Important Reminders

Homework assignment #12 due Wednesday April 15

MidTerm IV, Friday April 17. Material from Chapters 6, 11, 12, and 13. Please bring #2 pencil to test.
Chapter 6: The Solar System (Cont’d)
Summary: Four Major Features of our Solar System

Large bodies in the solar system have orderly motions.
All planets and most satellites have nearly circular orbits going in the same direction in nearly the same plane. The Sun and most of the planets rotate in this same direction as well.

Planets fall into two main categories: small, rocky terrestrial planets near the Sun and large, hydrogen-rich jovian planets farther out. The jovian planets have many moons and rings made of rock and ice. Pluto does not fit in either category.

Swarms of asteroids and comets populate the solar system.
Asteroids are concentrated in the asteroid belt, and comets populate the regions known as the Kuiper belt and the Oort cloud.

Several notable exceptions to these general trends stand out, such as planets with unusual axis tilts or surprisingly large moons, and moons with unusual orbits.
Four Major Features of the Solar System

1. Why do large bodies in our solar system have orderly motions?

2. Why are there two types of planets?

3. Where did the comets and asteroids come from?

4. How can we explain the exceptions to the ‘rules’ above?
Why are there two types of planet, when all planets formed from the same nebula?

Materials in the solar nebula

<table>
<thead>
<tr>
<th>Terrestrial Planets</th>
<th>Jovian Planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller size and mass</td>
<td>Larger size and mass</td>
</tr>
<tr>
<td>Higher density</td>
<td>Lower density</td>
</tr>
<tr>
<td>Made mostly of rock and metal</td>
<td>Made mostly of hydrogen, helium, and hydrogen compounds</td>
</tr>
<tr>
<td>Solid surface</td>
<td>No solid surface</td>
</tr>
<tr>
<td>Few (if any) moons and no rings</td>
<td>Rings and many moons</td>
</tr>
<tr>
<td>Closer to the Sun (and closer together), with warmer surfaces</td>
<td>Farther from the Sun (and farther apart), with cool temperatures at cloud tops</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Examples</th>
<th>Typical Condensation Temperature</th>
<th>Relative Abundance (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen and Helium Gas</td>
<td>hydrogen, helium</td>
<td>do not condense in nebula</td>
</tr>
<tr>
<td>Hydrogen Compounds</td>
<td>water (H$_2$O) methane (CH$_4$) ammonia (NH$_3$)</td>
<td>$&lt;150$ K</td>
</tr>
<tr>
<td>Rock</td>
<td>various minerals</td>
<td>500–1,300 K</td>
</tr>
<tr>
<td>Metals</td>
<td>iron, nickel, aluminum</td>
<td>1,000–1,600 K</td>
</tr>
</tbody>
</table>
Temperatures during solar system formation

- Initial parent molecular cloud is very cold, only \( \sim 10-30 \) K (273 K = water freezes).

- As gravity causes cloud to contract, it heats up (conservation of energy).

- Protostar gets hotter as it contracts, but still no core hydrogen fusion.

- Inner parts of the surrounding disk are hotter than the outer parts.
Inner parts of disk are hotter than outer parts.

Rock can be solid at much higher temperatures than ice.
The Frost Line

- The distance in solar nebula where ices can form (~150 K).
  - **Inside** the frost line: *too hot for hydrogen compounds*.
  - **Outside** the frost line: *cold enough for ices to form*.
- Between the present-day orbits of Mars & Jupiter, at ~3 AU.
Condensation & agglomeration

• Outside the frost line, ices form by **condensation** (gas phase --> solid phase directly).

• Inside the frost line, also happens for **metals & rocks**.
  – Below ~1600 K, gaseous metals & some types of rocks condense into small solid particles (grains). *This is near Mercury’s orbit.*
  – Other types of rock condense at lower temperatures.

• Small grains then grow by **agglomeration**, namely by colliding & sticking to make bigger particles.
  – “Collisions” are actually very gentle.
  – Sticking due to electrostatic forces (static electricity), not due to gravity for such small particles.
Formation of the terrestrial planets

- Tiny solid particles stick to form **planetesimals** ("pieces of planets")

- **Gravity** draws planetesimals together to form planets. This process of assembly is called **accretion**.

