Questions to Ponder about Solar System

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?

Questions to Ponder about Origins

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?

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

- The four innermost planets are called terrestrial planets
- Relatively small (with diameters of 5000 to 13,000 km)
- High average densities (4000 to 5500 kg/m³)
- Composed primarily of rocky materials

Density

\[ D = \frac{m}{V} \]

- 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
Jovian Planets are the outer planets (except for Pluto)

**The Jovian Planets**

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (10^8 km)</td>
<td>778.3</td>
<td>1.429</td>
<td>2.471</td>
<td>4.484</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>5.203</td>
<td>8.914</td>
<td>8.936</td>
<td>10.066</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>11.86</td>
<td>29.50</td>
<td>9.17</td>
<td>16.45</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.011</td>
<td>0.055</td>
<td>0.044</td>
<td>0.001</td>
</tr>
<tr>
<td>Revolution of orbit in ecliptic</td>
<td>3.14°</td>
<td>2.40°</td>
<td>1.77°</td>
<td>2.67°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>142,984</td>
<td>125,180</td>
<td>51,820</td>
<td>49,252</td>
</tr>
<tr>
<td>Equatorial diameter (Earth = 1)</td>
<td>11.30</td>
<td>10.44</td>
<td>4.047</td>
<td>3.813</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.899 x 10^27</td>
<td>5.986 x 10^27</td>
<td>8.683 x 10^26</td>
<td>1.024 x 10^26</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>317.8</td>
<td>95.56</td>
<td>14.51</td>
<td>17.35</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>1.386</td>
<td>0.697</td>
<td>2.190</td>
<td>2.112</td>
</tr>
</tbody>
</table>

- Jupiter, Saturn, Uranus and Neptune are Jovian planets
  - Large diameters (50,000 to 143,000 km)
  - Low average densities (700 to 1700 kg/m³)
  - Composed primarily of hydrogen and helium.

Pluto (dwarf planet) - Not terrestrial nor Jovian

- Pluto is a special case
  - Smaller than any of the terrestrial planets
  - Intermediate average density of about 1900 kg/m³
  - Density suggests it is composed of a mixture of ice and rock

Seven largest moons are almost as big as the terrestrial planets

<table>
<thead>
<tr>
<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>Diameter (km)</td>
<td>3474</td>
<td>5,100</td>
<td>15,600</td>
<td>16,300</td>
<td>5,150</td>
<td>2,875</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.83 x 10^23</td>
<td>4.8 x 10^24</td>
<td>1.4 x 10^26</td>
<td>1.0 x 10^29</td>
<td>1.3 x 10^30</td>
<td>2.5 x 10^24</td>
</tr>
<tr>
<td>Average density (g/cm³)</td>
<td>3.04</td>
<td>2.67</td>
<td>2.04</td>
<td>2.18</td>
<td>2.16</td>
<td>0.91</td>
</tr>
</tbody>
</table>

- Some (3) comparable in size to the planet Mercury (2 are larger)
- The remaining moons of the solar system are much smaller than these.

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 (Not in text but important)

- The spectrum of sunlight reflected from Titan

Spectroscopy of Titan (moon of Saturn)
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.

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 (aka dwarf planet) can be thought of as a large member of the Kuiper Belt

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

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

Magnetic Fields

- 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
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.

Comparing Terrestrial and Jovian Planets

<table>
<thead>
<tr>
<th>Terrestrial Planets</th>
<th>Jovian Planets</th>
</tr>
</thead>
<tbody>
<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>

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 heavy elements (>Li) were manufactured by stars after the origin of the universe itself, either by fusion deep in stellar interiors or by stellar explosions.

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.
- Radiocarbon age-dating of meteorites reveals that they are all nearly the same age, about 4.56 billion years old.

The interstellar medium is a tenuous collection of gas and dust that pervades the spaces between the stars. A nebula is any gas cloud in interstellar space.
Thoughtful Interlude

“The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.”

— Albert Einstein, 1950

Solar System Origins Questions

- How did the solar system evolve?
- What are the observational underpinnings?
- Are there other solar systems? (to be discussed at end of semester)
- What evidence is there for other solar systems?
- BEGIN AT THE BEGINNING...

