• The outer solar system
The Jovian Planets

Cassini image of Jupiter, Io, and Io's shadow (NASA/JPL)
The Jovian Planets

- Gas giants in the outer solar system
  - Formed outside of the “ice line” (where water could condense and freeze)
  - Grew massive enough to hold on to cold gas from outer (=colder) proto-solar nebula
  - Primary atmospheres
# The Jovian Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Average Distance from Sun (AU)</th>
<th>Mass (Earth Masses)</th>
<th>Equatorial radius (Earth radii)</th>
<th>Density (kg/liter)</th>
<th>Rotation Period (days)</th>
<th>Composition</th>
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<tbody>
<tr>
<td>Jupiter</td>
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<td>3.81</td>
<td>1.67</td>
<td>0.67</td>
<td>Hydrogen compounds, rock, H, He</td>
</tr>
</tbody>
</table>
The Jovian Planets

- Interior:
  - Rock and iron cores
  - Gaseous mantles and cloudy atmospheres
  - *Jupiter* & *Saturn*:
    - Enough gravity to compress hydrogen to liquid and metal form
The Jovian Planets

• Why are Jupiter’s and Saturn’s interiors so tightly compressed?
  ★ Recall: *Hydrostatic equilibrium*
  ★ Outward *pressure* force = inward *gravity* force
  ★ This requires the pressure to *increase inward*

• This is enough to *squeeze* hydrogen atoms so close together that they become a *metal*
  ★ That means the *electrons* are no longer bound to *nucleus*
  ★ Metals are *electric conductors* because electrons *move freely*
Jupiter Weather

Voyager fly-by time lapse (NASA)
Jupiter Weather

- Jupiter emits $2\times$ energy it receives from Sun!
  - **Dark** belts: IR-bright $\Rightarrow$ *warm* interior gas!
  - **White** zones: IR-dark $\Rightarrow$ *cold* surface clouds!
Jupiter Weather

- Jupiter is *heated* from within
- Recall: Liquid or gas heated from below will *rise*
  - Warm, low density gas floats to top
  - Cold, dense gas sinks down
- **Convection**!
  - **Belts**: gas rises to top
  - **Zones**: gas sinks down
- **Conveyor belt** action
Coriolis Effect

• On a *rotating* platform
  ★ Objects that *should* be going *straight* travel on *curved paths*
  ✤ Objects moving inward (towards the axis of rotation) curve *ahead* of the rotation
  ✤ Objects moving outward (away from the axis of rotation) curve such they *lag* the rotation

★ On *Earth* and *Jupiter*:
  ✤ Northern hemisphere winds are deflected *to the right*
  ✤ Southern hemisphere winds are deflected *to the left*
Coriolis Effect

- Earth is a *rotating* platform
  - You can experience the Coriolis effect by throwing a ball on a *merry go round*
  - Point of view of somebody *not* on the merry go round:
    - The merry go round *keeps moving* as the ball flies across
    - In this example, ball is caught by the same person who threw it
    - This is simply because the merry go round rotated as well
Coriolis Effect

- Earth is a *rotating* platform
  - You can experience the Coriolis effect by throwing a ball on a *merry go round*
  - Point of view of somebody *on* the merry go round:
    - The carousel *appears* as not moving
    - But the ball’s path actually turns!
    - On a *rotating* platform, objects move on *curved* paths!
Jet Streams on Jupiter

- Approx. 120 m/s (about 270 mph)
- Approx. 100 m/s (about 220 mph)
- Approx. 40 m/s (about 89 mph)
Jupiter Weather

Voyager fly-by time lapse (NASA)
The Great Red Spot

- A **high** pressure system
  - *Anti-cyclone*
    - centered on a high-pressure system
  - Bigger than *entire* Earth
  - Sits between two jet streams

- Has been **stable** for over 300 years
  - Earth’s storms lose strength over land
  - No *continents* on Jupiter, so no *dissipation*?
Saturn

- Very similar to Jupiter
  - Similar Composition
  - Metallic hydrogen core
  - Similar weather bands