- Planetesimals grow from few kilometers in size to 100’s of km in ~few Myr.

- Further growth inhibited destructive collisions between planetesimals. Only the largest ones survive to form planets.
Growth of planetesimals just like for the terrestrial planets (condensation, agglomeration, and accretion).

But beyond the frost line, both solid rock and solid ices are present.

This allows the “cores” of the Jovian proto-planets to grow to much larger masses (~10 M_{Earth}).
Formation of the gas giants: Part 2

Gravity of the massive rocky/icy Jovian cores

1. Draws in H and He gases from the solar nebula (gas accretion).

2. Allows the Jovian planets to achieve much larger final sizes & masses than the terrestrial planets.

(Remember, 98% of the solar nebula was gaseous H & He.)
Why are there two types of planets?

- Jovian planets are more massive because they formed outside the frost line.
  - Hydrogen compounds condense to form ICES.
  - Solid cores of Jovian planets grow large enough to accrete H & He gas from the solar nebula via gravity.
  - Outer solar system (>3 AU) forms gas giant planets.

- Terrestrial planets form where only metals & rock are solid, too hot to form ices.
  - Inner solar system forms only rocky planets.
Massive moons of Jovian planets form in miniature disks, analogous to planets forming in the solar nebula.
Four Major Features of the Solar System

1. Why do large bodies in our solar system have **orderly motions**?

2. Why are there **two types of planets**?

3. Where did the **comets and asteroids** come from?

4. How can we explain the **exceptions** to the ‘rules’ above?
• Comets & asteroids = leftover planetesimals.
  • Asteroids: rocky b/c they formed inside the frost line.
  • Comets: icy b/c they formed outside the frostline.

• The early Solar System had many more of these, causing many collisions in the first ~500 Myr.

• May have also delivered water to the Earth.
Evidence that planets formed from small pieces crashing into each other is seen in impact craters.
The End of Planet Formation

- Rocks, metals & ices go into solid bodies (planets, asteroids & comets).

- H & He gas amount to 98% of the mass of the nebula.
  - Some gas locked up in the Jovian planets.
  - The rest is blown away by the young solar wind or evaporated by Sun’s radiation.
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Formation of the Moon

Earth’s moon was probably created when a big (Mars-sized) planetesimal slammed into the newly forming Earth (~30 Myr ago).

Other giant impacts may be responsible for other exceptions like rotation of Venus and Uranus’ extreme tilt.
Four Major Features of the Solar System

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4. How can we explain the **exceptions** to the ‘rules’ above?
As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas. Large, diffuse interstellar gas cloud (solar nebula) contracts under gravity. Sun will be born in center. Planets will form in disk.

Hydrogen and helium remain gaseous, but other materials can condense into solid “seeds” for building planets. Warm temperatures allow only metal/rock “seeds” to condense in inner solar system. Cold temperatures allow “seeds” to contain abundant ice in outer solar system.

Solid “seeds” collide and stick together. Larger ones attract others with their gravity, growing bigger still. Terrestrial planets are built from metal and rock. The seeds of jovian planets grow large enough to attract hydrogen and helium gas, making them into giant, mostly gaseous planets; moons form in disks of dust and gas that surround the planets.


“Leftovers” from the formation process become asteroids (metal/rock) and comets (mostly ice).
When did the planets form?

- We cannot directly know a planet’s age. But we can find the ages of its rocks.
- Ages of rocks are determined by analysis of its various atoms and isotopes.
- We use radioactive decay of elements into other elements as a clock.
When did the solar system form?
(a.k.a. how old is this rock?)

- Age dating of rocks from planets tells us the time since the rock solidified. This time is younger than the age of the S.S. formation.
- Age dating of meteorites that are unchanged since they condensed and grew in the solar nebula tell us the solar system is about 4.6 billion years old.
Other Planetary Systems
Doppler shift due to stellar wobble from an unseen planet.
Doppler shift due to stellar wobble from an unseen planet.
How do we find planets around other stars?

