The Search for Life in the Solar System

HNRS 228
Reviewing Chapter 7
w/Professor Geller
What’s Up

- Environmental Requirements for Life (7.1)
  - Review Requirements for Life
    - Elements, Energy, Water, etc.
- Biological Tour of the Inner Solar System (7.2)
  - Terrestrial Planets
- Biological Tour of the Outer Solar System (7.3)
  - Jovian planets
- Spacecraft Exploration of the Solar System (7.4)
  - Remote Sensing, Robotics, Human Exploration, etc.
Environment for Life?

- Source of elements to build cells
- Source of energy
- Medium for transporting molecules
H₂O and CO₂ Phase Diagrams

(IMPORTANT environmental consideration)

Not in textbook
Guiding Questions in Comparative Planetology

• Are all the other planets similar to Earth, or are they very different?
• Do other planets have moons like Earth’s Moon?
• How do astronomers know what the other planets are made of?
• Are all the planets made of basically the same material?
• What is the difference between an asteroid and a comet?
• Why are craters common on the Moon but rare on the Earth?
• Why do interplanetary spacecraft carry devices for measuring magnetic fields?
• Do all the planets have a common origin?
Questions to Ponder about Origins

• What must be included in a viable theory of the origin of the solar system?
• Why are some elements (like gold) quite rare, while others (like carbon) are more common?
• How do we know the age of the solar system?
• How do astronomers think the solar system formed?
• Did all of the planets form in the same way?
• 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
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.

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

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (10^6 km)</td>
<td>57.9</td>
<td>108.2</td>
<td>149.6</td>
<td>227.9</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>0.387</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>1.000</td>
<td>1.88</td>
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<tr>
<td>Orbital eccentricity</td>
<td>0.206</td>
<td>0.007</td>
<td>0.017</td>
<td>0.093</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>7.00°</td>
<td>3.39°</td>
<td>0.00°</td>
<td>1.85°</td>
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<tr>
<td>Equatorial diameter (km)</td>
<td>4880</td>
<td>12,104</td>
<td>12,756</td>
<td>6794</td>
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<tr>
<td>Equatorial diameter (Earth = 1)</td>
<td>0.383</td>
<td>0.949</td>
<td>1.000</td>
<td>0.533</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$3.302 \times 10^{23}$</td>
<td>$4.868 \times 10^{24}$</td>
<td>$5.974 \times 10^{24}$</td>
<td>$6.418 \times 10^{23}$</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>0.0553</td>
<td>0.8150</td>
<td>1.0000</td>
<td>0.1074</td>
</tr>
<tr>
<td>Average density (kg/m³)</td>
<td>5430</td>
<td>5243</td>
<td>5515</td>
<td>3934</td>
</tr>
</tbody>
</table>
# Jovian Planets are the outermost 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 ($10^6$ km)</td>
<td>778.3</td>
<td>1429</td>
<td>2871</td>
<td>4498</td>
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<tr>
<td>Average distance from Sun (AU)</td>
<td>5.203</td>
<td>9.554</td>
<td>19.194</td>
<td>30.066</td>
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<tr>
<td>Orbital period (years)</td>
<td>11.86</td>
<td>29.46</td>
<td>84.10</td>
<td>164.86</td>
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<tr>
<td>Orbital eccentricity</td>
<td>0.048</td>
<td>0.053</td>
<td>0.043</td>
<td>0.010</td>
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<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>
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<tr>
<td>Equatorial diameter (km)</td>
<td>142,984</td>
<td>120,536</td>
<td>51,118</td>
<td>49,528</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>
</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>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>317.8</td>
<td>95.16</td>
<td>14.53</td>
<td>17.15</td>
</tr>
<tr>
<td>Average density (kg/m$^3$)</td>
<td>1326</td>
<td>687</td>
<td>1318</td>
<td>1638</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/m$^3$)
  - Composed primarily of hydrogen and helium.
iClicker Question

How can one calculate the density of a planet?
A Use Kepler's Law to obtain the weight of the planet.
B Divide the total mass of the planet by the volume of the planet.
C Divide the total volume of the planet by the mass of the planet.
D Multiply the planet's mass by its weight.
E Multiply the total volume by the mass of the planet.
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
iClicker Question

The terrestrial planets include the following:

A  Mercury, Venus, Earth, Mars and Pluto
B  Jupiter, Saturn, Uranus, Neptune and Pluto
C  Jupiter, Saturn, Uranus and Neptune
D  Earth only
E  Mercury, Venus, Earth and Mars
iClicker Question

The jovian planets include the following:
A  Mercury, Venus, Earth, Mars and Pluto
B  Jupiter, Saturn, Uranus, Neptune and Pluto
C  Jupiter, Saturn, Uranus and Neptune
D  Earth only
E  Mercury, Venus, Earth and Mars
iClicker Question

Which of these planets is least dense?

