectrum indicates the composition of the surface.
- The substances that make up the planets can be classified as gases, ices, or rock, depending on the temperatures and pressures at which they solidify.
- The terrestrial planets are composed primarily of rocky materials, whereas the Jovian planets are composed largely of gas.
Phases and Phase Diagram

[Diagram showing a phase diagram with regions for solid, liquid, and gas phases, and points A, B, C, and D indicating different phase transitions such as melting, freezing, sublimation, deposition, vaporization, and condensation.]
Spectroscopy of Titan (moon of Saturn)

(a) The spectrum of sunlight reflected from Titan
Spectroscopy of Titan (moon of Saturn)

The absorption lines of methane (CH₄) are produced in Titan’s atmosphere.

The absorption line of hydrogen (H) is produced in Sun’s atmosphere.

The absorption line of oxygen (O₂) is produced in Earth’s atmosphere.

(b) Interpreting Titan’s spectrum
Spectroscopy of Europa (moon of Jupiter)

The spectrum of Europa is almost identical to that of ice, indicating that the surface of Europa is mostly ice, not rock.
Hydrogen and helium are abundant on the Jovian planets, whereas the terrestrial planets are composed mostly of heavier elements.

Jupiter
- Multicolored clouds
- Storm

Mars
- Polar ice cap
- Extinct volcano
- Clouds
Asteroids (rocky) and comets (icy) also orbit the Sun

- Asteroids are small, rocky objects
- Comets and Kuiper Belt Objects are made of “dirty ice”
- All are remnants left over from the formation of the planets
- The Kuiper belt extends far beyond the orbit of Pluto
- Pluto can be thought of as the largest member of the Kuiper belt
  — “planet” by IAU agreement
Cratering on Planets and Satellites

- Result of impacts from interplanetary debris
  - when an asteroid, comet, or meteoroid collides with the surface of a terrestrial planet or satellite, the result is an impact crater

- Geologic activity renews the surface and erases craters
  - extensive cratering means an old surface and little or no geologic activity
  - geologic activity is powered by internal heat, and smaller worlds lose heat more rapidly, thus, as a general rule, smaller terrestrial worlds are more extensively cratered
Largest Volcano in Solar System (Olympus Mons)
Craters on the Moon
A planet with a magnetic field indicates an interior in motion

- Planetary magnetic fields are produced by the motion of electrically conducting substances inside the planet
- This mechanism is called a dynamo
- If a planet has no magnetic field this would be evidence that there is little such material in the planet’s interior or that the substance is not in a state of motion
• The magnetic fields of terrestrial planets are produced by metals such as iron in the liquid state

• The magnetic fields of the Jovian planets are generated by metallic hydrogen — with ionized molecules dissolved in it
The diversity of the solar system is a result of its origin and evolution

- The planets, satellites, comets, asteroids, and the Sun itself formed from the same cloud of interstellar gas and dust.
- The composition of this cloud was shaped by cosmic processes, including nuclear reactions that took place within stars that died long before our solar system was formed.
- Different planets formed in different environments depending on their distance from the Sun and these environmental variations gave rise to the planets and satellites of our present-day solar system.

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<tr>
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<th>Terrestrial Planets</th>
<th>Jovian Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the Sun</td>
<td>Less than 2 AU</td>
<td>More than 5 AU</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Composition</td>
<td>Mostly rocky materials containing iron, oxygen, silicon, magnesium, nickel, and sulfur</td>
<td>Mostly hydrogen and helium</td>
</tr>
<tr>
<td>Density</td>
<td>High</td>
<td>Low</td>
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</tbody>
</table>

Table 7.3: Comparing Terrestrial and Jovian Planets
Key Words

- asteroid
- asteroid belt
- average density
- chemical composition
- comet
- dynamo
- escape speed
- ices
- impact crater
- Jovian planet

- kinetic energy
- Kuiper belt
- Kuiper belt objects
- liquid metallic hydrogen
- magnetometer
- meteoroid
- minor planet
- molecule
- spectroscopy
- terrestrial planet
Comparative Planetology II: The Origin of Our Solar System
The diversity of the solar system is a result of its origin and evolution