Origin of Universe Preview (a la Big Bang) (will re-visit at end of semester)

<table>
<thead>
<tr>
<th>Era</th>
<th>Epochs</th>
<th>Main Event</th>
<th>Time after bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Vacuum Era</td>
<td>Planck Epoch</td>
<td>Quantum fluctuation inflation</td>
<td>&lt;10^-43 sec.</td>
</tr>
<tr>
<td></td>
<td>Inflationary Epoch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Radiation Era</td>
<td>Electroweak Epoch</td>
<td>Formation of leptons, bosons, hydrogen, helium and deuterium</td>
<td>&lt;10^-10 sec. 10^-3 sec. 1 sec - 1 month</td>
</tr>
<tr>
<td></td>
<td>Strong Epoch</td>
<td>Decoupling</td>
<td></td>
</tr>
<tr>
<td>The Matter Era</td>
<td>Galaxy Epoch</td>
<td>Galaxy formation</td>
<td>1 - 2 billion years</td>
</tr>
<tr>
<td></td>
<td>Stellar Epoch</td>
<td>Stellar birth</td>
<td>2 - 15 billion years</td>
</tr>
<tr>
<td>The Degenerate Dark Era</td>
<td>Dead Star Epoch</td>
<td>Death of stars</td>
<td>20 - 100 billion yrs.</td>
</tr>
<tr>
<td></td>
<td>Black Hole Epoch</td>
<td>Black holes</td>
<td>100 billion - ???</td>
</tr>
</tbody>
</table>

Abundance of the Chemical Elements

- At the start of the Stellar Era
  - there was about 75-90% hydrogen, 10-25% helium and 1-2% deuterium
- NOTE WELL:
  - Abundance of the elements is often plotted on a logarithmic scale
    - this allows for the different elements to actually appear on the same scale as hydrogen and helium
  - Abundance of elements on a linear scale is very different

Logarithmic Plot of Abundance

A Linear View of Abundance
Recall Observations

- Radioactive dating of solar system rocks
  - Earth ~ 4 billion years
  - Moon ~4.5 billion years
  - Meteorites ~4.6 billion years
- Most orbital and rotation planes confined to ecliptic plane with counterclockwise motion
- Extensive satellite and rings around Jovians
- Planets have more of the heavier elements than the sun

### Planetary Summary

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass (Earth=1)</th>
<th>Density (g/cm³)</th>
<th>Major Constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.06</td>
<td>5.4</td>
<td>Rock, Iron</td>
</tr>
<tr>
<td>Venus</td>
<td>0.82</td>
<td>5.2</td>
<td>Rock, Iron</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>5.5</td>
<td>Rock, Iron</td>
</tr>
<tr>
<td>Mars</td>
<td>0.11</td>
<td>3.9</td>
<td>Rock, Iron</td>
</tr>
<tr>
<td>Jupiter</td>
<td>318</td>
<td>1.3</td>
<td>H, He</td>
</tr>
<tr>
<td>Saturn</td>
<td>95</td>
<td>0.7</td>
<td>H, He</td>
</tr>
<tr>
<td>Uranus</td>
<td>14</td>
<td>1.3</td>
<td>Ices, H, He</td>
</tr>
<tr>
<td>Neptune</td>
<td>17</td>
<td>1.7</td>
<td>Ices, H, He</td>
</tr>
</tbody>
</table>

Other Planet Observations

- Terrestrial planets are closer to sun
  - Mercury
  - Venus
  - Earth
  - Mars
- Jovian planets further from sun
  - Jupiter
  - Saturn
  - Uranus
  - Neptune

Some Conclusions

- Planets formed at same time as Sun
- Planetary and satellite/ring systems are similar to remnants of dusty disks such as that seen about stars being born (e.g. T Tauri stars)
- Planet composition dependent upon where it formed in solar system

Nebular Condensation (protoplanet) Model

- Most remnant heat from collapse retained near center
- After sun ignites, remaining dust reaches an equilibrium temperature
- Different densities of the planets are explained by condensation temperatures
- Nebular dust temperature increases to center of nebula

