Comparative Planetology I: Our Solar System

Guiding Questions

1. Are all the other planets similar to Earth, or are they 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)

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

The Terrestrial Planets

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (AU)</td>
<td>0.397</td>
<td>0.723</td>
<td>1.000</td>
<td>1.524</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>0.241</td>
<td>0.615</td>
<td>1.985</td>
<td>1.881</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.270</td>
<td>0.007</td>
<td>0.017</td>
<td>0.091</td>
</tr>
<tr>
<td>Equation of node to the ecliptic</td>
<td>7.0°</td>
<td>3.7°</td>
<td>0.9°</td>
<td>1.0°</td>
</tr>
<tr>
<td>Equation of perihelion to the ecliptic</td>
<td>40.0°</td>
<td>40.0°</td>
<td>40.0°</td>
<td>40.0°</td>
</tr>
<tr>
<td>Eq. distance (Earth = 1)</td>
<td>0.383</td>
<td>0.722</td>
<td>1.000</td>
<td>0.531</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.055</td>
<td>0.815</td>
<td>5.975</td>
<td>0.064</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>5.433</td>
<td>5.253</td>
<td>5.525</td>
<td>5.904</td>
</tr>
</tbody>
</table>

- The four innermost planets are called terrestrial planets

Jovian Planets are the outer planets EXCEPT for Pluto

<table>
<thead>
<tr>
<th>Characteristic</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 (AU)</td>
<td>5.203</td>
<td>9.588</td>
<td>19.194</td>
<td>30.069</td>
<td>39.53</td>
</tr>
<tr>
<td>Number of moons</td>
<td>62</td>
<td>27</td>
<td>14</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>11.86</td>
<td>29.46</td>
<td>84.02</td>
<td>10,627</td>
<td>2481</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.046</td>
<td>0.053</td>
<td>0.043</td>
<td>0.010</td>
<td>0.023</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>1.3°</td>
<td>2.4°</td>
<td>0.7°</td>
<td>1.7°</td>
<td>2.9°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>142,898</td>
<td>133,266</td>
<td>51,118</td>
<td>24,974</td>
<td>1410</td>
</tr>
<tr>
<td>Eq. diameter (Earth = 1)</td>
<td>11.23</td>
<td>9.445</td>
<td>4.007</td>
<td>3.643</td>
<td>1.081</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.898 x 10²</td>
<td>5.684 x 10³</td>
<td>6.482 x 10⁴</td>
<td>1.024 x 10⁵</td>
<td>2.5 x 10⁶</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>0.004</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>1.226</td>
<td>6.87</td>
<td>13.18</td>
<td>14.31</td>
<td>1.09</td>
</tr>
</tbody>
</table>

- Jupiter, Saturn, Uranus and Neptune are Jovian planets

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

Density formula:

\[ D = \frac{m}{V} \]
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/m³
  - 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>Name</th>
<th>No.</th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (km)</td>
<td>147</td>
<td>1462</td>
<td>3138</td>
<td>5248</td>
<td>4804</td>
<td>3150</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>7.73 x 10²⁰</td>
<td>6.41 x 10²⁰</td>
<td>4.91 x 10²⁰</td>
<td>1.41 x 10²¹</td>
<td>1.08 x 10²²</td>
<td>1.86 x 10²²</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>3.40</td>
<td>3.55</td>
<td>2.79</td>
<td>1.94</td>
<td>1.01</td>
<td>0.68</td>
</tr>
</tbody>
</table>

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

Spectroscopy of Titan (moon of Saturn)
Spectroscopy of Europa (moon of Jupiter)

Hydrogen and helium are abundant on the Jovian planets, whereas the terrestrial planets are composed mostly of heavier elements.

Jupiter

Mars

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

Copernicus crater

Ejecta from Copernicus

100 km
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 diversity of the solar system is a result of its origin and evolution

<table>
<thead>
<tr>
<th>Table 2.3</th>
<th>Comparing Terrestrial and Jovian Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial Planets</td>
<td>Jovian Planets</td>
</tr>
<tr>
<td>Distance from the Sun</td>
<td>Less than 2 AU</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
</tr>
<tr>
<td>Composition</td>
<td>Mostly rocky materials containing iron, oxygen, silicon, magnesium, nickel, and sulfur</td>
</tr>
<tr>
<td>Density</td>
<td>High</td>
</tr>
</tbody>
</table>

- 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

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
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.
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

(b) The terrestrial planets built up by collisions and by the accretion of planetesimals by gravitational attraction. The Jovian planets formed by gas accretion.

(b) As a result of contraction and rotation, a flat, rapidly rotating disk forms. The matter concentrated at the center becomes the protosun.

1 cm
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
- nebularly
- nebular hypothesis
- Oort cloud
- planetesimal
- protoplanet
- protoplanetary disk (proplyd)
- protostar
- radial velocity method
- radioactive age-dating
- radioactive decay
- solar nebula
- solar wind
- T Tauri wind