A  Jupiter
B  Neptune
C  Pluto
D  Uranus
E  Saturn
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.
Spectroscopy of Titan

(a) The spectrum of sunlight reflected from Titan

(b) Interpreting Titan’s spectrum
Spectroscopy of Europa

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.
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 presence of Earth’s magnetic field is a good indication that
A there is a large amount of magnetic material buried near the North Pole.
B there is a quantity of liquid metal swirling around in the Earth's core.
C the Earth is composed largely of iron.
D the Earth is completely solid.
E there are condensed gasses in the core of the Earth.
The diversity of the solar system is a result of its origin and evolution.

<table>
<thead>
<tr>
<th>Distance from the Sun</th>
<th>Terrestrial Planets</th>
<th>Jovian Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td></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>
</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.
iClicker Question

Understanding the origin and evolution of the solar system is one of the primary goals of

A relativity theory.
B seismology.
C comparative planetology.
D mineralogy.
E oceanography.
In general, which statement best compares the densities of the terrestrial and jovian planets.

A  Both terrestrial and jovian planets have similar densities.
B  Comparison are useless because the jovian planets are so much larger than the terrestrials.
C  No general statement can be made about terrestrial and jovian planets.
D  The jovian planets have higher densities than the terrestrial planets.
E  The terrestrial planets have higher densities than the jovian planets.
Any model of solar system origins must explain the present-day Sun and planets

- 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.
- All of the planets orbit the Sun in the same direction, and all of their orbits are in nearly the same plane.
- 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 chemical 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 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.
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.
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 Summary (a la Big Bang)

<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>$&lt;10^{-10}$ sec.</td>
</tr>
<tr>
<td></td>
<td>Strong Epoch</td>
<td></td>
<td>$10^{-4}$ sec.</td>
</tr>
<tr>
<td></td>
<td>Decoupling</td>
<td></td>
<td>1 sec. - 1 month</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 engulf?</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
  - it does show relative differences among higher atomic weight elements better than linear scale

- Abundance of elements on a linear scale is very different
Logarithmic Plot of Abundance

Logarithmic Plot of Chemical Abundance of Elements

Relative Abundance

Chemical Species

H, He, C, N, O, Ne, Mg, Si, Si, Fe
A Linear View of Abundance

Linear Plot of Chemical Abundance

- Chemical Species: H, He, C, N, O, Ne, Mg, Si, Si, Fe
- Relative abundance scale: 0, 10000, 20000, 30000, 40000, 50000, 60000, 70000, 80000, 90000, 100000

The graph shows the relative abundance of various chemical species, with hydrogen (H) having the highest 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
## A 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)
- 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
Energy absorbed per unit area from Sun = energy emitted as thermal radiator

Solar Flux = Lum (Sun) / 4 x distance^2

[inverse square law]

Flux emitted = constant x T^4

[Stefan-Boltzmann Law]

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>SiO₄</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
The most abundant chemical element in the solar nebula

A  Uranium
B  Iron
C  Hydrogen
D  Helium
E  Lithium
A Pictorial View of Solar System Origins

Gas pressure attempting to expand the cloud

Gravitational force attempting to collapse the cloud

Nebula

The cloud spins more rapidly as it collapses because of conservation of angular momentum.
Pictorial View Continued
HST Pictorial Evidence of Extrasolar System Formation
HST Pictorial Evidence of Extrasolar System Formation
As a planetary system and its star forms
the temperature in the core of the
nebula

A  Decreases in time
B  Increases in time
C  Remains the same over time
D  Cannot be determined
As a planetary system and its star forms, the rate of rotation of the nebula

A  Decreases in time
B  Increases in time
C  Remains the same over time
D  Cannot be determined
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 heavier material were in the form of ice and dust particles.
(b) As a result of contraction and rotation, a flat, rapidly rotating disk forms. The matter concentrated at the center becomes the protosun.

- 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
Disk of gas and dust

Central star (blocked out in telescope to make disk visible)

Size of Pluto’s orbit
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.
Chondrules in a meteorite
(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 illustrates the relationship between temperature and distance from the center of the solar nebula. Water condenses to form ice beyond Jupiter, while methane condenses to form ice further out, near Neptune and Pluto. The temperature decreases as the distance from the center of the solar nebula increases, as indicated by the blue line on the graph.
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.
Biological Tour of the Solar System

- Consider problems posed for life on each of the following
  - Moon
  - Mercury
  - Venus
  - (Mars will be discussed in Chapter 8)
  - Jovian Planets
  - Other Moons
  - Asteroid, comets and other debris
Exploring the Solar System

- Observations from Earth
  - ground or orbit based

- Robotic spacecraft
  - Flybys, orbitals - remote sensing
  - Landers - in situ

- Human exploration
Food for Thought

For any celestial body in our solar system
- Consider the physical characteristics found on that celestial body
- Consider how these characteristics would effect the possibilities of the evolution of life on that celestial body
- Consider a known extremophile to test for survivability on that celestial body and why that particular extremophile might be worthwhile to test on that particular celestial body