Nebular Condensation Physics

- Energy absorbed per unit area from Sun = energy emitted as thermal radiator
- Solar Flux = Lum (Sun) / 4 x distance²
- Flux emitted = constant x T⁴ (Stefan-Boltzmann)
- Concluding from above yields $T = \text{constant} / \text{distance}^{0.5}$
Nebular Condensation Chemistry

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Freezing Point</th>
<th>Distance from Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>10 K</td>
<td>&gt;100 AU</td>
</tr>
<tr>
<td>H₂O</td>
<td>273 K</td>
<td>&gt;10 AU</td>
</tr>
<tr>
<td>CH₄</td>
<td>35 K</td>
<td>&gt;35 AU</td>
</tr>
<tr>
<td>NH₃</td>
<td>190 K</td>
<td>&gt;8 AU</td>
</tr>
<tr>
<td>FeSO₄</td>
<td>700 K</td>
<td>&gt;1 AU</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1000 K</td>
<td>&gt;0.5 AU</td>
</tr>
</tbody>
</table>

Nebular Condensation Summary

- Solid Particles collide, stick together, sink toward center
  - Terrestrials -> rocky
  - Jovians -> rocky core + ices + light gases
- Coolest, most massive collect H and He
- More collisions -> heating and differentiating of interior
- Remnants flushed by solar wind
- Evolution of atmospheres

A Pictorial View of Solar System Origins

![Pictorial View of Solar System Origins](image)

Pictorial View Continued

![Pictorial View Continued](image)

HST Pictorial Evidence of Extrasolar System Formation

![HST Pictorial Evidence of Extrasolar System Formation](image)

HST Pictorial Evidence of Extrasolar System Formation

![HST Pictorial Evidence of Extrasolar System Formation](image)
The Sun and planets formed from a solar nebula

- According to the nebular condensation hypothesis, the solar system formed from a cloud of interstellar material sometimes 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 later in stars, and cast into space when stars exploded).

- 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 Sun formed by gravitational contraction of the center of the nebula.
- After about 10³ 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 heavier material were in the form of ice and dust particles.

- The Sun formed by gravitational contraction of the center of the nebula.
- After about 10³ 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 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 later in stars, and cast into space when stars exploded).

- 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 material were in the form of ice and dust particles.

- The Sun formed by gravitational contraction of the center of the nebula.
- After about 10³ 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.

![Diagram](a) Within the disk that surrounds the protosun, solid grains collide and clump together into planetesimals. Planetesimals Protosun

![Diagram](b) The terrestrial planets built up by collisions and by the accretion of planetesimals by gravitational attraction. The Jovian planets formed by gas accretion. Terrestrial planets Jovian planets Gas

![Diagram](c) After 10 million years, the 100 have evolved into 22 planetesimals, and after a total elapsed time of 446 million years, four planets result.

Astronomers have discovered planets orbiting other stars.

- Geoff Marcy is using the 10-meter Keck telescope in Hawaii to measure the Doppler effect in stars that wobble because of planets orbiting around them.
- So far, he and other teams have found more than 100 extrasolar planets.
Finding Extrasolar Planets

- Doppler Shift
- Of unseen companions
- Photometry
- Measure the light
- Gravitational lensing
- A general relativistic effect

Transit Detection of Exoplanets

Extrasolar Planets

Most of the extrasolar planets discovered to date are quite massive and have orbits that are very different from planets in our solar system.

Astronomical Jargon

- asteroid
- asteroid belt
- average density
- chemical composition
- comets
- density
- degassing
- ice
- impact crater
- inner planet
- orbital energy
- Kuiper belt
- Kuiper belt objects
- liquid metallic hydrogen
- meteorite
- minor planet
- molecule
- spectroscopy
- terrestrial planet
- accretion
- astrometric method
- atomic number
- brown dwarf
- center of mass
- chemical differentiation
- condensation temperature
- core accretion model
- disk instability model
- extrasolar planet
- half-life
- interstellar medium
- jets
- Kelvin-Helmholtz contraction
- meteorite
- nebula
- nucleosynthesis
- Oort cloud
- planetesimal
- protoplanet
- protoplanetary disk
- protostar
- radial velocity method
- radioactive age-dating
- radioactive decay
- solar nebula
- solar wind
- T Tauri wind
- transit
- transit method