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</tbody>
</table>

The table above compares the characteristics of Terrestrial and Jovian Planets.
Guiding Questions

1. What must be included in a viable theory of the origin of the solar system?
2. Why are some elements (like gold) quite rare, while others (like carbon) are more common?
3. How do we know the age of the solar system?
4. How do astronomers think the solar system formed?
5. Did all of the planets form in the same way?
6. Are there planets orbiting other stars? How do astronomers search for other planets?
Any model of solar system origins must explain the present-day Sun and planets

1. The terrestrial planets, which are composed primarily of rocky substances, are relatively small, while the Jovian planets, which are composed primarily of hydrogen and helium, are relatively large.

2. All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane.

3. The terrestrial planets orbit close to the Sun, while the Jovian planets orbit far from the Sun.
The abundances of the chemical elements are the result of cosmic processes

- The vast majority of the atoms in the universe are hydrogen and helium atoms produced in the Big Bang
All the heavier elements were manufactured by stars later, either by thermonuclear fusion reactions deep in their interiors or by the violent explosions that mark the end of massive stars.
The **interstellar medium** is a tenuous collection of gas and dust that pervades the spaces between the stars.
The abundances of radioactive elements reveal the solar system’s age

- Each type of radioactive nucleus decays at its own characteristic rate, called its half-life, which can be measured in the laboratory
- This is the key to a technique called **radioactive age dating**, which is used to determine the ages of rocks
- The oldest rocks found anywhere in the solar system are **meteorites**, the bits of meteoroids that survive passing through the Earth’s atmosphere and land on our planet’s surface
- Radioactive age-dating of meteorites, reveals that they are all nearly the same age, about 4.56 billion years old
The Sun and planets formed from a solar nebula

- The most successful model of the origin of the solar system is called the nebular hypothesis.
- According to this hypothesis, the solar system formed from a cloud of interstellar material called the solar nebula.
- This occurred 4.56 billion years ago (as determined by radioactive age-dating).
The chemical composition of the solar nebula, by mass, was 98% hydrogen and helium (elements that formed shortly after the beginning of the universe) and 2% heavier elements (produced much later in the centers of stars, and cast into space when the stars died).

The nebula flattened into a disk in which all the material orbited the center in the same direction, just as do the present-day planets.
• The heavier elements were in the form of ice and dust particles
The Sun formed by gravitational contraction of the center of the nebula. After about $10^8$ years, temperatures at the protosun’s center became high enough to ignite nuclear reactions that convert hydrogen into helium, thus forming a true star.
The planets formed by the accretion of planetesimals and the accumulation of gases in the solar nebula.

(a) Within the disk that surrounds the protosun, solid grains collide and clump together into planetesimals.
(b) The terrestrial planets built up by collisions and by the accretion of planetesimals by gravitational attraction. The Jovian planets formed by gas accretion.
The graph shows the relationship between temperature (K) and distance from the center of the solar nebula (AU). Key points include:

- Mercury
- Venus
- Earth
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune
- Pluto

Water condenses to form ice at a certain point, and methane condenses to form ice at a different point.
The computer simulation begins with 100 planetesimals orbiting the Sun.

After 30 million years, the 100 have coalesced into 22 planetesimals...

...and after a total elapsed time of 441 million years, four planets remain.
(a) A jet from a young star
(b) Winds from young stars
Key Words

- accretion
- astrometric method
- atomic number
- brown dwarf
- center of mass
- chemical differentiation
- chondrule
- condensation temperature
- conservation of angular momentum
- core accretion model
- disk instability model
- extrasolar planet
- half-life
- interstellar medium
- jets
- Kelvin-Helmholtz contraction

- meteorite
- nebulosity
- nebular hypothesis
- Oort cloud
- planetesimal
- protoplanet
- protoplanetary disk (proplyd)
- protosun
- radial velocity method
- radioactive age-dating
- radioactive decay
- solar nebula
- solar wind
- T Tauri wind