We detect planets around other stars by looking for a periodic motion of the stars they orbit ("wobbling").

We measure the motion through the Doppler shift of the star’s spectrum.
How do we find planets around other stars?

The size of the wobble tells us the planet’s **mass**.
(Newton’s law of gravity)

The period of the wobble tells us the **radius** of its orbit.
(Kepler’s 3rd law)

Current searches have a velocity sensitivity of
~2 meters/sec!!
Discovery of extrasolar planets

• 1995: Planet found around a nearby star (51 Peg) through radial velocity measurements.
  – Mass of $0.5 \, M_{\text{Jupiter}}$
  – Distance of $0.1 \, \text{AU}$.

• VERY exciting discovery, and also VERY unexpected.
The massive planet around 51 Peg
(relative planet sizes are shown correctly below, but relative spacings between orbits are not)

Orbital distance of 51 Peg B (0.05 AU)
Over 170 known **extrasolar planets** (almost all found by RV method)

About 10% of nearby stars have massive planets.

Most are more massive than Jupiter and closer to their star than Earth is to Sun: **unlike our own solar system.**

Revisions to theory needed: Massive planets can **migrate** inward from their birthplaces.
Known extrasolar planets have very different properties than planets in our solar system.
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Transiting extrasolar planets

“primary eclipse” = planet goes in front of the star
HD 209458:
First known transiting extrasolar planet
We can also detect very close-in planets if they eclipse their star (like to eclipsing binary stars).

Fraction of starlight blocked tells us planet’s size.

Combined with the mass from radial velocity data, we find the planet’s density and hence typical composition!!
Planetary transits at IR wavelengths can tell us the planet’s temperature

- Thermal emission from the planet compared to the star is larger at infrared wavelengths.
Planetary transits at IR wavelengths can tell us the planet’s temperature

- Before eclipse = \textit{star + planet}
- During eclipse = \textit{star only}
- Change in IR brightness is the energy emitted by the planet.

- Luminosity depends on:
  - Size of an object, and
  - Temperature of an object

- Size is known from transit data at optical wavelengths, so use IR data to find T \sim 1200 \text{ K}. 
Can we take a direct image of an extrasolar planet?
Can we take a direct image of an extrasolar planet?

- Radial velocity method is indirect.
  - Measure minimum mass for planet.
  - Only sensitive to inner planets (<~5 AU)

- Direct imaging would be very desirable
  - Sensitive to planets at larger separations
  - Measure properties of planet (e.g. temperature)
  - Fundamental human appeal
Can we take a direct image of an extrasolar planet?

• VERY difficult
  – Planets have very small separations from their stars
    • Ex: if the distance to the nearest star is here to California, Jupiter would be a marble @ 80 meters from the star
  – Reflected light (visible wavelengths) of the planet is extremely faint: factor of \( \sim 1 \) billion
  – Emitted light (infrared wavelengths) of the planet is still very faint: factor of \( \sim 1 \) million

• Imaging of planets around Sun-like stars is currently not possible. Several ground-based and space-based projects in near future are tackling this goal.
Can we take a direct image of an extrasolar planet?

- May be much easier by looking around young stars (few Myr old). Newly formed planets could be hot & bright.
Is the Earth Unusual?

• We don’t know, since Earth-like planets cannot be found yet around other stars.

• Current methods can only detect massive (Jupiter-like) planets.

• Theoretical models aren’t good enough to tell if terrestrial planets are common or rare.
Could life exist on any of the known extrasolar planetary systems?

- Highly unlikely: all known extrasolar planets are likely to be gas giant planets

- However, life might be able to reside on moons around these planets.

- Also, the presence of Jupiter-mass planets may be an indirect sign that formation of terrestrial-mass planets is likely.
Searching for other Earths

- **Kepler** (2007 launch): will monitor 100,000 stars for 4 years to search for transits of Earths around other stars.

![Diagram of the Kepler spacecraft](image)