- Quantitative differences:
  - Smaller metal core
  - Smaller magnetic field
  - Much more pronounced ring system
Saturn’s Hexagon

- Saturn’s **hexagon**: Peculiar pattern at **South Pole**
- This is a **stable vortex**
  - Recent **experiments** explain the appearance of this pattern
  - Inner and outer cylinder rotate at **different** rates
  - Hexagon forms when **pole** rotates at **different rate** than equator

Science Magazine, 8 April 2010
Aurora Borealis

- When they hit Earth’s magnetic field
  - They **spiral** around field lines
  - Move down towards **poles**
  - Hit **atmosphere**
  - Excite emission **lines**
Aurorae

- Jupiter and Saturn show **aurorae**
  - **Energetic particles** from the Sun
    - *Trapped* in magnetic field
    - *Collide* with atoms
    - Generate *emission lines*

- Requires:
  - *Strong* magnetic field
    - Jupiter’s magnetic field: **20,000** x stronger than Earth’s!
A magnetic “dynamo” requires:

- Rapid rotation
- A liquid, conducting interior
- Convection
Uranus and Neptune

• Smaller than Saturn & Jupiter
  ★ Not as much hydrogen
  ★ Significant Water content
  ★ Smaller atmospheres
  ★ No metallic hydrogen

• Blue color:
  ★ Methane
    ✤ Absorbs red light
    ✤ Reflects blue light
Uranus rotation

• Uranus axis is tilted by 98°.

• It is thought that this is due to a large planetesimal impact.

• Uranus moons also orbit in a plane that is tilted by the same amount.

• What can we say about Uranus moons?
  
  ★ They must have formed after the impact
All Jovian planets have ring systems.

Saturn’s rings:
- Discovered by Galileo.
- As Saturn moves through orbit, we can see different orientations of the rings.
- When seen edge-on, rings disappear.
- They must be incredibly thin!
- 70,000 km across
- 20 m thick!
Ring Systems

- Maxwell (1855):
  - No single sheet of matter strong enough to make solid ring
  - Must be made of particles
  - That means the inner rings move faster than the outer rings
  - Doppler shift (measured)

- Ring particles:
  - Snow flake to boulder sized
Ring Structure: Resonances

- Cassini division (and other gaps)
  - 2:1 Resonance
    - Exactly half orbital period of Saturn’s moon Mimas (=2:1)
    - Every other orbits, particles in gap get kicked the same way
    - That alters their orbit, i.e., they get kicked out of the gap
Ring Structure: Resonances

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  ★ Every other orbits, particles in gap get kicked the same way
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  ★ Resonances occur when orbital periods are simple integer ratios
    ✦ E.g., 3:2
Moons inside ring system:

Shepherd moons (Pandora & Prometheus) guide particles into narrow rings.

Inner moon's gravity pulls forward - Moves orbits outward.

Outer moon's gravity pulls back - Moves orbits inward.

Particles pile up in the middle, making a sharp ring.

Prometheus (Cassini, NASA/JPL)

Pandora

Shepherds
Effect on moons on rings
Ring Origins

- Rings are **short-lived** (few hundred million years)
  - Magnetospheres (gas) *drag* particles *off* their *Kepler orbits*.
  - They migrate *inward*, fall onto planet

⇒ Rings must be **replenished** from time to time
  - This explains why Jupiter only has a *mini-ring* system:
    - It just hasn’t had a recent ring injection

- But *how* can we replenish the rings?
  - The answer: *Tides!*
The Roche Limit

- Rings are probably made from *shredded moons*
  - A moon is *held together* by its own *gravity*
  - We know that *tidal forces* pull objects *apart*
    - When *tidal* force becomes *larger* than moon’s own *gravity*
  ⇒ Moon is *ripped apart*

Tides win, moon breaks

Gravity wins, moon stable
The Roche Limit

- **Roche** limit:
  - Inside **2.44 planet radii**, objects can be shredded by tides
  - **Independent** of the size of the moon!
  - Shredding **continues** to smaller and smaller particles
  - ** Stops** only once **other forces** hold matter together
    - **Chemical** forces (rock)
- Jovian Planets:
  - Ring systems all **very close** to Roche radius
One Ring to Rule them all?

- 2009: Spitzer Infra-Red telescope discovered *mysterious* giant ring (200 x larger than other rings)
  - Nature and origin still unclear

Artist’s conception, based on Spitzer observations (NASA/JPL)
Satellite Systems

- **Neptune**: 13 Satellites
- **Uranus**: 27 Satellites
- **Saturn**: 62 Satellites
- **Jupiter**: 63 Satellites

*Distance from Planet Center (km)*

Earth's Moon for comparison
Satellite Properties:

• Outer solar system satellites:
  ★ Densities below 3kg/liter
  ⇒ Rock and Ice mixture

• Most inner satellites:
  ★ Tidally locked (facing same side to planet)

• Most outer satellites:
  ★ Irregular orbits (high eccentricity and/or inclination)
Satellite Properties:

- **Surface:**
  - Dark color - probably dust
  - Craters show bright, icy interior

- **Satellites** over 400 km diameter:
  - Spherical

- **Satellites** under 400 km diameter:
  - Irregular shapes

- **Why?**
Question:

• Suppose you wanted to build a tall sand castle from dry sand. What size of satellite would you pick to build it on?

A) A big one
B) A small one
C) Size shouldn’t matter

* Bigger moons have higher surface gravity:
  ⇒ Sand castles and other structures will...
  ⇒ Fluffy ice structures will be flattened
  ⇒ *Big moons* pull themselves into *spherical* shape
Satellite Origins

- Where do the satellites **come from**?
  - **Inner** (regular) satellites orbit in planet’s **equatorial plane**
  - **Outer** (irregular) satellite orbits are **different** from rotation

- Inner Satellites:
  - Likely formed with planet from disk
  - **Same process** that formed the **solar system**!

- Outer Satellites:
  - **Captured** comets or asteroids
Capture

- Orbital *capture*
  - Requires a *third* object
  - *Slingshot* into orbit
  - Orbit orientation *random*
  - High *eccentricity*
The Galilean Moons
The Galilean Moons

- **Galilean** Moons, inner to outer:
  - Io, Europa, Ganymede, Callisto ("I Eat Green Carrots")
  - Among the *most interesting* solar system objects
  - All show signs of *geological activity*!
    - Inner satellites more active than outer ones
    - Surface temperatures: 110K - 130K

<table>
<thead>
<tr>
<th>Name</th>
<th>Radius</th>
<th>Mass (lunar masses)</th>
<th>Density (kg/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>1800km (bulged)</td>
<td>1.22</td>
<td>3.5</td>
</tr>
<tr>
<td>Europa</td>
<td>1560km</td>
<td>0.66</td>
<td>3.0</td>
</tr>
<tr>
<td>Ganymede</td>
<td>2631km</td>
<td>2.03</td>
<td>1.9</td>
</tr>
<tr>
<td>Callisto</td>
<td>2410km</td>
<td>1.48</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Io
**Io**

- Young surface
  - No impact craters
  - Freshly covered in sulfur compounds
  - Active *volcanoes*!

⇒ *Liquid* interior! But why?

- *Tidal* heating
- But it is *phase locked* to Jupiter!
- It’s *Europa’s* tides that heat Io!

⇒ All *water* evaporated ⇒ high density!
Tidal heating of Io
Europa

- Surface
  - Very few impact craters
  - Covered with cracks
  - Water ice
  - "Freckles": Volcanic bumps (recall: pancake domes on Venus)
- Red surface pigmentation: Mineral rich water seepage
Europa

• Tidal heating from Io and Ganymede
  ★ Europa possibly has *liquid ocean* underneath Ice surface
  ★ Conditions might be *suitable* for existence of *life!*

• Ice geology
  ★ In outer solar system, water *ice* acts like *rock*, water as magma
  ★ Similar tectonic process as on Earth
Ganymede & Callisto

- **Ganymede:**
  - 800 km thick ice crust
  - Some fault lines, few craters
  - Possibly molten core and subsurface ocean

- **Callisto:**
  - Least differentiated
  - Oldest surface
  - Least amount of tidal heating